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Development of Guidelines for Implementation of Horizontal Directional Drilling

Prepared By
Youssef M. A. Hashash
Omar Baltaji
Guangchao Xing
Yongxi Liang

University of Illinois at Urbana-Champaign

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16. Abstract

While the fundamentals of horizontal directional drilling (HDD) technology are well known, the implementation of HDD involves utilizing a vast range of equipment and installation procedures. This project developed HDD guidance documents to provide the Illinois Department of Transportation with metrics to evaluate a proposed HDD installation. This report compiled information collected during this project, including a literature review, HDD case histories observation, and an industry survey. Four main guidance documents, including the proposed HDD Guidelines, HDD Guidance Specifications, Permit Submittal Checklist, and Inspector Checklist, are the main products developed from the project.

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Members of the Technical Review Panel (TRP) were the following:

- Heather Shoup, TRP Co-chair, Illinois Department of Transportation
- Joseph Angeli, TRP Co-chair, Illinois Department of Transportation
- Dan Brydl, Federal Highway Administration—Illinois Division
- Rebecca Tharp, Illinois Department of Transportation
- Jan Twardowski (retired), Illinois Department of Transportation
- Eric Holmes, Illinois Department of Transportation
- Megan Swanson, Illinois Department of Transportation
- Joseph Olson, Illinois Department of Transportation
- Douglas Dirks, Illinois Department of Transportation
- Giancarlo Gierbolini, Illinois Department of Transportation
- Bernard Griffin, Illinois Department of Transportation
- Marshall Metcalf, Illinois Department of Transportation
- Orlando Salazar, Baroid Industrial Drilling Products
- Dave Schuster, Schuster Pump
- Kevin Riechers, Illinois Department of Transportation
- Garrett Miller, Illinois Department of Transportation

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the collected data. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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EXECUTIVE SUMMARY

While the fundamentals of horizontal directional drilling (HDD) technology are well known, the implementation of HDD involves utilizing a vast range of equipment and installation procedures. An HDD installation needs to achieve two goals: (a) install utility element and (b) minimize the impact on existing infrastructure affected by the HDD operation.

The main objectives of this study are to (a) document the performance of selected HDD installations in Illinois, (b) conduct a survey of selected HDD contractors regarding their experience and needs, and (c) develop guidelines with quantitative metrics that can be used as the basis for evaluating proposed HDD installations for Illinois Department of Transportation (IDOT) permit review and construction projects.

The research project spanned three years and consisted of multiple research activities. More than 400 documents related to HDD were collected and reviewed. Nine HDD projects, distributed across the State of Illinois, were observed and documented. An online survey for HDD professionals collected information on their HDD experience, industry practice, and industry needs. The main outcomes of this research project were four proposed guidance documents, which aim to assist in the permitting, design, construction, and inspection of HDD under IDOT assets. These four guidance documents are the proposed HDD Guidelines, HDD Guidance Specifications, Permit Submittal Checklist, and Inspector Checklist. The lessons learned from the HDD observations, the industry survey, and the literature review were summarized and used to develop the guidance documents.

The guidance documents are designed to be compatible and complementary. The proposed HDD Guidelines is a document that that guides through all stages of HDD, including design, permitting, construction, inspection, and quality assurance. The proposed HDD Guidance Specifications is a document including a list and description of the requirements needed for permitting an HDD project. The proposed Permit Submittal Checklist is a checklist describing the requirements needed for permitting an HDD project. The proposed Inspector Checklist is a checklist that an on-site inspector can use to ensure a HDD project is performed as planned. It also contains directions for the inspector on how and what to document during an HDD project.

This final report compiles all information collected for this research project. Chapter 1 describes the project, its objectives, and its scope. Chapter 2 summarizes the main findings of the literature review. The full literature review is synthesized in Appendix F. Chapter 3 provides an overview of nine field observation case histories of selected HDD installation under Illinois Department of Transportation roadways and main lessons learned from them. The full case histories are available in Appendix G. Chapter 4 presents the results of the industry survey, while the questionnaire used in the survey is presented in Appendix H. Chapter 5 summarizes the development of the four guidance documents, which are presented in Appendices B, C, D, and E. Chapter 6 provides conclusions and identifies topics for future research. The users of the information provided in this report are fully responsible for evaluating the adequacy of the information for their own applications. The authors make no warranties as to the adequacy or applicability of the information for a specific project.

TABLE OF CONTENTS

CHAPTER 1: PROJECT SCOPE 1

CHAPTER 2: SUMMARY OF THE LITERATURE REVIEW 5

CHAPTER 3: OVERVIEW OF FIELD OBSERVATION OF SELECTED HDD INSTALLATIONS UNDER IDOT ROADWAYS 9

CHAPTER 4: INDUSTRY SURVEY 16

CHAPTER 5: DEVELOPMENT OF GUIDANCE DOCUMENTS 28

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH 30

APPENDIX A: GLOSSARY OF TERMS 31

APPENDIX B: PROPOSED HDD GUIDELINES 45

APPENDIX C: PROPOSED HDD GUIDANCE SPECIFICATIONS 64

APPENDIX D: PROPOSED PERMIT SUBMITTAL CHECKLIST 89

APPENDIX E: PROPOSED INSPECTOR CHECKLIST 92

APPENDIX F: LITERATURE REVIEW 95

APPENDIX G: FIELD OBSERVATION OF SELECTED HDD INSTALLATION UNDER IDOT ROADWAYS 284

APPENDIX H: INDUSTRY SURVEY QUESTIONNAIRE 621

LIST OF FIGURES

Figure 1. Graph. Locations of the nine observed case histories. 9
Figure 2. Chart. Respondents' years of experience. 17
Figure 3. Chart. Rig size typically used. 17
Figure 4. Chart. Max boring diameter observed by the respondents. 18
Figure 5. Chart. Max boring length observed by the respondents. 18
Figure 6. Chart. Percentage of projects for which soil investigation (borings) was done prior to drilling. 19
Figure 7. Chart. Design typically provided to respondents. 20
Figure 8. Chart. Minimum depth of cover to pavement typically used. 20
Figure 9. Chart. Minimum thickness of vertical and horizontal cover to utilities typically used. 21
Figure 10. Chart. Tracking systems used by the respondents. 22
Figure 11. Chart. Method of downhole pressure monitoring. 24
Figure 12. Chart. Method for checking impact of HDD on ground surface. 25
Figure 13. Chart. Method for moving heavy equipment and machinery over roads on site. 25
Figure 14. Flow chart. The design of four proposed guidance documents. 28

LIST OF TABLES

Table 1. Summary of the Observed Case Histories 11

CHAPTER 1: PROJECT SCOPE

PROJECT DESCRIPTION

While the fundamentals of horizontal directional drilling (HDD) technology are well known, the implementation of HDD involves utilizing a vast range of equipment and installation procedures. An HDD installation needs to achieve two goals: (a) install utility element and (b) minimize the impact on nearby infrastructure. The variability in equipment, installation procedures, and operator skills coupled with the uncertainties associated with operating underground makes achieving these goals challenging. In contrast, overly prescriptive rules regarding equipment and procedures can stifle innovation and introduce unnecessary costs for HDD methods. Therefore, it is highly desirable to develop HDD guidelines that provide the Illinois Department of Transportation (IDOT) with quantitative metrics to evaluate a proposed HDD installation without imposing an undue burden on the installation contractor.

RESEARCH GOALS

The objectives of this study were to (a) document the performance of selected recent HDD installations in Illinois, (b) conduct a survey of selected HDD contractors regarding their experience and needs, and (c) develop guidelines with quantitative metrics that can be used as the basis for evaluating proposed HDD installations for IDOT permit review and construction projects. The conditions under which HDD is feasible and permissible are still to be defined. The developed guidance documents can be used by IDOT and HDD contractors during the project design and construction phases. They can assist IDOT personnel in evaluating proposed HDD activities and their potential impact on existing infrastructure. Proposed guidance documents are included in the appendices for statewide use by Operations, which can be adapted to provide (a) guidance in the *Bureau of Design and Environment (BDE) Manual*, (b) recommendations for soil data needed and evaluation guidance, which can be incorporated into IDOT's *Geotechnical Manual*, and (c) recommendations for the development of a special provision for HDD installation of pipe culverts, storm sewers, and other transportation-related utilities, which has the potential for incorporation into the *Standard Specifications for Road and Bridge Construction*.

The proposed work was divided into the following tasks:

Task 1: Review of Existing Information

Hashash et al. (2011) conducted a study for IDOT to research the effects of HDD for utilities under pavement and within the right-of-way of the State of Illinois to aid in the preparation of the policy and procedures for administering HDD permit requests. The report covered Phase I of the work, which included the following:

- Research for the development of general information and recommendations on the following:
    - Cost comparison of directional drilling with the Jack and Bore method.

    - Horizontal and vertical location requirements and clearances.
    - Industry codes and other government regulations or provisions.
    - Preservation and restoration of highway facilities, appurtenances, natural features, and vegetation and limitation on the utility activities in a right-of-way.
    - Protection of traffic during and after installation, including traffic control, access control, open pits, material storage, vehicle parking, the timing of projects, and length of time to construct.
    - Direct and indirect environmental and economic effects, including loss or impairment of productive agriculture and liabilities associated with future relocations.
- Observation of a directional drilling project with a larger sized pipe diameter to better understand the process and evaluate for possible conflicts of interest.
- Establishment of preparatory information to continue onto Phase II, including the following:
    - Recommendations on what should be studied.
    - A listing of possible sources of damage to roadways.
    - A preliminary decision on the viability of the HDD construction method as well as its possible restrictions.
    - Procedures for the directional bore method to reduce damage to sidewalks and driving pavement.

Since 2011, additional research on HDD in Illinois was completed. Moreover, new developments on HDD have been published. In this task, information and literature related to HDD developed since the 2011 study (Phase I) were compiled with the following steps:

- Inventoried current and new technologies that are in use in Illinois.
- Collected prior observations and documented damage due to HDD installations.
- Reviewed published literatures for new HDD cases as well as guidelines being used by other departments of transportation or agencies in the US or elsewhere around the world.
- Drew from related topics, such as drilled shaft construction, as needed to innovate and enhance current knowledge and practice.

Information about HDD in the State of Illinois was compiled in part from permit information that IDOT already had as well as reported problems that resulted during construction.

Task 2: Observe Selected HDD Installations

Task 2a: Under this task, opportune HDD installations were identified whereby the firsthand installation process could be observed. These installations additionally provided the opportunity to collect detailed information on the installation process and information on the impact of the installation on roadways. This allowed for the development of well-documented case histories that could also be used to develop guidelines. The soil boring data and associated laboratory test results of observed sites were also obtained and included.

Task 2b: A detailed questionnaire for HDD contractors was created to allow for the systematic collection of information on (a) detailed installation procedures, (b) technical challenges faced in the field, and (c) barriers to the adoption of new and better technology.

Task 3: Evaluation of Factors Relevant to HDD Installation and Their Impact

In this task, the information collected under Tasks 1 and 2 was synthesized to systematically evaluate the following:

- Understanding of materials and soil-structure interactions.
- Impact of material type and size for the permanent pipes (steel, HDPE, PVC, etc.) and depths of installation.
- Metrics to evaluate the impact of proposed installation procedures, torque ranges, pull speed, entry angles, exit angles, drill head types, amount of overall water use, drill fluid mixtures, post grouting, and the like on anticipated performance.
- Information on in-situ soil.
- Impact of over ream size on stability, considering the soil amendment, depth of the bore, and size of the pipe.
- Relevance and composition of drilling fluid.
- Development of guidelines to assess construction feasibility of working room, including anticipated pit depths and sizes.

Task 4: Development of HDD Guidance Documents and Final Report

Task 4a: The guidance documents included the proposed HDD Guidelines, HDD Guidance Specifications, Permit Submittal Checklist, and Inspector Checklist. These documents were developed partly in collaboration with IDOT with a future aim of integration into applicable IDOT policy and specification documents such as the *Geotechnical Manual*, Operations' *Utility Permit Guide*, the *Bureau of Design and Environment (BDE) Manual*, and the *Standard Specifications for Road and Bridge Construction* with a primary focus on geotechnical aspects. Towards the end of this task, a presentation was made at a meeting of affected agencies to solicit their input on the draft guidelines.

Task 4b: This report compiles all information collected from this project, including the literature review, case histories, contractor experience, evaluation of factors relevant to HDD, conclusions of the evaluation, and recommendations for feasibility assessments and construction installation as well as recommended installation specifications.

STRUCTURE OF FINAL REPORT

Chapter 1 describes the project, its objectives, and its scope. Chapter 2 summarizes the main findings of the literature review. The full literature review is synthesized in Appendix F. Chapter 3 provides an overview of the nine field observation case histories of selected HDD installation under IDOT roadways and the main lessons learned from them. The full case histories are available in Appendix G. Chapter 4 presents the results of the industry survey, while the questionnaire used in the survey is presented in Appendix H. Chapter 5 describes the development of the four guidance documents, which are presented in Appendices B, C, D, and E. Chapter 6 provides conclusions and identifies topics for future research. Appendix A presents the glossary of terms.

CHAPTER 2: SUMMARY OF THE LITERATURE REVIEW

INTRODUCTION

Around 400 documents related to HDD were collected and reviewed in this project. These documents include conference papers, journal papers, codes, standards, guideline documents and manuals, theses, books, and book chapters. The documents in this literature review were divided into four categories: (a) nontechnical documents (~50 documents); (b) technical documents (~200 documents); (c) case studies (~100 documents); and (d) codes, guidelines, and specifications (~30 documents). The main takeaways were summarized in a literature review. Case studies were summarized as well in Table 8, comparing project conditions and parameters as well as highlighting the lessons learned. The lessons learned from the literature review were integrated into the final guidance documents. **While this is a brief portion of the literature review, the full literature review can be found in Appendix F**.

NONTECHNICAL TOPICS

The reviewed documents covered a range of topics related to HDD. The nontechnical topics included (a) history of HDD, (b) advantages of HDD, (c) applications of HDD, (d) environmental considerations, and (e) managerial aspects. The details of each topic are available in Appendices F.1, F.2, and F.3.

For example, risk events were identified and summarized in section F.3.4.1. The critical risks that were identified include, but are not limited to, (1) hydraulic fracturing, (2) collapsing soil/lost hole, (3) loss of circulation, (4) high annular pressure, (5) abnormally slow production, (6) reduced drill cuttings return, (7) drill string stuck in the hole, (8) delays from wait on vacuum truck, (9) wire-line malfunction/damage, (10) down-hole tooling malfunction/damage, (11) surface equipment malfunction/damage, (12) delays from wait on the owner, (13) delays from wait on equipment/services, (14) pilot hole deviations, (15) flow to exit, (16) drilling fluid/solids control work, (17) weather delay, (18) water production, (19) conductor casing delays, (20) damaged product line, and (21) product line stuck in the hole.

TECHNICAL TOPICS

The technical topics covered in the literature review included (a) site investigation, (b) geometric design, (c) pipe design, (d) fluid design, (e) construction equipment, (f) alternative construction methods, and (g) performance and quality control. The details of each topic are available in Appendices F.4 and F.5.

For example, in section F.5.1, Lueke and Ariaratnam (2003) point out that horizontal drilling parameters that could affect surface deformations include (1) borehole pressure, (2) depth of cover, (3) soil density, (4) back-ream rate, (5) soil composition, (6) annular space, and (7) reamer type and diameter. These parameters will need to be carefully examined during the process of approving HDD constructions.

CASE HISTORIES

The literature review of case histories contained more than 100 documents. Sixty-eight of those case histories were summarized in Table 8, comparing projects' conditions and parameters as well as highlighting lessons learned, which can be found in Appendix F.

Some examples of the lessons learned in the review of documented case studies are as follows:

- Soil investigation before construction is very important for the design and safety of the project. Depending on the field investigation implications, ground improvement may be required before drilling starts. Jeyapalan (2010) describes a lake-crossing HDD project, which was awarded for 1.74 million dollars with a time frame of 90 days but ended up costing more than 6 million dollars and lasting 1,000 days. According to Jeyapalan (2010), the large-diameter pipe installed using HDD ran over budget because of problematic soil conditions (loose sands, gravel, and cobbles). The design was based on incomplete information on the soil conditions. The paper also describes some of the complications that resulted from ambiguous contracts, highlighting the limits of authorities of different entities. Lueke et al. (1998) describes the soil improvement that was performed before the installation of a 2,296.6 ft (700 m) long crossing for a high-pressure pipeline. This was due to the realization that the proposed path will pass through coal mines containing exposed seams of coal that were extensively mined, creating unstable slopes. Grouting was performed via 105 grout holes.

- Pressure calculations are essential for design and safety aspects. Monitoring pressure during drilling and maintaining it below the maximum allowable pressure is crucial. Multiple methods for dealing with zones of high hydro-fracture risk are available. Burnam et al. (2002, 4) describe the installation of a 100 ft (30.5 m) long, 30 in. (76.2 cm) steel force main: "*A minimum depth beneath Trout Creek was established by performing a hydro-fracture analysis, based on cavity expansion theory. With the soils in close proximity to the bore path, a minimum depth of 7.6 m (25 ft) below the creek was established. This minimum depth was specified, allowing the contractor to deepen the alignment at their choice.*" Performing pressure calculations (borehole stability analysis) might save a project from complications by reducing the chances of hydro-fracture. M. Gelinas et al. (2010) present a project where a hydro-fracture caused the authorities to change the construction method, preventing the completion of the bore with HDD. The design of the 771 ft (235 m) long, 15.7 in. (40 cm) diameter HDPE water pipe was to be installed at an invert depth of 14 ft (4.3 m). Shell et al. (2012) provide another example where pressure calculations were performed, and the actual pressures measured are presented.

- Mixed-faced conditions could also cause difficulties in HDD implementation. Robison et al. (1997, 132) document two HDD installations. In one of the installations, "*the first ream was attempted using a 0.44-m (1.2-ft) barrel reamer, back-reaming from the West Canyon towards the drill. However, the barrel reamer advanced approximately 427-m (1500-ft) until it reached the harder quartz-diorite. The barrel reamer was unable to advance through the quartz-diorite. Consequently, the barrel reamer was removed, and a 0.44-m (1.44-ft) diameter hole-opener was installed.*"

- The lessons from using different HDD product materials were also summarized. These include some examples of large-diameter pipe installations that employed ductile iron pipes and were presented in Ehrin and Carpenter (2006) and Carpenter, Schwarzlose, and Whitaker (2005). Some examples of large-diameter pipe installations that employed fusible polyvinyl chloride (FPVC) pipes were presented in Shae, King, and Botteicher (2010) and Price, Olson, and Staheli (2015).

- Diverse HDD technologies adopted in practice were presented by case studies. Some examples of HDD installations that employed the intersect method (drilling from both ends) were presented in Tu, Ma, and Zhao (2011) and Zhang, Zhou, and Ma (2011). Ellenberger et al. (2014) document the installation of one of the longest large-diameter crossings in the US. According to Ellenberger et al. (2014, 421), the HDD installation crossing the St. Johns River aimed at installing 6,500 ft (1981 m) of 36 in. (91.4 cm) steel pipe: "*Prior to drilling operations, 60-in* (152.4-cm) *diameter conductor casing was installed by pneumatic hammer on each side of the River, including 80-ft* (24.4-m) *on the west side and 190 ft* (57.9-m) *on the east side. The conductor casings stabilized the surface near the entry/exit points, the areas with the highest potential for ground disturbance and drilling fluid to return to the surface. The pilot hole was drilled using the intersect method with a drill rig on each side of the river to reduce the distance spoils need to travel back to the entry/exit point, which reduced the potential for inadvertent returns to occur.*"

CODES, GUIDELINES, AND SPECIFICATIONS

The review of codes, guidelines, and specifications covered a wide range of topics. The topics include methods for calculating pull loads as well as downhole pressure and maximum allowable pressure, installation and operating loads and stresses, comparisons made in the literature to actual field measurements, and dealing with areas of high risk to hydro-fracture. The topics also include advantages and disadvantages of different pipe materials, adjustment of fluid design according to soil conditions, selection of reamer type according to soil conditions, advantages of HDD over open cut and other trenchless technologies, and monitoring of ground and pipe performance.

The literature review of codes, guidelines, and specifications was summarized and integrated into the proposed guidance documents.

Some examples of the lessons learned from those documents include the following:

- If a hydro-fracture evaluation indicates that high risks of hydro-fracture exist at certain locations or segments of the HDD bore, Bennett and Wallin (2008) suggested employing measures such as relief wells, piezometers, conductor casings, and monitoring drilling fluid returns at the drill rig. Gelinas and Mathy (2004) suggested that the bore path should be designed to either avoid areas of problematic soils or minimize the length of the bore path within them.

- Slavin and Scholl (2014) pointed out that although the ASTM F1962 method is explicitly intended for use with polyethylene (e.g., high-density polyethylene [HDPE]) pipes, and the

Pipeline Research Council International (PRCI) method was initially developed for steel pipes, accounting for the relatively high bending stiffness of this product, both procedures have been used for estimating HDD pull loads for pipes of various materials.

- ASTM D6286 (1998) stated that water without additives is not an effective drilling fluid for two reasons. First, it does not have any cuttings-carrying capability. Second, it does not possess any gel-strength properties for building a mud rind on the borehole wall.

CHAPTER 3: OVERVIEW OF FIELD OBSERVATION OF SELECTED HDD INSTALLATIONS UNDER IDOT ROADWAYS

INTRODUCTION

Nine HDD projects were observed and documented in this report. This documentation was possible with the help of numerous contributors, including IDOT personnel, contractors, and consultants. The HDD projects, which are all of midi or maxi size, varied in length from 60 ft (18.3 m) to more than 6,000 ft (183 m). The projects were distributed over the State of Illinois, as illustrated in Figure 1. In this report, the projects are herein documented in chronological order and named after the cities in which they were performed. Note that the project in Quincy was the first project observed, before the official start of this research project; hence, very little information was collected about it. The order in which the HDD projects appear in this report is as follows: Quincy, Hennepin, Pecatonica, Elsah, Highland, Jacksonville, Farmer City, Litchfield, and Rochelle.

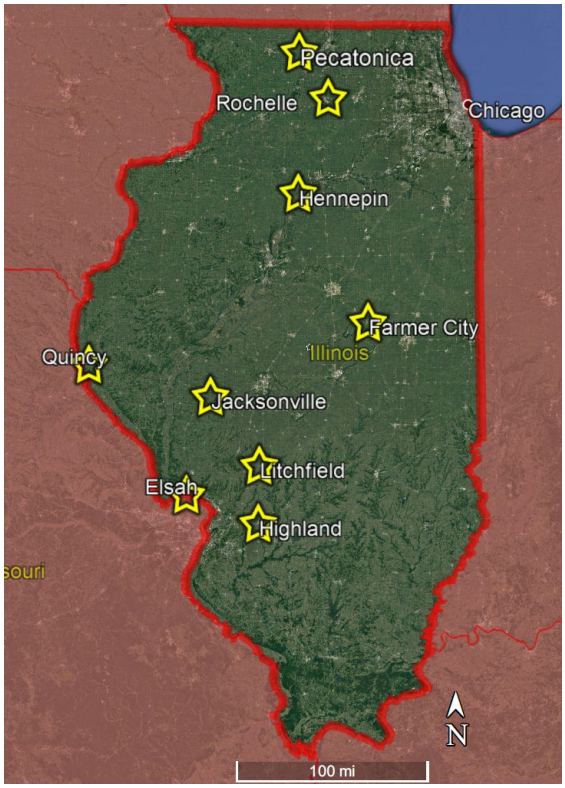


Figure 1. Graph. Locations of the nine observed case histories.

DOCUMENTATION OF SELECTED HDD INSTALLATIONS

The documentation of each case started with a description of their goal, settings, and site conditions of the project. A description of the design and foreseen challenges are provided if available. The execution of the project and its performance is then described in detail. Each observation is concluded with the lessons learned from it.

The information about installed product pipes in each observation is as follows:

- In the Quincy project, a 12 in. (30.5 cm) plastic pipe was installed beneath the pavement on Harrison Street.

- In the Hennepin project, a 24 in. (61 cm) HDPE pipe culvert was installed under IL-26, next to an existing 24 in. (61 cm) corrugated steel pipe.

- In the Pecatonica project, a 20 in. (50.8 cm) NICOR steel gas transmission line was installed parallel to Conger Road to replace the existing 12 in. (30.5 cm) pipe, which was abandoned in place.

- In the Elsah project, a 24 in. (61 cm) steel natural gas pipeline was installed under IL-100. This installation crossed beneath the Mississippi River.

- In the Highland project, a 12.75 in. (32.4 cm) natural gas transmission line, with an uncased 0.5 in. (1.27 cm) thick steel wall, was installed under IL-143 parallel to US-40. The installation crossed two parking lots.

- In the Jacksonville project, a 10 in. (25.4 cm) steel casing was installed under IL-104 and the adjacent BNSF Railway. A 4 in. (10.16 cm) PVC water main was installed inside the casing.

- In the Farmer City project, a 12 in. (30.5 cm) HDPE casing was installed beneath I-74, and then an 8 in. (20.3 cm) HDPE water main was installed inside the casing.

- In the Litchfield project, a 16 in. (40.6 cm) restrained joint (RJ) PVC forced sewer main was installed inside a 24 in. (6 cm) HDPE casing under I-55.

- In the Rochelle project, two parallel steel casings, 20 in. (50.8 cm) and 12 in. (30.5 cm) in diameter, were installed under I-39, north of the interchange with IL-38. The 20 in. casing was to house a water main, while the 12 in. (30.5 cm) was to house a sewer main.

Table 1 summarizes the length, bore diameter, incidents that occurred during those installations, and approximate depth of cover at incident locations. **The full description of each project is documented in Appendix G**.

Table 1. Summary of the Observed Case Histories

Case Name	Bore Diameter (in.)	Bore Diameter (cm)	Bore Length (ft)	Bore Length (m)	Incidents	Approximate Depth of Cover at Incident Locations
Quincy	18	45.7	60	18.3	N/A	N/A
Hennepin	36	91.4	160	48.8	Bore collapse	N/A
Pecatonica	30	76.2	635	193.5	2 Inadvertent returns	6, 8 ft (1.8, 2.4 m)
Elsah	36	91.4	6250	1905	1 Inadvertent return	25 ft (7.6 m)
Highland	18	45.7	1100	335.3	Multiple inadvertent returns	< 15 ft (4.6 m)
Jacksonville	15	38.1	200	61	N/A	N/A
Farmer City	18	45.7	400	122	Hydro-fracture	8 ft (2.4 m)
Litchfield	30	76.2	330	100.6	N/A	N/A
Rochelle	30 & 24	76.2 & 61	440	134.1	2 Sinkholes	5, 8 ft (1.5, 2.4 m)

COMPILATION OF LESSONS LEARNED

A compilation of lessons learned from the selected HDD installations is as follows:

- The movement of heavy machinery on the road, especially those with metal treads, has the potential to cause significant distress for the pavement. Measures should be employed to protect pavement from damage due to heavy construction equipment such as the use of neoprene pads or crane mats.

- A proper pipe layout and handling plan should be prepared prior to the commencement of construction, taking into consideration the topography of the area and the full length of the pipe. Without doing so, the pipe might be subjected to sharp angles, which may affect its integrity or reduce its final quality or durability.

- Proper soil investigation should be performed prior to commencement of construction. This will inform the designer and contractor of any ground challenges and potentially improve their decisions. For example, the design of the fluid mix is significantly influenced by the type of soil to be expected.

- Choosing a fluid mix that is suitable for the soil conditions encountered is essential for a successful installations.

- Handling spoils might be challenging when the topography limits machine accessibility (like vacuum trucks).

- Low temperatures cause many difficulties for HDD operations. They could result in equipment freezing and breakdown, delays, and negatively impact the productivity of the crew. It is recommended to avoid working in low temperatures by adjusting the HDD job schedule.

- Equipment maintenance and cleaning before any HDD job can prevent delays and financial losses.

- Drilling at shallow depths increases the risks of impacting the ground surface. This was clear when two incidents of inadvertent return occurred when the drill bit was at relatively shallow depths. To avoid such occurrences in those sections, the fluid pressure should be controlled. Since reducing the fluid pressure might increase the risk of bore clogging—especially in long bores, pressure relief holes should be adopted. Thus, pressure relief holes are optional.

- Selecting a reaming system that allows excavators to help in the reaming process could reduce the thrust demand on the rig. This type of reaming system can keep drill strings present across the whole length of the bore after the pilot drilling is completed. Nevertheless, it may still require numerous drill rods.

- Large working areas on both sides of a project can facilitate operations and reduce disruption to adjacent roads.

- Long, large-diameter installations can be performed using the HDD method. The diameter is limited by local equipment, cost, contractor, practicality, etc.

- The contractor's experience and capability of handling issues swiftly are essential for the success of high-complexity projects.

- Adoptions of advanced methods and equipment such as the tracking system (gyro-system), drilling method (the intersect method), and conductor casings, is helpful to the successful completion of HDD construction.

- Calculating downhole pressure properly is beneficial and is a practice that should be adopted and generalized.

- The use of a fluid recycling system can reduce expenses for the contractor and could save natural resources such as water.

- Detailed construction daily reports are extremely valuable in documenting the progress and issues of HDD constructions and providing guidance for future HDD projects. Similar reports should be prepared for other projects.

- Monitoring the continuity of the fluid return and its volume is a beneficial practice that allows the contractor to detect hydraulic fracture and adjust the drilling procedure accordingly.

- Despite the pressure calculations, inadvertent returns have occurred near the exit and entrance pits. This is a risk that is always associated with the HDD construction method, and owners and departments of transportation should be aware of it.

- Using HDD for long and shallow installations comes with a great risk of inadvertent returns that may undermine overlying structures and utilities. This should be avoided by using a greater depth of embedment or other means of protection.

- The movement of heavy equipment on pavement may impact the pavement by cracking it, allowing for inadvertent returns to pass through it, which magnifies the issue at hand.

- Pressure relief holes are used to reduce downhole pressure in predefined locations far away from utilities or critical points of the profile. Pit holes, which are drilled to identify the location and depth of utilities, could serve as pressure relief holes in some cases. However, using these pit holes as pressure relief holes is not recommended because the fluid flow should not occur adjacent to utilities.

- Fluid mixes are usually bentonite-based. Fluid mixes that are not bentonite-based could also be used in industry for some ground conditions.

- The occurrence of inadvertent returns in the early stages of drilling in certain locations may suggest a chance of repeating inadvertent returns in the same or surrounding locations during later stages of construction.

- Selecting an adequate reamer type is essential in avoiding a pressure build-up inside the hole. For example, compaction reamers are suitable for coarse-grained soils but not for fine-grained soils, which cannot consolidate quickly as reaming is happening.

- Railways impose special restrictions on HDD construction (e.g., frequent stops as trains pass) and design (e.g., deeper embedment depth) that must be considered when planning for HDD projects.

- The necessary length of casing should be properly estimated prior to construction in order to avoid the need to attach extra casing sections while pulling the pipe. Attaching extra sections to the casing while the casing is bent inside the boring could cause significant delays.

- Trench support should be provided for deep trenches to protect laborers that have to go into the trenches, if this is needed (for example, to change the drilling bit, attach reamer, fix the pipe, etc.).

- Pressure calculations are essential for checking the possibility of fracking, and important design modifications might be made such as using pressure relief holes or increasing the depth of cover.

- Using pressure relief holes and increasing the depth of cover could effectively reduce the risk of fracking.

- Fracking is susceptible at shallow depths, even though high strength of clay deposits can exist.

- Swabbing might help in cleaning the boring and preventing blockages that may lead to pressure accumulation and possible fracking.

- A product pipe—and even a casing—might be damaged if subjected to high stresses due to dragging on the ground or being excessively bent. A plan should be prepared for handling the pipe, and the bend angles must be calculated and kept within safe limits to protect the pipe.

- HDD installations under pavements that are below the level of the entry and exit points have extra vulnerability for frac-out, because the elevation difference would increase the pumping pressure. In these cases, large elevation difference would become an important factor to cause frac-out.

- Extra caution should be applied to critical highways like interstates since damaging them would result in significant traffic disruption and large repair costs.

- Installing multiple lines in one area might give contractors extra confidence. This may encourage them to quickly execute similar lines, which might result in additional problems. The drilling, reaming, and fluid pumping rates should always be monitored and kept below acceptable limits.

- The presence of inspectors is necessary for the duration of the whole HDD process, including casing and product pipe pulling.

- The alignment of casing should be tested during and after the pilot drilling stage. Corrections should also be made at this point, rather than waiting after reaming or pipe pulling, when adjustments might be infeasible.

- Contractor experience is crucial for critical projects, including those with crossings beneath interstate highways.

- Coordination between the contractor and the local authorities (city council, police department, etc.) may save all parties a lot of time and cost.

- HDD installations that pass through mixed soil conditions, especially soil-rock interface, pose considerable technical challenges and elevated levels of risk. Controlling the alignment in those installations is usually more difficult, and repeated attempts might remove excessive amounts of soil, which may result in sinkholes. It is preferable, if possible, to conduct the whole drilling process in one soil or rock type to eliminate soil-rock interface challenges.

- Monitoring the rig pressure can provide insights into ground conditions.

- Soil investigation is essential for HDD projects, especially those that pass under critical structures. It helps identify possible challenges in advance and allows for design and construction adjustments to be made.

- In critical projects, enough offset from the entry and exit points to the limits of the highway should be maintained. This would create a buffer zone and prepare for possible frac-outs. The length of this buffer zone depends on the depth of embedment, the length of the installation, ground conditions, and the importance of the overlying structures and utilities.

- Inadvertent returns are more likely to occur in areas with weaker soils. On one project, they occurred in the relatively weaker and recently filled sinkholes.

CHAPTER 4: INDUSTRY SURVEY

INTRODUCTION

An essential step that precedes any attempt to utilize technology in a better and safer manner is to understand the state of practice of the industry in the location of interest. To understand the state of practice of the HDD industry in the State of Illinois, a questionnaire was prepared to survey contractors and HDD professionals about their methods, materials, equipment, procedures, and to benefit from their experiences regarding technical challenges that may be encountered in the field and how to deal with them. It also allowed the audience surveyed to provide their suggestions and feedback. The questionnaire was made electronically via Google Forms. It was reviewed by the Technical Review Panel (TRP) members and was adjusted per their feedback.

The questionnaire was composed of four parts. Part 1 inquired about the length of experience of the respondent and the size (diameter and length) of HDD installations with which he/she is typically engaged. This is important because bores with different sizes vary in their construction methods, equipment, and challenges. Part 2 inquired about essential technical details about the contractors' methods of design, construction, testing, and quality control. Part 3 inquired about technical challenges and problems that the respondent may have witnessed and about the way he/she dealt with them. Part 4 asked about the guidelines document the respondent typically uses, if he/she is interested in a follow-up conversation, and any suggestions or feedback he/she has.

A list of over 70 HDD professionals and companies was compiled from different sources: online searches, acquaintances on HDD cases observed by the University of Illinois at Urbana-Champaign (UIUC) team, and TRP members' contacts and recommendations. The list included HDD companies that varied in size and years of experience. Most of the companies were located in Illinois, while the remaining companies were located outside of Illinois, but occasionally are engaged in jobs in Illinois.

The survey started on December 4, 2019, and responses were received till the end of February 2020. The final version of the questionnaire that was sent out is presented in Appendix H. Seventeen responses were received via different methods: directly through Google Forms, handwritten responses scanned and sent via email, or through phone calls. The approximate return rate was 25%. The responses to the survey are summarized in this chapter.

EXPERIENCES IN HDD

The respondents had different lengths of experience with HDD, as presented in Figure 2, with the average experience (of the 15 responses received on this question) at 21 years.

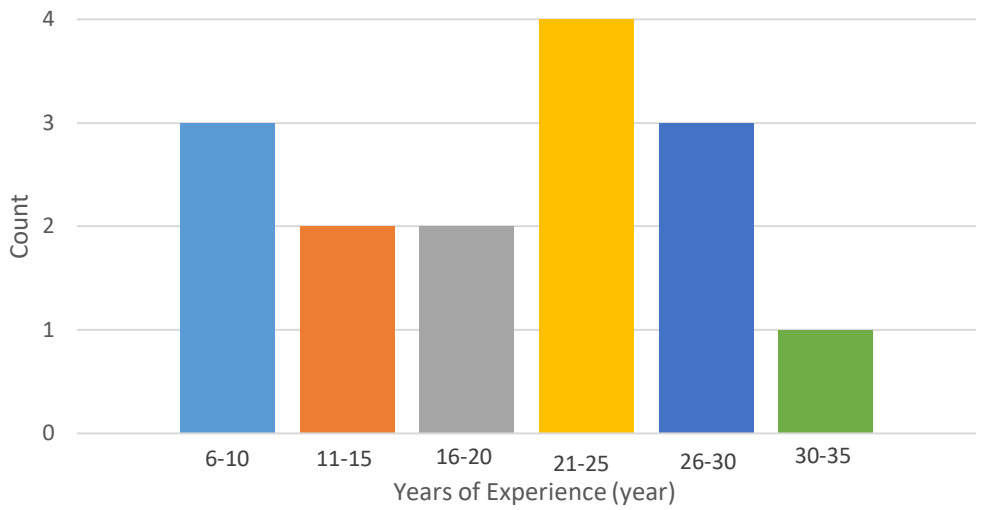


Figure 2. Chart. Respondents' years of experience.

The rig size typically used or observed by the respondents was distributed over the three rig sizes in the market (Mini, Midi, Maxi), as presented in Figure 3. Slavin (2011, 1) defined mini-HDD as "a class of HDD typically employed for boring segments less than 600-ft (183-m) in length, at depths up to 15-ft (4.57-m), and placing pipes up to 12-in (30.5-cm) in diameter. The equipment is characterized by a thrust or pullback capability of up to 20,000 lbs (9070 kg), or possibly greater, with torque less than 950 ft-lbs (1.28 kN-m) and weigh less than 9 tons (19842 lbs)." Midi-HDD is defined by Slavin (2011, 8) as a category that has "greater capabilities than mini-HDD but much less than maxi-HDD equipment which is capable of accurately boring holes on the order of a mile in length, and placing pipes of 24 in. (61 cm) or greater, at depths up to 75 ft (22.9 m)." Thereafter, according to Slavin (2011, 7), maxi-HDD is defined as HDD machines that can "weigh as much as 30 tons (27215 kg), or greater, and are appropriate for placing pipes under larger rivers or other major obstacles."

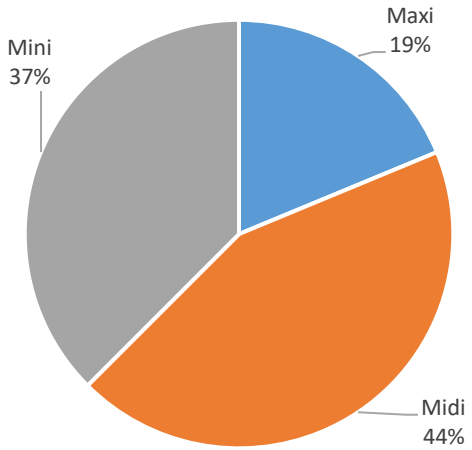


Figure 3. Chart. Rig size typically used.

The diameter of the largest boring ever bored or observed by the respondents varied between 14 and 72 in. (35 and 183 cm). The binned distribution of the responses is presented in Figure 4.

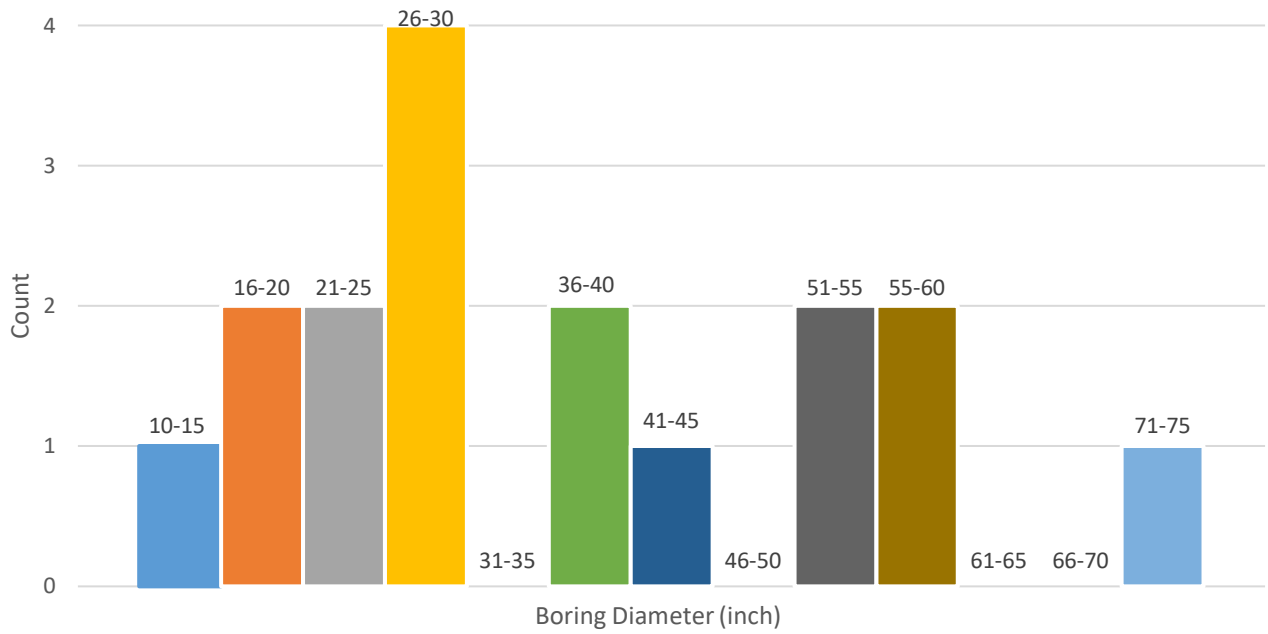


Figure 4. Chart. Max boring diameter observed by the respondents.

The length of the longest boring ever bored or observed by the respondents varied between 550 and 11,635 ft (168 and 3,550 m). The binned distribution of the responses is presented in Figure 5.

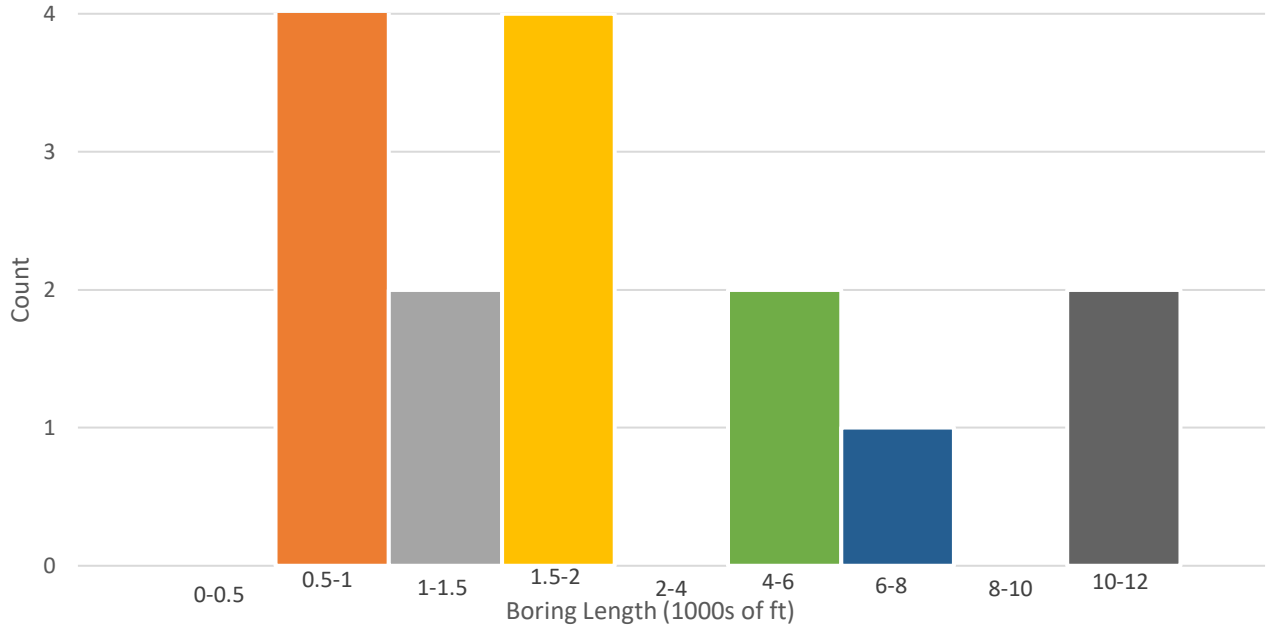


Figure 5. Chart. Max boring length observed by the respondents.

The results demonstrate that the responses came from a population with rich experiences, exposure to different boring diameters and lengths, and familiarity with different equipment.

PERFORMANCE OF HDD

Most respondents reported a very small percentage of the projects for which soil investigation (soil borings, etc.) data was available to them prior to the start of construction operations. Three of the five companies that reported percentages of 40% or above are those that are typically engaged with large projects (as they use Maxi rigs). The binned distribution of the responses is presented in Figure 6.

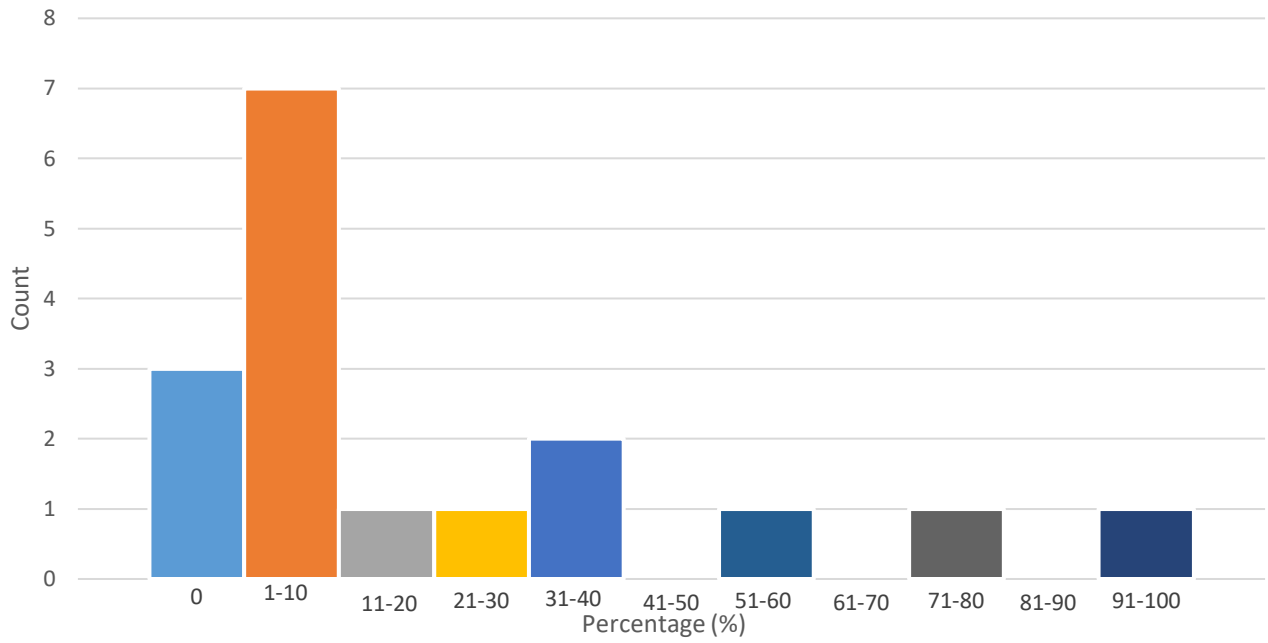


Figure 6. Chart. Percentage of projects for which soil investigation (borings) was done prior to drilling.

In most instances, soil investigation was either not performed for HDD projects, or the results were not made available to contractors who were performing the drilling.

The soil investigation data, when available, came from borings (15 responses), observations from test pits (6 responses), lab testing (5 responses), and ground surface inspection (5 responses).

When asked about the design provided to them, 47% of the respondents reported that the design included entry and exit points. Thirty-five percent reported that the design included the full profile, while the rest (18%) reported that no design was typically provided for them. This distribution is presented in Figure 7.

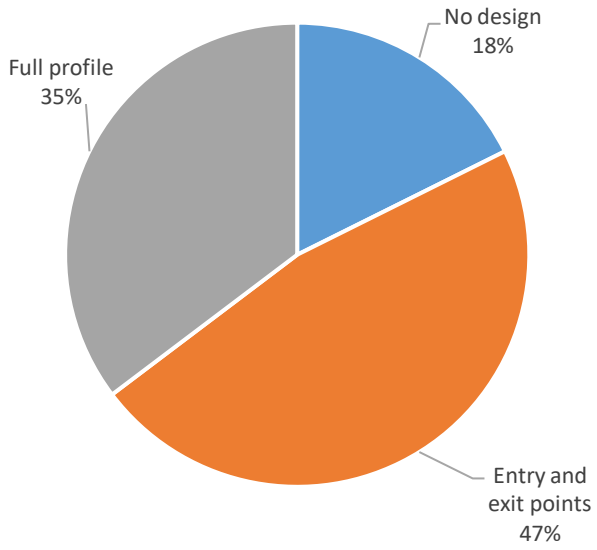


Figure 7. Chart. Design typically provided to respondents.

The minimum depth of cover to pavement reported varied between 2 ft (0.6 m) up to 25 ft (7.6 m), as presented in Figure 8. For more than 75% of the cases, minimum depths of cover varied between 2 and 5 ft (0.6 to 1.5 m) , among which 3 ft (0.9 m) was the most adopted minimum depth (about 46%). The 25 ft (7.6 m) and 10 ft (3 m) minimum depth of cover to pavement reported came from contractors who are typically engaged with large projects (as they use Maxi rigs). In comparison, the 5 ft (1.5 m) minimum depth of cover came from a contractor typically engaged with medium projects (as they use the Midi rig).

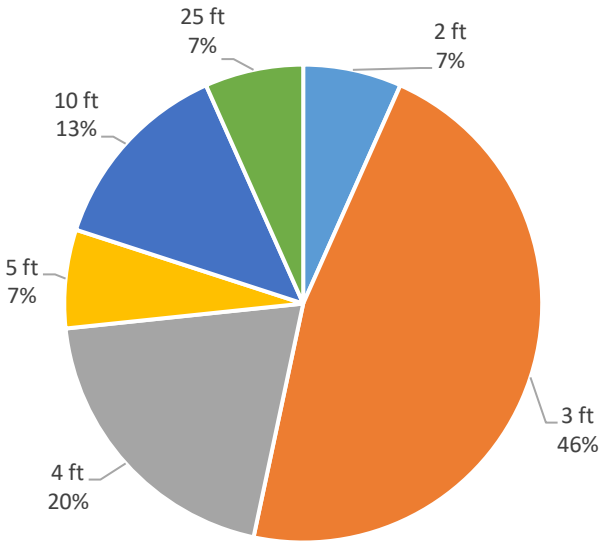


Figure 8. Chart. Minimum depth of cover to pavement typically used.

The minimum thickness of vertical and horizontal cover from utilities reported varied between 1.5 and 5 ft (0.45 and 1.5 m), with around two-thirds reporting the use of 2 ft (0.6 m), as presented in Figure 9. The 5 ft (1.5 m) thickness of cover reported came from a contractor that uses a Maxi rig.

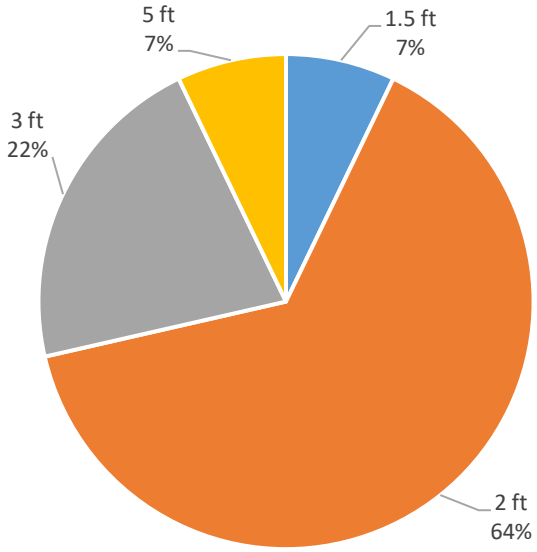


Figure 9. Chart. Minimum thickness of vertical and horizontal cover to utilities typically used.

Different drill bits and downhole tools were used by the respondents. The reported types were duck bill bits (appeared in 7 responses); PDC (polycrystalline diamond compact bits) (3 responses); spade bits (2 responses); square bits, mill tooth bits, steep tapered bits, and TriCone bits (3 responses); jetting assembly, downhole motor for rock, and pneumatic hammer for rock (1 response).

A variety of reamers were used as well. The reported types were beaver tail reamer (6 responses), compaction reamer (5 responses), hole opener (4 responses), fluted reamer (4 responses), fly cutter reamer (3 responses), barrel reamer (2 responses), helical reamer (2 responses), spiral reamer (2 responses), and mix master reamer (1 response).

Most respondents (76%) reported the use of the walkover system only, as presented in Figure 10. Twelve percent reported the use of both the walkover and wireline systems. Twelve percent reported the use of walkover, wireline, and surface coil systems. The wireline systems and the surface coil systems were used by contractors that employed Maxi rigs. One contractor that employed a Midi rig reported the usage of a wireline system.

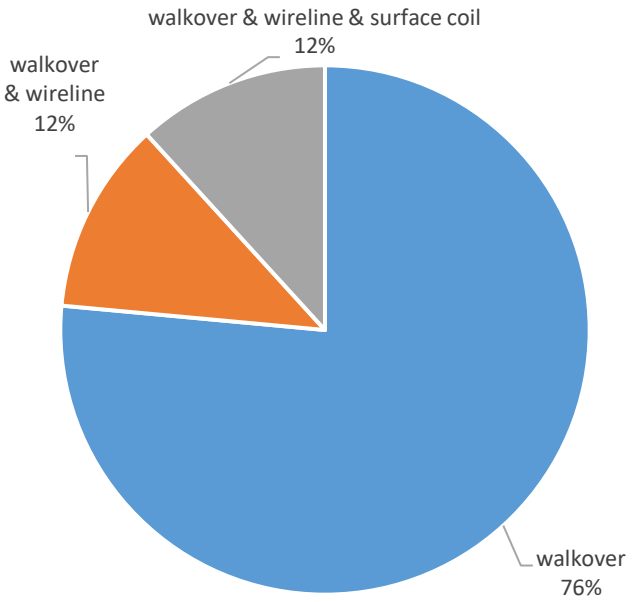


Figure 10. Chart. Tracking systems used by the respondents.

The respondents reported the components of the drilling fluid mixes they used when drilling in coarse-grained soils. All mixes reported were composed of bentonite in addition to zero or more of the following additives: polymer additives such as NoSag and Quicktrol, PAC polymers, SuperVis, Platinum Pac, Poly Plus, Rod Ease, suspension fluid, cobble commander, and drill ease. Some respondents mentioned that the design was adjusted based on the required filter cake thickness, gel strength, and viscosity. Some respondents mentioned that in these kinds of soils, the priority is to reduce fluid loss and to hold the walls of the hole.

On the drilling fluid mixture design, Orlando Salazer from Baroid (Orlando Salazer, personal communication [phone call], January 29, 2020), who has expertise with fluid mixture design, provided his recommended mix and the reasoning behind it:

- Bentonite, which builds the filter cake.
- Soda ash, which increases the pH value between 8.5 and 9.5 and drops calcium percentage.
- Quicktrol Gold LV Polymer, which supplements the filter cake allowing it to prevent fluid from seeping out of the hole.
- Easy mud gold encapsulates the cuttings of the clay so they do not stick together.
- No sag adds suspension for bentonite (cross link polymer).

The recommended mix proportions per 100 gallons of water (per 378.5 liters of water) are as follows:

- Soda ash: 1 lb (0.45 kg).
- Bentonite (bore gel): 30 lb (13.6 kg).
- Quicktrol gold lv: 0.5–1.5 lb (0.23-0.68 kg).
- No sag: 0.5–1 lb (0.23-0.45 kg).

For fine-grained soils, two respondents stated that they also used the same mixes that they normally use for coarse-grained soils. Most respondents mentioned that they used bentonite in addition to zero or more of the following additives: detergent soap, surfactants, and easy mud. Some respondents mentioned that those additives were added to help break down the clay, keep it from swelling, and reduce sticking. Three respondents stated that they used a polymer-based system instead of a bentonite mix for fine-grained soils.

Salazar provided his recommended mix and the reasoning behind it:

- For borings less than 10 in. (25.4 cm) diameter and less than 400 ft (122 m) in length: Claydrill polymer, used to encapsulate clay cuttings and disperse them, also helps prevent the clay from sticking to tools.
- For borings with larger diameters or longer length bores: Bentonite, easy mud gold, soda ash, and surfactants are used, so that nothing sticks to it. Polymers may not be used in this case since they do not have suspension capacity.

Five respondents reported using a two-speed viscometer to test the drilling fluid onsite before pumping it, while two respondents reported the use of the marshal funnel. Two respondents stated that they visually inspect the fluid, while five respondents stated that they do not perform any testing.

Salazar listed some of the drilling fluid tests that he sometimes performs as part of his specialized job (on fluid mix and design):

- Viscosity test: using viscosity cup and funnel.
- Density or mud weight: using a mud scale.
- Sand content: using a sand content test kit. This test measures the content of sand in bentonite because all bentonite has sand in it. Sand content of less than 1% is favored.
- Viscometer to test the gel strength (it also gives the plastic viscosity and yield point): 10 sec. and 10 min. gel strength.
- Filtration press test: done by pressurizing the fluid in a barrel with a filter paper at 100 psi (689.5 kPa) for 30 minutes then measuring the volume of the filtrate to the nearest one-tenth of a milliliter. The thickness of the filter cake can be also measured in this test. This thickness is usually measured in tens of thirty seconds of an inch (e.g., 10/32nd in., 0.794 cm).

- Hardness and pH tests for the filtrate.

Most respondents that typically work on Midi rigs and all those who work on Mini rigs reported that they did not estimate operational or failure pressures. In contrast, all three respondents who work on Maxi rigs and one of the respondents who work on a Midi rig reported that they do calculate failure pressures. Two of those said that they used the Delft method for this purpose. Hence, only 24% of the respondents had performed the failure pressure calculations before drilling starts.

Most respondents mentioned that they used rig gauges and visual inspection of the return of fluids to indirectly monitor fluid pressures during installation. If they find out that the returns are less than expected (significantly less than the fluid pumped down the hole), and that advancing the rods is requiring huge thrust or torque (measured via the rig gauges), they infer that the fluid pressures downhole are building, possibly due to a blockage inside the hole. An exception to this is during pilot drilling, where the drill bits are typically equipped with pressure sensors whose readings are received by the walkover system, and then can be conveyed verbally by the person with the walkover receiver to the rig operator. The same four respondents that reported calculating failure pressures mentioned that they additionally monitor the downhole pressure using downhole pressure tools. Hence, only 24% of the respondents directly monitor downhole pressures with downhole sensors, as demonstrated in Figure 11.

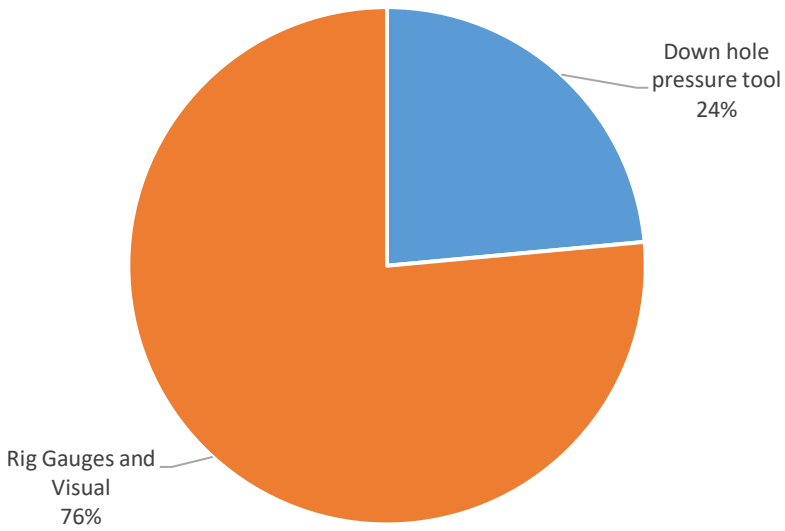


Figure 11. Chart. Method of downhole pressure monitoring.

Different methods of testing the health of the pipe after installation were reported by the respondents: pressure tests, blowing a plug through to test the continuity of the pipe, and visual inspection. Around half of the respondents mentioned that this testing is typically done by the owner, engineer, or a third-party company.

The impact of HDD on the ground surface (including any roads under which the HDD was performed) was checked via visual inspection for cracks by 94% of the respondents. Only one respondent reported surveying using a level, as presented in Figure 12.

Around half of the respondents mentioned that they moved their heavy equipment over roads, on-site using neoprene pads. Approximately one-quarter of the respondents reported using trailers even for short distances. The rest reported the usage of wooden boards, tires, crane mats, and steel plates. The distribution of the methods reported is presented in Figure 13.

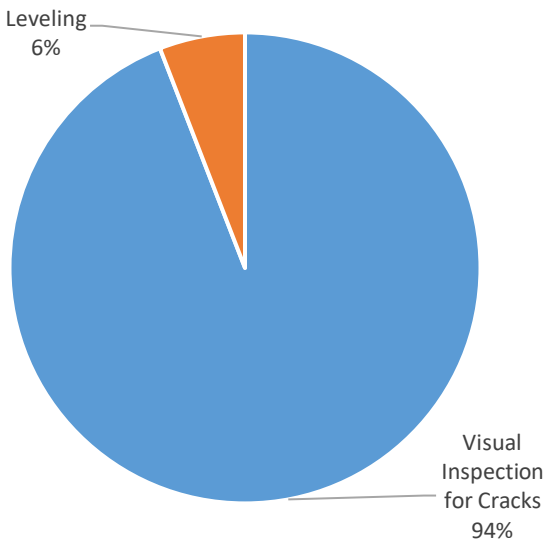


Figure 12. Chart. Method for checking impact of HDD on ground surface.

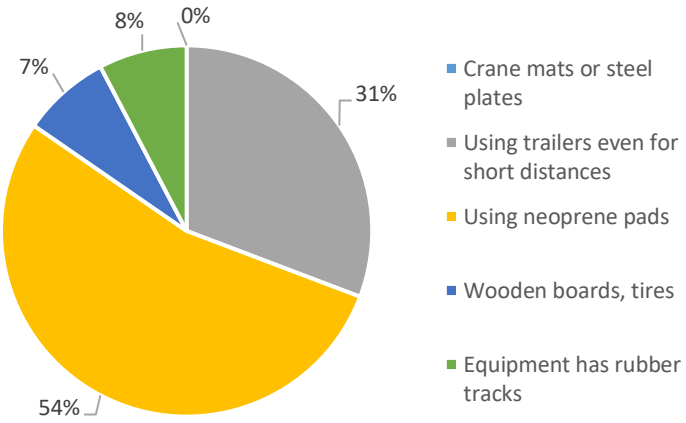


Figure 13. Chart. Method for moving heavy equipment and machinery over roads on site.

ENCOUNTERED PROBLEMS DURING HDD

Three respondents reported that they did not experience hydraulic fracture or inadvertent returns, while the rest stated they did. Different interpretations for the reasons for those incidents were given, including small thickness of overburden, not monitoring the return of fluid to containment pits,

cracks or fissures in the ground, loose soils, soils with rock fractures and cobbles, sudden soil changes, high groundwater table, the existence of old wells, improper fluid mix, high reaming speed, and reamer selection. One respondent mentioned that a compaction reamer caused inadvertent returns, while an open-face reamer solved the problem.

After the occurrence of an inadvertent return, the respondents reported surrounding the area with sandbags and then cleaning the fluid with vacuum trucks. The methods used by the respondents to avoid or reduce the severity of these issues included adding relief holes, changing mix design, cleaning the hole (swabbing) more often, and reducing pulling speed.

Four respondents reported that they did not experience ground heave or settlement, while the rest mentioned they did. The reported incidents were all incidents of ground heave and occurred due to hydro-fracture. After the ground was heaved, the pavement was excavated and then patched.

Thirteen respondents reported that they had not experienced sinkholes. One respondent mentioned that he experienced one in a loose formation. Another respondent discussed excess large-diameter reaming passing through sections of the boring with coarse-grained soils resulted in sinkholes which, in turn, meant that surface casings had to be used. One respondent mentioned that hitting a stormwater sewer resulted in a sinkhole. Another respondent mentioned that hitting a pocket of loose debris and cobbles resulted in a sinkhole, which he then grouted and changed the path of the boring.

All but one of the respondents reported that they encountered an unknown or unlocatable utility or an underground obstacle while drilling. One respondent mentioned that this could occur when a new utility is installed under an old utility, and the driller confuses the old one with the new one and ends up hitting it. The respondents dealt with this issue by changing the path of the boring or digging and removing the obstacle, when possible. Emergency 911 was called in an incident in which a gas line was hit. The damaged utilities were uncovered and repaired.

All but four of the respondents mentioned that they had to abandon a boring at least once. The reasons given for this included the inability to advance the pilot hole due to hitting cobbles, fractured rock, unknown obstacles or buried fill, and not satisfying design tolerances. This could happen (a) in difficult soils not allowing the bit to get the desired inclination; (b) at soil-rock interface, which requires good design to allow the bit to penetrate the rock, usually steeper entry angles; and (c) in running sand. The reasons given for abandoning a boring also included failure of the drill pipe and the drilling string getting stuck for different reasons, including gravel and cobble collapse in the hole (in this case, a lot of fluid is pumped to try to get the drilling string loose, or it might be dug from the surface, or, in the worst case, the hole and the equipment are abandoned). After the borings were abandoned, the respondents reported different ways they dealt with the abandoned boring: grouting the boring, doing nothing (especially for small borings), or filling the boring with drilling fluid.

OTHER FEEDBACK

Two respondents reported that that they had developed internal guidelines or were part of best practices boards. Three mentioned that they referred to drill manufacturer guidelines. One

respondent mentioned that he used the HDD good practices book while another mentioned that he referred to ASTM F1962 code. Eight respondents did not mention which document they referred to.

Four respondents reported that the documents they referred to covered all or most of what they need to know, while the rest either did not use a document or found that the documents they were using are lacking. One respondent mentioned there were a lot of safety concerns, specifically with gas mains, for which guidelines were not clear. He reported that some companies would avoid potholing to search for existing utilities and simply go deep in their bores. He remarked that, ultimately, this would just complicate future works and "litter their right-of-ways."

One respondent expressed that there were various variables to consider in a guidelines document. They include product material and size, ground conditions, bend radius of drill stem, drill size, length of bore, grade of bore (example: sewer), and existing utilities.

Around 70% of the respondents showed interest in follow-up conversations to better understand their feedback.

One respondent suggested that special care should be given to planning, studying site conditions, and selecting proper materials and equipment. He mentioned that borings even as small as 4 to 6 in. (10 to 15 cm) bores can cause problems. Another respondent suggested the use of an HDPE fused pipe for carrier pipes or casings. Another respondent emphasized the vast differences between different kinds of borings and their requirements, as well as the need to consider those differences.

CHAPTER 5: DEVELOPMENT OF GUIDANCE DOCUMENTS

INTRODUCTION

The four guidance documents developed in this research project are the following:

- **Proposed HDD Guidelines**: a document to guide through all stages of HDD—design, permitting, construction, inspection, and quality assurance.
- **Proposed HDD Guidance Specifications**: a document with a list and description of the requirements needed for permitting an HDD project.
- **Proposed Permit Submittal Checklist**: a checklist with the requirements needed for permitting an HDD project.
- **Proposed Inspector Checklist**: a checklist that an on-site inspector can use to ensure the HDD project is performed as planned. It also contains directions for inspectors on how and what to document during an HDD project.

These documents described above aim to assist permitting, design, construction, and inspection of HDD under IDOT assets. The lessons learned from the HDD observations, the industry survey, and the literature review were used in developing the four guidance documents. They are designed to complement one another, as demonstrated in Figure 14.

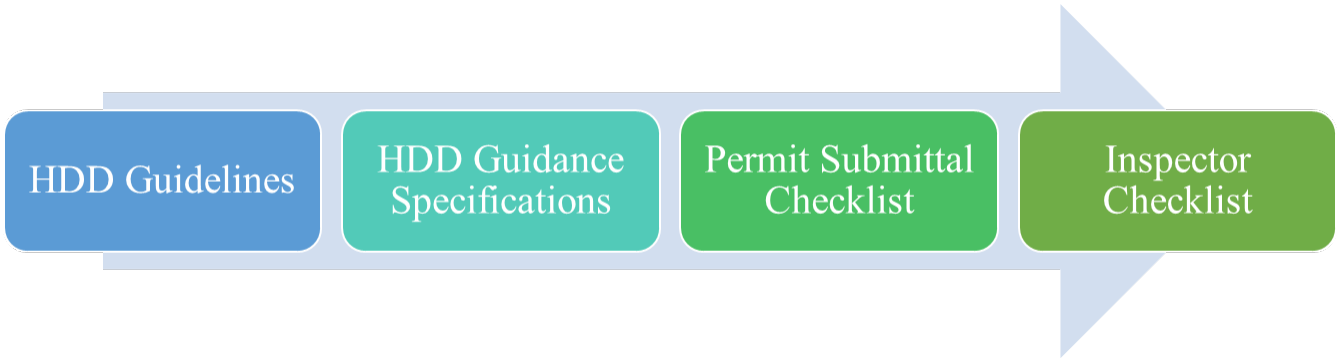


Figure 14. Flow chart. The design of four proposed guidance documents.

PROPOSED HDD GUIDELINES

The guidelines document represents a digest of the primary takeaways from the literature review, field observations, industry survey, as well as published guidelines documents and books. However, it is not a replacement for any reference documents. The guidelines document is divided into three sections: before construction, during construction, and after construction. A copy of the guidelines document can be found in Appendix B.

PROPOSED HDD GUIDANCE SPECIFICATIONS

The purpose of this document is to facilitate HDD permitting by listing some of the essential requirements. This document references existing IDOT policy and specification documents to avoid repetition or conflict with their requirements. The prepared draft can be found in Appendix C.

PROPOSED PERMIT SUBMITTAL CHECKLIST

The permit submittal checklist is a list of items to be submitted to IDOT during the permit stage. The checklist is divided into nine sections that cover project description, site investigation, design, contractors' information and qualifications, project logistics, execution plans, public safety plans, quality assurance plans, and final delivery plans. A copy of this document can be found in Appendix D.

PROPOSED INSPECTOR CHECKLIST

The inspector checklist is an expansive list of items that the HDD inspector may monitor during an HDD project. The list is divided into three parts: before, during, and after construction. Those three sections guide the inspector to check that the employed plans and methods are compatible with those approved in the permit. It also directs the inspector's attention to key aspects that are often overlooked. A copy of this document can be found in Appendix E.

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH

Horizontal directional drilling provides an alternative, noninvasive, and economical technology to install pipelines and utilities beneath existing infrastructure, including roadways and waterways. The implementation of HDD involves a range of equipment and installation procedures. An HDD installation needs to achieve two goals: (a) install utility element and (b) minimize the impact on nearby infrastructure. This study developed HDD guideline documents that provide IDOT with metrics to evaluate a given proposed HDD installation. As an outcome of this study, the following four guidance documents were created:

- **Proposed HDD Guidelines**: a document to guide through all stages of HDD—design, permitting, construction, inspection, and quality assurance.
- **Proposed HDD Guidance Specifications**: a document with a list and description of the requirements needed for permitting an HDD project.
- **Proposed Permit Submittal Checklist**: a checklist with the requirements needed for permitting an HDD project.
- **Proposed Inspector Checklist**: a checklist that an on-site inspector can use to ensure the HDD project is performed as planned. It also contains directions for inspectors on how and what to document during an HDD project.

This report also contains a literature review (Appendix F), field observations of selected HDD installation under IDOT roadways (Appendix G), and an industry survey conducted as part of this project with a focus on Illinois installations (Chapter 4 and Appendix H). Some topics are beyond the scope of this report and require future research. These topics include the following:

- Seismic and liquefaction impact on critical HDD installed pipelines.
- The effects of pipe material, curvature radius, and standard dimension ratio on pipe resistance to fluid pressure.
- Overview of rheological properties of drilling mud as well as determining and using rheological properties of drilling mud in HDD design and installation.
- More case histories about the impact of HDD installation on surface and structures, for example, installation of HDPE pipe with a diameter greater than 11.8 in. (300 mm).
- Guidance on high-pressure testing in HDD-installed pipelines.

APPENDIX A: GLOSSARY OF TERMS

Alternative Project Delivery Methods (APDM) – Methods to deliver projects that are intended to streamline project design and construction and integrate the knowledge, creativity, experience, and passions of design and construction professionals project conception to completion.

Annular pressure – The pressure that results from drilling fluid located in the annular space between the drill pipe and the wall of the hole being cut.

Annulus – In HDD, the annulus refers to the space that surrounds either the drill pipe or the product pipe and is enclosed by the borehole wall.

API – American Petroleum Institute located in Washington, DC.

Apparent viscosity – A measure of resistance to flow caused by mechanical friction between solids in mud.

ASC – Accredited Standards Committee located in McLean, Virginia.

ASCE – American Society of Civil Engineers.

ASTM – The American Society for Testing and Materials located in West Conshohocken, Pennsylvania.

AWWA – American Water Works Association located in Denver, Colorado.

Azimuth – Horizontal direction expressed as an angle measured clockwise from any meridian. In HDD, azimuths are typically measured from the magnetic north.

Back reaming – See reaming. In back reaming, the reamer moving direction is from the exit point side to the entry point side, in contrast to front reaming.

Barrel reamer – An enclosed cylindrical soft soil-reaming tool with cutting teeth and fluid nozzles arrayed on the end faces. Barrel reamers may be designed with specific buoyancies to aid in hole enlargement.

BBS – Bureau of Bridges and Structures.

BDE – (IDOT) Bureau of Design and Environment.

Bent sub – A short, threaded piece of pipe with an axial offset or angle used in a drill string to produce leading-edge asymmetry.

Bentonite – A colloidal clay composed primarily of montmorillonite that swells when wet. Because of its gel-forming properties, bentonite is a major component of drilling fluids.

Bore salvage method – A method used to remove stuck pipes to rescue boreholes. For example, pipe ramming is a good technique that can free a pipe stuck in a borehole. When the pipe ramming

technique is used, a pipe rammer (e.g., a fabricated sleeve) is attached to the end of a partially installed produce pipe and a winch is used to assist the rammer during operation. In many cases, the percussive power of the pipe rammer is enough to free the stuck pipe and allow it to be removed from the ground.

Bottom hole assembly (BHA) – The combination of bit, downhole motor, subs, survey probe, and nonmagnetic collars assembled at the leading edge of a drill string.

Boulder – A particle of rock that does not pass through a 12 in. (30 cm) square opening.

Breakover – In HDD, the overbend is required to align the prefabricated pull section with the borehole during pullback without inducing plastic deformation or unacceptable flexural stresses in the pipe.

Buoyancy control – Modification of the pull section's unit weight to achieve the desired buoyancy during pullback. In HDD, the most commonly used method of buoyancy control is to fill the pull section with water as it is installed in the borehole.

Casing – For HDD installation, a casing is the pipe that is driven into the borehole by hydraulic jacks or ramming. Casing is usually not the product pipe. It is used to support the borehole to prevent it from collapsing inwards. For product pipe, a casing is a product pipe installed to carry one or more utilities inside it.

Capstan effect – A phenomenon in which the tension on either side of a line around a capstan may differ due to the presence of frictional forces.

Carriage – The component of a horizontal drilling rig that travels along the frame and rotates the drill pipe. It is analogous to a top-drive swivel on a vertical drilling rig.

Cartridge method – A method of connecting the joints during installation, one at a time, and is preferred in locations where right-of-way (ROWs) or easements are limited.

CATV – Cable Television.

CCTV – Closed-circuit Television.

Centralizer – A cylindrical add-on tool to stabilize the drill rod, reamer, and product pipe by keeping them towards the center of a borehole, which aids in maintaining the same alignment as the previously drilled pilot hole or reaming pass.

CFR – Code of Federal Regulations.

Changed face condition – A soil condition that occurs when a bore path moves from one soil formation to another.

CLSM – Controlled Low Strength Material.

CMAR – Construction Management at Risk.

Compaction head – A wedge-shaped drilling bit, which is used for cutting and displacing the soil as well as for steering.

Conductor barrel method – A method in which casings are rammed into the ground at a predetermined angle until desirable soil conditions are met. The spoil is removed from the casing with an auger or core barrel. Drilling proceeds within the casing in the desirable soil conditions. In addition to assisting drilling operations at the start, the conductor can also serve as a friction-free section during pullback. The Conductor Barrel Method is claimed to prevent situations in unstable soils, where drilling fluids under pressure force their way into waterways or wetlands by acting similarly to containment cells.

Conductor casing – A steel pipe that is installed along the designed HDD alignment that extends from the entry or exit point at the surface to some predetermined point below the surface. The conductor casing is typically used to stabilize loose or otherwise adverse soils and serves as an open conduit for drilling fluid. Conductor casing is typically a temporary measure used to facilitate the HDD pilot hole and reaming operations. It is removed either before, or during, the pullback of the product pipeline. It is also the first string set below the structural casing (i.e., drive pipe or marine conductor run to protect loose near-surface formations and to enable circulation of drilling fluid).

Conduit – A broad term that can include pipes, casing, tunnels, ducts, or channels.

Consistency index (CI) – A parameter that indicates the viscosity of a fluid. The higher the consistency index, the thicker the mud. The consistency index depends on the solids content and the viscosity of the fluid's liquid phase. The consistency index increases with a solids content and the concentration of polymer additives. To transport cuttings effectively, the consistency index should be relatively high.

Contract – The written Agreement between the Department and the Contractor setting forth the obligations of the parties thereunder, including, but not limited to, the performance of the work, the furnishing of labor and materials, and the basis of payment. The contract includes the invitation for bids, proposal, letter of award, contract form and contract bond, Specifications, Supplemental Specifications, Special Provisions, general and detailed plans, and any Agreements required to complete the construction of the work in an acceptable manner, including authorized extensions thereof, all of which constitute one instrument.

Contractor – The individual, firm, partnership, joint venture, or corporation contracting with the Department for the performance of prescribed work.

Control panel – A panel containing gauges, hydraulic valves, and controls that are used to operate the horizontal drilling rig.

COSHH – Control of Substances Hazardous to Health Regulations.

CoVAWRs – Control of Vibration at Work Regulations.

CPR – Cardiopulmonary Resuscitation.

Cuttings – Soil or rock removed from the borehole as it is advanced or enlarged.

DB – Design-Build.

DCCA – Directional Crossing Contractors Association.

DDM – Design Decision Model.

Delft method – A method based on cavity expansion theory to evaluate and quantify the risk of hydro-fracture and calculate the allowable drilling fluid pressure for the HDD project.

Density – The mass or weight of a substance per unit volume. In HDD, drilling fluid density can be expressed in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft^3), or kilograms per cubic meter (kg/m^3).

Department – The Department of Transportation of the State of Illinois with principal offices of business at Springfield, when the State is the awarding authority.

Detection Wire – Electronic detection material for non-conductive piping products.

DGE – District Geotechnical Engineer.

DIP – Ductile iron pipes.

Downhole motor – A device that uses hydraulic energy produced by drilling fluid flow to achieve mechanical bit rotation.

Downhole probe – A device, commonly referred to as a "probe," containing instruments that measure inclination, azimuth, and tool face.

Drill bit – A tool that cuts soil or rock at the leading edge of a drill string, usually by mechanical means. It is attached to the lead portion of the drill string during pilot hole operations. The types of drill bit include duck bill bit, Polycrystalline diamond compact (PDC) bit, spade drill bit, square drill bit, mill tooth bit, steep taper bit, TriCone bit, etc.

Drill pipe – High strength, hollow steel pipes joined to form a string used to transmit rotational torques and thrust and to transport drilling fluid from the drill rig to the downhole tools. The drill pipe connects the horizontal drilling rig with the bit or reamer and facilitates both pumping drilling fluid and advancing or retracting the bit or reamer.

Drill rod – See drill pipe.

Drill stem – See drill pipe.

Drill string – The total length of drill pipe in the borehole, including the bottom hole assembly.

Drilling fluid – A mixture of water, a viscosifier (typically bentonite), and/or polymers that is pumped to the drill bit or reamer to facilitate cutting, transport drilled spoil, stabilize the borehole, cool and clean cutters, and reduce friction between the product pipe and the wall of the hole. The drilling fluid usually consists of water, bentonite, and any approved additives such as environmentally safe polymers, lubricants, and viscosifiers.

Drilling mud – See drilling fluid.

Duct – Small plastic or steel pipes that enclose wires or cables for electrical or communication usage.

Engineer – The Chief Engineer/Director of Highways of the Department of Transportation of the State of Illinois, or authorized representative limited by the duties entrusted to that person, when the State is the awarding authority. The County Superintendent of Highways or the County Engineer when the County is the awarding authority. The County Superintendent of Highways or the County Engineer, and the Chief Engineer/Director of Highways of the Illinois Department of Transportation when the Illinois Department of Transportation is the awarding authority and the County supervises construction. The City Engineer or Engineer employed by the Municipality, when a city, village, or town is the awarding agency. The City Engineer or Engineer employed by the Municipality, and the Chief Engineer/Director of Highways of the Illinois Department of Transportation when the Illinois Department of Transportation is the awarding agency and a city, village, or town is supervising construction.

Entry point – The point on a drilled segment where the pilot-hole bit initially penetrates the ground surface. The horizontal drilling rig is positioned at the entry point.

Entry/exit angle – The angle relative to the horizontal plane at which the drill string enters or exits the ground surface during pilot-hole drilling.

EPA – Environmental Protection Agency.

EPC – Engineering/Procure/Construction.

EPCM – Engineering/Procure/Construction Management.

Exit point – The point on a drilled segment where the pilot-hole bit emerges from the ground surface. The pipeline pull section is typically positioned at the exit point.

FDOT – Florida Department of Transportation.

Filter cake – A layer of drilling fluid that lines the borehole to prevent fluids from entering the surrounding soil. The drilling fluid creates a thin layer that cakes the borehole so that the permeation of the native soil is reduced or eliminated.

Finite element method (FEM) – A widely used method for numerically solving differential equations arising in engineering and mathematical modeling.

Finite volume method (FVM) – A method for representing and evaluating partial differential equations in the form of algebraic equations.

Flow index (FI) – Represents the degree of deviation from Newtonian behavior of the fluid within a specified range of shearing rate. The flow index of a Newtonian fluid is 1.0, such as for water or glycerin. The flow index of drilling mud is usually less than 1.0. The lower the magnitude, the greater the deviation from Newtonian behavior.

Fluid recycling system – A system used for HDD to utilize the drilling mud.

Fluid return – Drilling fluid that is expected to flow back to the entry or exit point.

FPVC – Fusible Polyvinyl Chloride.

FPVCP – Fusible Polyvinyl Chloride Pipe.

Frac-out – Unintentional return of drilling fluids to the surface.

Front reaming – See reaming. In front reaming, the reamer moving direction is from the entry point side to the exit point side, in contrast to back reaming.

Funnel viscosity – The ratio of the speed of the slurry as it passes through the outlet tube (shear rate) to the force (weight of the slurry), causing the slurry to flow (shear stress).

GDM – Geotechnical Design Manual.

GDR – Geotechnical Data Report.

Gel – In the HDD industry, an informal term for bentonite.

Gel strength – The shear stress measured at a low shear rate after a mud has set quiescently for a period of time.

Geotechnical Baseline Report (GBR) – A statement representing the known ground conditions on a project site. The objective of the GBR is to define and allocate the risks associated with subsurface constructions.

GPR – Ground-penetrating Radar.

GPS – Global Positioning System.

Grout – A pumpable mixture, typically comprising water, cement, fine sand, fly ash, bentonite, and/or chemical components, that is commonly used to fill voids or annular spaces, strengthen incompetent soil or rock, or prevent the flow of groundwater.

HAGDMS – Highway Agency Geotechnical Data Management System.

HAVS – Hand-Arm Vibration Syndrome.

HDD – Horizontal Directional Drilling.

HDPE – High-density Polyethylene.

Herschel-Bulkley (H-B) model/fluid – A generalized model of a non-Newtonian fluid, in which the strain experienced by the fluid is related to the stress in a complicated, non-linear way.

HMWPE – High Molecular Weight and High-Density Polyethylene.

Hole opener – A rock-reaming tool that utilizes roller cutters to cut harder material which cannot be penetrated with a fly cutter.

Horizontal Directional Drilling (HDD) – A method of installing buried piping by controlled, (guided within specified limits) horizontal drilling.

Hydraulic cylinder – A linear actuator that applies a unidirectional force through a unidirectional stroke.

Hydraulic fracturing – A specific occurrence in non-fissured cohesive soils when the pressure of the drilling fluid exceeds the strength and confining stress of the surrounding soils, and the excess pressure fractures the soil around the bore.

Hydrocyclone – A conical device that directs drilling fluid flow in a spiraling manner, thereby setting up centrifugal forces that aid in separating solids from the fluid.

Hydro-fracture – See Hydraulic fracturing.

Hydrofracture – See Hydraulic fracturing.

Hydrolock – Creation of a hydraulic cylinder in front of the reamer and/or compactor and/or product line after loss of circulation that can exert more pressure than the rig can thrust. It happens when the external pressure being put on the product pipe from groundwater pressure, drilling fluid pressure, and/or soil conditions exceeds the drill rig's pullback capability or the product pipe's tensile strength.

Hydro-lock – See Hydrolock.

Hydrostatic pressure – The force exerted by a body of fluid at rest; it increases directly with the density and the depth of the fluid and is expressed in psi or kPa. The hydrostatic pressure of freshwater is 0.433 psi/ft (9.792 kPa/m) of depth. In drilling, the term refers to the pressure exerted by the drilling fluid in the borehole.

Hydrostatic test – A process to test product pipe for strength and leaks.

I.D. – Inner diameter.

IDOT – Illinois Department of Transportation.

Inadvertent return – Uncontrolled flow of drilling fluid to the surface at a location other than the entry or exit point.

Inclination – The angular deviation from true vertical or horizontal. In drilling, the inclination is typically expressed in degrees and is measured from vertical.

Intersect method – The intersect method of drilling uses two drills, one at each end of the bore's design path. One of the drills has a magnetic source mounted on the boring head assembly (BHA) instead of a steering tool. The magnetic source allows the rig without the magnet to determine the distance and azimuth to the source. Both rigs drill pilot bores toward each other until the bores intersect. The drill with the magnetic source then continues the bore to the end of the design path.

ITP – Inspection and Testing Plan.

Jetting – Advancing a drilled hole using the hydraulic cutting action generated when drilling fluid is exhausted at high velocity through the leading edge of a drill string.

Joint – A single section of threaded drill pipe. A joint of drill pipe is typically 30 ft (9.1 m) to 33 ft (10 m) in length.

Loss of formation – Collapse of the borehole. It is common in loose soil situations, especially random fill.

Lost circulation – The loss of drilling fluid to a formation, usually in cavernous, fissured, or coarsely permeable beds, evidenced by the complete or partial failure of the drilling fluid to return to the surface as it is being circulated in the hole.

Lost circulation material (LCM) – The collective term for substances added to drilling fluids when drilling fluids are being lost to the formations' downhole.

Lost returns – See lost circulation.

MAGLE – Managing Agent's Geotechnical Liaison Engineer.

Magnetic-steering tool – An HDD tool that sends real-time positioning data from downhole to engineers on the surface so they can monitor and steer the drill bit. Typically located 6 to 30 ft behind the drill bit.

Maxi-HDD – HDD machines that can weigh as much as 30 tons (27215 kg) or greater and are appropriate for placing pipes under larger rivers or other major obstacles.

MDPE – Medium-density Polyethylene.

MDR – Manufacturers Data Report.

MIA – Miami International Airport.

Midi-HDD – A category of HDD that has greater capabilities than mini-HDD but much less than maxi-HDD equipment, which is capable of accurately boring holes on the order of a mile in length and placing pipes of 48 in. (122 cm) or greater, at depths up to 200 ft (61 m).

Mini-HDD – A class of HDD typically employed for boring segments less than 600 ft (183 m) in length, at depths up to 15 ft (4.57 m) and placing pipes up to 12 in. (30.5 cm) in diameter. The equipment is characterized by a thrust or pullback capability of up to 20,000 lb (9070 kg), or possibly greater, with torque less than 950 ft-lb (1.28 kN-m) and weight less than 19842 lb (9 tons).

MISIP – Mississippi River.

Mixed-faced conditions – A type of soil condition where two or more different soil types are encountered in the path of the directional drilling machine.

Mixed-metal hydroxide (MMH) – A compound containing hydroxide anions in association with two or more metal cations. MMH particles are extremely small and carry multiple positive charges. They can associate with bentonite to form a strong complex that exhibits high shear-thinning properties, with high and fragile gel strengths, high yield point, and low plastic viscosity.

Mohs hardness – A relative scale of hardness based on 10 commonly available minerals that provides a measure of a mineral's resistance to scratching on a scale of 1 (softest) to 10 (hardest).

Montmorillonite – A clay mineral often used as an additive in drilling mud. It is a hydrous aluminum silicate capable of reacting with such substances as magnesium and calcium.

MSDS – Material Safety Data Sheets.

MTBM – Microtunnel Boring Machines.

Mud motor – A progressive cavity positive displacement pump (PCPD) placed in the drill string to provide additional power to the bit while drilling.

Mud pass – See swab pass.

MUTCD – Manual on Uniform Traffic Control Devices.

MW – Magnetic Source Well.

MWC – Middlesex Water Company.

NASTT – North American Society for Trenchless Technology.

NMUTCD – National Manual on Uniform Traffic Control Devices.

NYSDOT – New York State Department of Transportation.

O.D. – Outside Diameter.

ODOT – Ohio Department of Transportation.

One Call – A utility locator service that notifies the owners of buried utilities in a given location so that utilities can be marked in the field with either paint or flags, which follow a predetermined color code for each type of utility, prior to conducting an excavation.

Open type pullback method – A method in which the drilling fluid is used instead of water for buoyancy control. A special pull head with openings and connection subs for the PE pipe and product pipeline is used. Prior to pullback, the PE pipe is connected to the pull head with long bolts to the inner connection sub at first, then the product pipeline is welded to the outer sub of the pull head. When the pipeline is pulled in, drilling mud in the borehole flows into the PE pipe continuously through the openings. When pullback is completed, drilling mud in the PE pipe can be discharged with a sand pump or with compressed air and then pulled out of the PE pipe for reuse.

OSHA – Occupational, Safety, and Health Administration.

Over-reaming – See Reaming.

Overbend – In HDD, a vertical bend in the drilled path that progresses downward, or the vertical bend formed in the aboveground pull section during pullback when the pull section is elevated to achieve alignment with the borehole.

P.C. – Point of curvature.

P.I. – Point of inflection.

PCB – Polychlorinated Biphenyls.

PCCP – Prestressed Concrete Cylinder Pipe.

PDC – Polycrystalline Diamond Compact.

PE – Polyethylene.

Pilot hole – A small-diameter hole directionally drilled along a designed path in advance of reaming operations and pipe installation. It is the initial controlled, drilled horizontal shaft used to guide the enlargement to design size and eventual installation of the product pipe.

Pipe ramming – a trenchless method for the installation of steel pipes and casing.

Plastic viscosity (PV) – a parameter of the Bingham plastic model that represents the fluid flow resistance. A low PV indicates that the HDD drilling can be rapid because of the low viscosity of mud exiting at the bit. High PV is caused by a viscous base fluid and by excess colloidal solids.

Polymer – A substance that consists of large molecules formed from smaller molecules in repeating structural units. Various polymers are used in commercial drilling fluid products to achieve a drilling fluid with specific properties.

PPI – The Plastic Pipe Institute.

PRCI – Pipeline Research Council International.

Pre-ream – The act of enlarging a pilot hole by pulling or pushing cutting tools through the hole before reaming.

Pressure relief hole – A mitigation measure that involves drilling a vertical borehole along the HDD alignment that provides a controlled conduit for drilling fluid flow. If annular pressures are high, drilling fluid, which flows in the path of least resistance, will flow through the relief borehole in an area where it can easily be contained, as opposed to surfacing at an inaccessible location due to hydraulic fracturing of the soil. Pressure relief holes have been successfully used on some crossings but are not common practice.

Pressure while drilling (PWD) tool – A tool provides real-time data of annular pressures behind the drill bit. It can indicate sudden increases in annular pressures, which may indicate an annular blockage or other problems.

Progressive cavity positive displacement pump (PCPD) – A type of positive displacement pump that moves water or slurries by converting electrical energy to hydraulic energy. It transfers fluid by means of the progress, through the pump, of a sequence of small, fixed shape, discrete cavities, as its rotor is turned.

Product pipe/line – Permanent pipeline for operational use.

Pull back – The act of installing a pipeline in a horizontally drilled hole by pulling it to the horizontal drilling rig from the end of the hole opposite the rig.

Pullback – The pipe installation pulled back by a swivel/pulling head connected behind the reamer, which pulls the prepared product pipe into place.

Pullback assist method – A method that is used to free stuck pipe by directly installing the product pipe. When drilling underwater or in loose flowing soil conditions, a condition known as hydrolock, the percussive action of a pipe rammer in this situation is used to help free the immobilized pipe.

Pull-back force – The tensile load applied to a drill string during the pullback process.

Pull section – A prefabricated pipeline segment typically staged near the HDD exit point prior to installation in the drilled hole.

PVC – Polyvinyl Chloride.

QCP – Quality Control Plan.

Reamed hole – The hole cut during the reaming stage of HDD construction.

Reamer – A cutting tool that is pushed or pulled through the borehole to enlarge the hole to a sufficient diameter for installation of the product pipe.

Reaming – A process in which the pilot hole is enlarged in one or more successive cutting passes to a final diameter that will accommodate the pipeline that is to be installed. The back-reaming hole opener is attached to the drill pipe and rotated and pulled back through the pilot hole to enlarge the bore in one or more passes to the size needed for product pipe installation.

Rig up – Placing and assembling the various parts of equipment that make up the rig and preparing the rig for drilling.

Rock quality designation (RQD) – A field measurement quantifying the degree of jointing or fracture in a rock mass. Measured as a percentage of the total length of all sound rock core pieces more than 4 in. (10.2 cm) in length divided by the total length of the rock core run.

ROW – Right-of-way.

Shale shaker – A device that utilizes vibrating screens to remove larger solid particles from circulating drilling fluid. The fluid passes through the screen openings while solids are retained and moved off of the shaker by the vibrating motion.

Sinkhole – A depression of hole in the ground caused by a frac-out during HDD construction.

Spoil – Excavated soil or rock.

SPT – Standard Penetration Test.

Standard Dimension Ratio (SDR) – A parameter to rate durability against pressure. It is calculated by the ratio of pipe outside diameter over pipe wall thickness.

Starter casing – See conductor casing.

Structure – Any pipeline, utility, building, structure, bridge, pier, roadway pavement, or similar construction partially or entirely located within a zone of active excavation.

SUE – Subsurface Utility Engineering.

Superstructure – A building or part of a building built above the foundation. In this report, roadway pavement is also considered to be a superstructure.

Surface casing – See conductor casing.

Swab pass – A non-cutting pass that is conducted prior to the pullback of the product line. It is used to flush cuttings and other minor debris out of the reamed hole. It essentially serves to confirm that the reamed hole is free and clear and ready to accept the product pipeline. The swab pass is the final step before installing the product and is performed by pulling a plug through the hole to remove cutting debris and drilling fluid.

Swabbing a joint – Pulling a joint back toward the rig while pumping drilling fluid to flush cuttings through the annular space. Swabbing one or more joints is one of the first methods HDD contractors employ to regain drilling fluid circulation if it is lost.

Thief zone – A formation encountered during drilling into which circulating fluids can be lost.

THWN – Thermoplastic Heat and Water-resistant Nylon-coated.

TMP – Transportation Management Plan.

Tool face – The direction of the asymmetry of a directional drilling string. A directional drilling string progresses in the direction of the tool face. Tool face is normally expressed as an angle measured clockwise from the top of the drill pipe in a plane perpendicular to the axis of the drill pipe.

TPH – Total Petroleum Hydrocarbons.

Trip – The act of withdrawing (tripping out) or inserting (tripping in) the drill string.

Tripping – The process of withdrawing or inserting a drill pipe from the drilled hole.

Tripping back – The process of reinserting pipes into the drilled hole.

TT – Trenchless Technology.

Tube-a-Manchette (TAM) – A manchette tube is a PVC or metal pipe in which rubber sleeves cover holes that are drilled in the pipe at specific intervals. In TAM grouting, a double packer is used to pump the grout into the manchette tube until the packer is halfway past the set of the holes drilled into the tubes. Grout is pumped into the hole between confining packers by applying pressure. The pressure pushes the grout past the small rubber sleeves to cover perforation, rupture the sleeve grout, and enter the soil.

Tunnel boring machine (TBM) – A machine used to excavate tunnels with a circular cross-section through various soil and rock strata.

TW – Tool Well.

TW/THW – Thermoplastic high heat-resistant and water-resistant.

UCS – Unconfined Compressive Strength.

UFGS – Unified Facilities Guide Specifications.

UFPO – Underground Facilities Protection Organization.

UIUC – University of Illinois at Urbana-Champaign.

Utility – The privately, publicly, municipally, or cooperatively owned line, facility, or system for producing, transmitting, or distributing communications, cable television, power, electricity, light, heat, gas, oil crude products, water, steam, or wastewater. The term "utility" shall also mean the utility company, inclusive of any wholly-owned or controlled subsidiary. Utility, as defined here, includes street lighting systems, traffic signal systems, railroad warning device systems, or fire/police pre-emptors, or their collateral cables and conduits.

VCWRC – Village Creek Water Reclamation Center.

Viscosity – A measure of the resistance of a liquid to flow. Resistance is brought about by the internal friction resulting from the combined effects of cohesion and adhesion.

Volatile Organic Compounds (VOC) – Compounds that have a high vapor pressure and low water solubility.

Walkover system – A tracking system that requires the locator operator to walk over the top of the drill head with a receiver to determine its depth and position. It uses a sonde, or transmitter, behind the drill head to register angle, rotation, direction, and temperature data. This information is encoded into an electromagnetic signal and decoded by a receiver (usually a hand-held locator) at the surface.

Wash-out – An enlarged region of a wellbore, including casing. Wash-out enlargement can be caused by excessive bit jet velocity, soft or unconsolidated formations, in-situ rock stresses, mechanical damage by bottom hole assembly (BHA) components, chemical attack, and swelling or weakening of shale as it contacts fresh water.

Wash pipe – A drill pipe that is run or rotated concentrically over a smaller drill pipe so that the smaller (internal) pipe can be freely moved or rotated.

Wireline – An insulated copper wire that runs from the downhole surveyor's computer console in the drill cab, through the interior of the drill pipe, down to the gyro steering probe that is located near the bit. A new wireline connection is added after each joint of the drill is added. If the wireline breaks downhole, or if there is a bad connection, the flow of power would be interrupted, and communication with the probe is lost. To correct this, the drill pipe is withdrawn, and the wireline connection is checked until the problem area is found.

Wireline tracking system – A magnetic guidance system to read the inclination and azimuth of the drill bit. It can also verify the location of the drill bit by wire grids laid on the ground surface. The signal is transmitted through the wireline fitted within the drill string.

WZTC – Work Zone Traffic Control.

Yield point (YP) – A parameter to represent the resistance of the initial flow of fluid or the stress required in order to move the fluid.

APPENDIX B: PROPOSED HDD GUIDELINES

TABLE OF CONTENTS

USER GUIDANCE 46

B.1 DESCRIPTION OF HDD 47

B.2 BEFORE CONSTRUCTION 48

B.2.1 Site Investigation 48

B.2.2 Feasibility Study 48

B.2.3 Risk Management 49

B.2.4 Design 50

B.2.5 Pipe Handling 55

B.2.6 Selection of Equipment and Machinery 55

B.2.7 Public Safety Plans 56

B.2.8 Additional Requirements 57

B.2.9 Scheduling 57

B.3 CONSTRUCTION 58

B.3.1 Site and Machinery Preparation 58

B.3.2 Pilot Drilling 58

B.3.3 Reaming 59

B.3.4 Pipe Preparation and Pulling 59

B.3.5 Site Restoration 59

B.4 AFTER CONSTRUCTION 60

B.4.1 Quality Assurance Plan 60

B.4.2 Final Delivery Plan 60

B.5 REFERENCES 61

USER GUIDANCE

This document was prepared based on a broad literature review, over three hundred documents, conclusions from field observations, conclusions of an industry survey in addition to guidelines documents, and books such as the following:

- The American Society of Civil Engineers (ASCE) manual: Pipeline Design for Installation by Horizontal Directional Drilling – 2nd Edition (Skonberg and Muindi 2014).
- The Pipeline Research Council International (PRCI) Manual: Installation of Pipelines by Horizontal Directional Drilling. An Engineering Design Guide (Watson 1995).
- North American Society for Trenchless Technology (NASTT) Manual: Horizontal Directional Drilling Good Practices – 4th Edition (Bennett and Ariaratnam 2008).
- Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling (Latorre, Wakeley, and Conroy 2002).
- Trenchless Technology Piping: Installation and Inspection (Najafi and Federation 2010).
- Horizontal Directional Drilling (HDD): Utility and Pipeline Applications (Willoughby 2005).
- Pipeline Geohazards: Planning, Design, Construction and Operations (Puckett and Scholl 2019).

This document represents a digest of the primary takeaways and is not a replacement for any of the guideline documents mentioned above. The guidelines above were cited as needed and can be used as the main reference when designing and executing HDD projects.

B.1 DESCRIPTION OF HDD

A typical HDD execution is composed of three main stages: pilot bore drilling, reaming, and pipe pulling. Given the geometric design of the installation profile, the horizontal drilling rig is placed at the entry point, and the drill bit is attached to the drill pipe. The drilling starts inclined and is steered to follow the target profile until the bit surfaces at the exit point. The steering is guided by a tracking system that provides the drilling tool's location, depth, and orientation using a tracking sensor installed near the drill bit. After the drill bit surfaces at the exit point, it is replaced by a reamer, which is pulled to enlarge the bore. Alternatively, a reamer may be installed on the entry side, with the hole enlargement process proceeding from entry to exit. Reaming could be accomplished using reamers of different sizes till the target bore diameter is reached. Then, the pipe is connected to the reamer via a swivel and pulled back through the bore. During those three stages, drilling fluid is injected under pressure to stabilize the hole by creating the filter cake and to suspend and transport cuttings. The used drilling fluid is either disposed of or recycled. Different pipe types are used for HDD and are selected based on the application.

HDD projects typically start with a **site investigation** and a study of its constraints and challenges, which guides the initial **geometric design** of the installation profile. The corresponding **pull loads** and **fluid pressures** are calculated in an iterative process that includes **fluid design**, **flow,** and **drag** calculations. A suitable **fluid system** is selected. The product pipe is **designed** and may be **coated**. Suitable **steering, tracking, and reaming systems** are selected. The capability of the **drill pipe** to handle the installation loads is sometimes checked. Depending on the site conditions and limitations, special **construction methods** and **technologies** might be employed. HDD process and results should be **inspected** before, during, and after construction.

B.2 BEFORE CONSTRUCTION

B.2.1 Site Investigation

A site investigation is composed of surface and subsurface investigations. Surface investigation involves the topography of the area and its surroundings, especially structures that might be impacted by HDD operations. This investigation guides the design and construction by identifying the constraints (e.g., elevation differences, high traffic roads, critical structures, limited right-of-way, source of water, work hours restrictions, existence of electric systems that would interfere with HDD tracking systems, etc.).

Subsurface investigation for HDD projects targets two main objectives:

1. Detection of utilities and other underground obstacles in the vicinity or along the target profile. Skonberg and Muindi (2014) suggest that this is especially necessary when the HDD alignment is to pass within 10 ft (3 m) of those utilities.

2. Identification of the subsurface soil and groundwater conditions. This is essential for designing the profile and conducting pressure calculations. It is also essential for the fluid mix design.

Skonberg and Muindi (2014) suggest that borings should be located off the drilled path centerline to reduce the possibility of drilling fluid inadvertently surfacing through the borings during HDD operations and that the borings should penetrate 20 to 30 ft (6 to 9 m) below the depth of the proposed drill path to provide information for design modifications and anticipated pilot-hole deviations during construction. Special care should be given to areas of geologic transition (e.g., from soil to rock), which could potentially bring great challenges to the drilling operations (e.g., making it hard to drill along the profile and risking the creation of sinkholes). The groundwater table should be located. Site investigation should include the measurement of soil gradation, unit weight, the relative density of coarse-grained soils, plasticity and consistency of fine-grained soils, rock quality designation, structural features, and a stratigraphy of the soil profile. The importance of this data is described by Gelinas and Mathy (2004). Contaminated soils should also be identified during this investigation.

B.2.2 Feasibility Study

Based on the collected information, the feasibility of using HDD should be studied. Technical, contractual, and economic feasibilities are the basic components of this feasibility study. Conditions that usually make HDD less feasible include adverse subsurface conditions (e.g., soil containing more than 50% of cobbles, very loose coarse-grained soils, highly contaminated soils), site constraints, scheduling constraints, high risk of undiscovered utilities or underground obstacles, tight profile tolerances, adverse weather conditions, etc. When comparing the cost of HDD to other methods, societal costs such as traffic disruption, noise, and duration might be considered (McKim 1997a; Tighe et al. 1999; Bush and Simonson 2001).

B.2.3 Risk Management

HDD comes with a set of risks that have to be identified and taken into consideration. Ariaratnam, Allouche, and Lueke (1998, 21) indicate that "*HDD can have a higher magnitude of risk, compared to open cut. Potential risks for an HDD contractor include failure to complete the bore successfully, safety of workers, environmental issues, damage to structures, and hitting other underground utilities or structures.*" HDD has lower risks in other aspects, such as the safety of workers and the chance of encountering utilities at greater depths (Woodroffe and Ariaratnam 2008).

Kramer et al. (2002) and C. Murray, Osbak, and Bayat (2013) list some of the risks commonly associated with HDD:

- Hydraulic fracturing.
- Inadvertent returns.
- Sinkholes.
- Stuck equipment.
- Exceeding acceptable tolerances due to subsurface conditions or human mistakes.
- Loss of fluid return.
- Excessive movements and deformations of ground, structures, utilizes, or other assets.
- Failure of pipe during or after installation.
- Failure of temporary works such as shafts or by-pass pumping during construction.
- Equipment malfunctioning.
- Slow production or stoppage of equipment due to natural or man-made obstructions, varying subsurface conditions, weather conditions, equipment malfunctioning.
- Disruption to residents and loss of public amenity.
- Disruption to businesses and commerce.
- Disruption to traffic and increased accident levels.
- Disruption to adjacent utilities.
- Environmental impacts (e.g., noise and vibration).
- Penalties for failure to meet deadlines for completion.

Methods for managing risk such as: geotechnical baseline reports, risk registers, monitoring programs, or contractual methods may help in distributing risk or reducing costs. Selecting well-trained and experienced contractors and crews is also essential for reducing risk.

Additionally, the southern part of Illinois is in a location with high seismic activity. Therefore, the resiliency of critical pipelines crossing through soils with high liquefaction potential needs to be assessed.

B.2.4 Design

B.2.4.1 Geometric Design

With site-specific data, the geometric design of the installation profile can be completed. The drilled path is typically defined by six parameters: entry and exit points, entry and exit angles, the radius of curvature, and depth of cover (Watson 1995). The PRCI manual (Watson 1995) and the ASCE HDD Pipeline Design Manual (Skonberg and Muindi 2014) provide general guidelines for selecting those parameters. Note that the designed radius of curvature of the profile needs to be greater than the minimum radius of curvature that a pipe can withstand. This depends on the pipe material, anticipated installation loads, and final operating parameters of the pipeline or utility.

Avoiding hydraulic fracture is an important criterion when selecting the depth of the alignment. Other criteria include avoiding problematic soils or utilities, reducing surface settlement or heave, etc. This is especially critical for important structures or environmentally sensitive features, for which a depth of cover no less than 40 ft (12.2 m) is sometimes suggested (Hair and Associates 2008). A minimum depth of cover of 3 ft (0.9 m) is widely used for small-scale installations; however, a much deeper cover might be needed for long or large-diameter installations. This is explained further in Section B.2.4.4.

The location of adjacent utilities and underground obstructions should be noted while designing the HDD profile. Adequate clearances should be allowed between the HDD profile and underground elements. Although a clearance on the order of 2 to 3 ft (0.6 to 0.9 m) is commonly used for smaller diameter installations, greater clearances are recommended to reduce the risk of utility strikes and/or other damages.

The borehole diameter is usually 1.5 times bigger than the diameter of the casing or product line to be installed (if no casing is used). This annular void allows for the return of fluid and the navigation of the casing or pipe while pulling it into the borehole. However, for boreholes larger than 24 in. (60 cm) in diameter, a 1.5 ratio might be excessive, and the borehole diameter is limited to 12 in. (30.5 cm) more than the diameter of the casing.

B.2.4.2 Pipe and Casing Design

During and after HDD installation, the product pipe and casing are subjected to different kinds of loads. These loads and stresses should be estimated, and a pipe that has sufficient strength to withstand these loads should be selected. The installation loads are also important for selecting the drilling rig, which should be able to provide enough pull load to overcome those forces to pull the

pipe into the borehole. Installation loads include resistance force between the pipe and the borehole wall, resistance force at the curves caused by Capstan effect and bending/stiffness effect, and the drag force of drilling fluid caused by its viscosity (Yan et al. 2018). Above ground loads due to the interaction between the pipe and pipe rollers (or ground surface) are also considered.

Currently, the ASTM F1962 model (ASTM 2011) and Pipeline Research Council International (PRCI) models (Huey, Hair, and McLeod 1996) are the most widely used estimations for model installation loads, installation stresses, operating loads, and operating stresses (Yan et al. 2018). Although the ASTM method is explicitly intended for use with polyethylene (e.g., HDPE) pipe, and the PRCI method was initially developed for steel pipe, accounting for the relatively high bending stiffness of this product, both procedures have been used for estimating HDD pull loads for pipes of various material (Slavin and Scholl 2014). Cai et al. (2017) conducted a comparison between six different methods for calculating pulling load, and they concluded that the PRCI method, among other methods, is suitable for steel pipes, while the ASTM F1962 method, among other methods, is suitable for polyethylene pipes. Equations for installation loads, installation stresses, operating loads, and operating stresses are found in Skonberg and Muindi (2014) and the PRCI manual (Watson 1995).

Selecting the pipe and casing materials is a major decision in the design phase. This decision is constrained by application requirements, state and federal laws, economic considerations, safety considerations, and other considerations. Steel and HDPE are the most commonly used materials, although varieties of ductile iron pipes and fusible PVC pipes are alternatives. Some pipes require extra protection, such as steel pipes which are usually coated to protect them from corrosion over the design life and wear during pulling. Multiple pipes might be installed in a single reamed hole.

B.2.4.3 Drilling Fluid Design

According to Ariaratnam and Beljan (2005, 118), "*When drilling through sand and gravel, a drilling fluid needs to serve two important functions: stabilization of the borehole and suspension and transportation of cuttings. When drilling through clay, the same functions need to be performed; however, an additional requirement of the fluid is to retard swelling and reduce sticking of the soil to the downhole tooling and product line being installed. Geological conditions may vary between fine and coarse soils; consequently, different combinations of drilling fluid additives will be needed to perform the required functions under actual conditions."*

Ariaratnam and Beljan (2005) suggest that, in general, for coarse soils, bentonite should be used. While for fine soils, polymers added to a bentonite base are sometimes recommended. In practice, some polymer-based fluid mixes are used for fine-grained soils without the use of bentonite.

Water without additives is not effective as a drilling fluid. On one hand, it does not have any cuttings-carrying capability. On the other hand, it does not possess any gel-strength properties for building a mud rind on the borehole wall (ASTM-1998). A fluid mixture containing only natural clays and water will make only a heavy, clay-laden fluid that will not have the capability (viscosity) to carry the drill cuttings up-hole and will not make a thin mud rind on the borehole wall to inhibit its collapse (ASTM-1998).

The main rheological properties of drilling mud that have been defined and can be measured include (1) funnel viscosity, (2) plastic viscosity, (3) yield point, (4) apparent viscosity (effective viscosity), (5) flow index, (6) consistency index, and (7) gel strength (Shu, Ma, and Lan 2014). These properties are important for estimating the downhole pressure, as explained in the next section. They are usually obtained via lab testing, such as using a 6-speed viscometer.

B.2.4.4 Borehole Stability

Drilling fluid follows the path of least resistance. Ideally, this path is through the annulus of the borehole, which leads back to the drilling fluid containment pits at the entry and exit points. If, however, the annulus of the borehole is obstructed, for example, if the borehole caves in, or partially caves in, the fluid might follow another path into the soil surrounding the borehole. In some cases, the fluid flows into the subsurface and up to the ground surface. Drilling fluid that ascends to the ground surface is commonly known as an inadvertent drilling fluid return. This inadvertent return might or might not be associated with soil failure, typically referred to as hydro-fracture. Hydro-fracture occurs in a small percentage of inadvertent fluid returns (Sparks, Snider, and Sauls 2010). Inadvertent returns most often occur near the entry and exit points where soil cover is thin and may also occur along preexisting fractures or voids, at exploratory boring locations, or along the sides of existing structures such as piles or utility poles (Sparks, Snider, and Sauls 2010).

Hydro-fracture occurs when the annular pressure exceeds the strength of the soil surrounding the borehole, causing shear or tensile failure of the surrounding soil (Rostami 2017). The probability of a sudden increase in annular pressure is much higher during pilot drilling compared to other stages, primarily due to the small area of the annulus and cutting bed development at the bottom of the borehole, which increases the risk of hydraulic fracture (Rostami 2017).

According to Skonberg and Muindi (2014), the following can increase the risk of inadvertent returns and hydro-fractures:

- *Highly permeable soils such as gravel*
- *Soils consisting of loose sands or very soft clays*
- *Soil and bedrock materials with very low permeability but jointed or fractured (slicken-sided clays or rock fractures)*
- *Clay soils that have a tendency to swell in the presence of fluids*
- *Considerable elevation differences between either the entry or exit point and ground elevations along the HDD alignment*
- *Disturbed soils such as fill or in soils adjacent to piles or other structures*
- *Areas along the HDD alignment where depth of cover is less than 40 ft (12 m)*
- *Locations along the HDD alignment where significant variations in density and/or composition of ground conditions are encountered (i.e., overburden/bedrock contact and other types of mixed-interface transition zones)*
- *Use of inappropriate downhole tooling or drilling practices.* (Skonberg and Muindi 2014, 50)

Predicting hydro-fracture can identify areas of relatively higher risk of surficial drilling fluid impact. Although drilling fluid and pumping parameters can be adjusted to reduce the risk of inadvertent returns, their possibility cannot be eliminated (Skonberg and Muindi 2014).

Studies have revealed that the two primary factors affecting hydraulic fracturing in soil are fluid pressure in the borehole and depth of cover. Fluid pressure in an open borehole is determined by the weight of the drilling fluid and resistance to flow of the drilling fluid returns, and is proportional to the bored length and overall depth of the crossing (Ariaratnam et al. 2003).

To evaluate the possibility of hydro-fracture, two quantities must be calculated: the failure pressure at which hydro-fracture occurs and the fluid pressure necessary to conduct HDD operations. At any point, if the fluid pressure approaches the failure pressure, hydro-fracture is expected to occur, so maintaining the pressure at all points below the failure pressure helps prevent hydro-fracture. Also, minimum pressure should be maintained inside the borehole to prevent caving. This pressure is a function of the in situ effective stresses and the shear strength of the surrounding soil.

Maximum Allowable Pressure

There are two common mechanisms of failure around the borehole (cavity): shear strength of soil and initial stresses in the soil medium. At greater depths, tensile failure is a common type of fracture in cohesive soil, and at shallow depths shear failure occurs in low-cohesive and frictional soils (Rostami 2017).

The most common methods for calculating maximum allowable pressures are the Delft's method (Luger and Hergarden 1988) and the Queen's Equations (Xia and Moore 2006). The Delft's method considers the shear failure (Rostami 2017), while the Queen's Equations distinguish between the tensile failure (hydro-fracture) and shear failure (blow-out). Lan (2018) also distinguished those two failure patterns and developed another method for calculating max pressure. Lan (2018), using a series of medium-scale laboratory tests, reported that the Delft equation consistently overestimated allowable mud pressures. Buenker (2015) found the infeasibility of using the original Delft equation in bedrock, so he used the Hoek-Brown criterion in the cavity expansion theory and derived some analogous equations of the Delft equation for bedrock.

Actual Pressure

At the design phase, the in-hole pressure can be estimated and compared to the maximum allowable pressure to check the adequacy of the selected profile, especially the thickness of the cover at all points. The most commonly used methods are the Bingham Plastic Model and the Power-Law Model. Using equations and rheological properties of drilling mud, these methods can estimate the actual pressures in-hole. The Herschel-Bulkley Model is also used, but it is much more complex than the abovementioned two models. Rostami et al. (2015) and Rostami (2017) compared measured pressures from two HDD projects to estimates of those two models. The comparisons were remarkably good.

Dealing with Critical Zones

If the hydro-fracture evaluation indicates that high risks of hydro-fracture exist at certain locations or segments of the HDD bore, Bennett and Wallin (2008) suggested employing measures such as relief wells, piezometers, conductor casings, and monitoring drilling fluid returns at the drill rig. Conductor casings are installed at the entry points to bypass weak soils and reduce the potential inadvertent returns at those locations typically characterized by shallow covers. Once installed, drilling is performed inside the conductor casing. The intersect method is sometimes used to decrease the risk of hydro-fracture. The intersect method involves drilling pilot holes from both sides of the crossing (entry and exit point), with one pilot hole intersecting the other pilot hole somewhere near the middle. The risk of hydro-fracture is reduced because the annular pressure required for each individual pilot hole is less than that required for a single pilot hole crossing the entire length.

According to Skonberg and Muindi (2014), where HDD installations face a significant impact from inadvertent returns, the following may be considered:

- *Pressure while drilling (PWD) tool: This tool provides real-time data of annular pressures behind the drill bit. The tool can indicate sudden increases in annular pressures, which may indicate an annular blockage or other problems.*
- *Drilling fluid testing: Frequent testing of drilling fluids being pumped downhole and returning to the surface provides relevant data to analyze for comparison with annular pressure calculations and to identify trends.*
- *Drilling practices: Drilling methods to increase the likelihood of maintaining drilling fluid returns during pilot-hole drilling include swabbing (retracting and reinserting each drilled joint) and the use of weeper subs, which introduces drilling fluid to the annulus along with the drilled profile.*
- *Proper contingency planning is critical for an effective response to inadvertent returns. It is important not to delay or affect the HDD operations, particularly during pre-reaming or pull back. Planning should include:*
    - *Identifying methods of rapid detection (access to the drill alignment and associated areas)*
    - *Having suitable containment materials (silt curtain, hay bales, sandbags, excavation tools, plywood sheeting, etc.) at the HDD site to contain an inadvertent return in the event it occurs*
    - *Identifying the length of time before cleanup begins (if in a traveled street, then it is most likely immediate; however, it may be more suitable in other areas to allow the bentonite gel to set and dry)*
    - *Listing regulatory agencies that should be notified in the case of an inadvertent return event*
    - *Establishing ingress/egress routes and methods into environmentally sensitive areas to minimize disturbance from equipment and personnel*
    - *Determining short- and long-term monitoring requirements, if any, for areas of inadvertent fluid release that are not accessible and where mitigating measures are impractical or not feasible (i.e., flowing waterways, inaccessible wetlands, etc.)* (Skonberg and Muindi 2014, 51)

B.2.5 Pipe Handling

Handling the casing and pipe, especially while pulling, is a stage that should be planned at the design phase. It is highly recommended that the pipe be pulled as one segment (fully welded or fused), which decreases the time of pulling and reduces the chances of bore failure and stuck pipes. It is necessary to check that the right-of-way is sufficient to lay out the pipe and pull it as one segment while designing its profile and location. Pipe handling and pulling machinery and equipment, such as excavators, roller-stands, and swivels, should also be enough in number to enable the pulling of the casing and pipe without exceeding stress and deformation limits. The pulling scheme should be designed, and the bending angles should be calculated and checked.

B.2.6 Selection of Equipment and Machinery

Adequate machinery and equipment should be selected for the HDD project. The drill rig should be able to drill the hole, pull the pipe in place, and pump enough fluid during the drilling. The fluid system should be able to mix and supply the needed drilling fluid. The pipe handling machinery should handle the pipe without subjecting it to intolerable stresses or deformations. The spoils handling system should be able to contain and dispose of spoils without negatively impacting the environment.

The tracking system should be selected while considering the required tolerances and the effective range of different tracking systems. The drill bit and the reamers should be selected based on the soil or ground condition. Jetting assemblies are commonly used for soft to medium consolidated soil conditions, while mud motors are adopted in ground conditions ranging from hard soil to very hard rock (Ariaratnam and Allouche 2000b). The slanted area is usually increased with respect to increasing softness of the ground to benefit from more passive pressure and allow for steering the bit. Selecting an adequate reamer is explained in Allouche, Ponnam, and Shu (2012):

- *Reamers of clayey soils: The primary concern in clayey soils is breaking up the clay into small chunks that can be mixed with the drilling fluid to create flowable slurry. If too large, cuttings can ball up on the reamer and increase the amount of pullback force required to install the product pipe. Borehole stability is typically not an issue in clayey soil so principal features to be used in clayey soils includes a minimal surface area in the case of a cutting reamer to avoid balling up of clay and adequate number of high-pressure jets to promote cutting, mixing and cleaning of the cutting faces. The reamers used in clayey soils are either compaction (or barrel type) or fly cutter types.*
- *Reamers for sandy soils: Problems encountered when drilling in sandy soils include high resistance to pulling back the product pipe and borehole instability. The reamer must have good mixing capacity to form flowable slurry, pump sufficient volumes of drilling fluid to account for losses of drilling fluid due to percolation into the sandy soil and allow the drilling fluid to flow along the incoming pipe product towards the exit end of the hole. Hence, it is important to consider the size, number and location of nozzles as well as passage of slurry from the front end of the reamer to the rear end, while designing the reamer.*
- *Reamers for rocky formations: In rocky formation the reamer experiences high lateral loads in addition to torque and drag forces due to the applied tensile load, load distribution among the*

cutters, rock failure mechanics, torsional loading, and normal force loading due to reamer bending. Reamers for rock formations works like a hole opener, grinding the hard rock. Drilling fluid discharge rate should be adequate to form slurry and avoid the problem of unstable borehole.

- *Reamers for cobble/gravel formation: Cobble/gravel formations present the most unfavorable condition for carrying out HDD installations. Cobble/gravel is loose hard rock where borehole stability is a significant challenge. Reamers for this formation type should incorporate aggressive cutting features together with an outstanding mixing capability to form a stable borehole.* (Allouche, Ponnam, and Shu 2012, 1347)

Further discussion of reamers and their issues can be found in (Albert 2013). Usually, the reamer size shall be 1.5 times the O.D. of the pipe. In cases where the pipe is larger than 24 in. (61 cm), it is common practice to enlarge the borehole to 12 in. (30 cm) greater than the O.D. of the pipe to be installed. Large-size boreholes typically require multiple phases of reaming, gradually enlarging the borehole.

B.2.7 Public Safety Plans

Public safety plans should be prepared prior to the commencement of the project. They must include the following:

- Transportation management plan, which is required if traffic modification (e.g., detour, lane closure, or traffic staging) is needed.
- Safety plan covering the safety measures to be taken on-site to protect labor and the public from equipment and construction threats (e.g., electrocution, contaminated soils, etc.).
- Contingency plans to deal with possible risks during HDD. This includes the course of action in the case of the following:
    - Frac-out.
    - Inadvertent returns.
    - Sinkhole.
    - Excessive deformation of ground or structures.
    - Stuck equipment.
    - Loss of return.
    - Intolerable deviation from planned profile.
    - Pipe failure during or after pulling.
    - Hitting an underground obstacle or utility.

- Environmental plan, which might be required in some cases (e.g., noise in urban areas, dealing with contaminated soils).

B.2.8 Additional Requirements

Additional elements may be needed for some projects. They include the following:

- Monitoring plan: possible requirement if construction is expected to impact critical structures.
- Entry and exit pits support system design: required if the projected excavated pits exceed 6 ft (2 m) in depth.
- Survey plan: may be required if construction is expected to impact structures (such as roads, bridge piers, structures, etc.) to verify that the deformations caused, if any, are within tolerable ranges. This plan should at least consist of a pre-construction set of measurements and a post-construction set of measurements.
- Pipe testing: pipe testing requirements before construction are related to the pipe material and applications. More details can be found in the ASCE manual (Skonberg and Muindi 2014).

B.2.9 Scheduling

The schedule needs to be thoroughly planned, taking into consideration site constraints. Multiple shifts might be required for feasibility or social reasons. If possible, it is recommended to schedule the drilling in moderate weather conditions to avoid very low temperatures which can reduce the productivity of crews and cause frequent equipment malfunctions and delays (due to freezing).

B.3 CONSTRUCTION

B.3.1 Site and Machinery Preparation

Before construction begins, the locations of the entry and exit points are marked by a surveyor. The existing utility locations are also marked. The machinery and equipment are set up within the boundaries of the right-of-way, easements, or other work areas and access are coordinated with property owners. It is highly recommended that machinery and equipment be tested before being mobilized to save any delays due to machinery or equipment malfunction. Supporting decks, such as timber mats, might be required if the soil in the right-of-way is weak and cannot support the weight of the machinery. All heavy machinery must be transported via vehicles with rubber tires. Vehicles with tracks (treads) should not be allowed on the roads before and throughout the construction, unless measures are taken to protect the pavement from damage. The spoils handling system is set up, including spoils containing trenches, vacuum trucks, or recycling systems. The fluid is mixed via the fluid system and tested if required. When a temporary soil retention system is needed, its design should be submitted in advance to the Bureau of Bridges and Structures (BBS) for approval.

B.3.2 Pilot Drilling

The tracking system is tested before the start of drilling, and the rig sensors should be functional. The drilling bit should be clean, and its nozzles should be open to allow the passage of the drilling fluid. If a mud motor is going to be used, it should be reconditioned, inspected, and functioning. The drilling can then proceed at the designated entry point. A detailed drilling log is typically kept by the contractor, documenting the duration required to drill each rod, the drilling fluid discharge rate, thrust and rotary pressures, and notes relative to drilling behavior. In addition to the drilling log, the steering technician documents details relative to the position and curvature of the pilot hole. This typically includes the length of each rod, the inclination, the azimuth, and surface tracking data. In some cases, the annular pressure is also recorded.

Drilling fluid returns to the fluid containment pit at the entry point and is monitored throughout the pilot hole. The volume of the return is estimated and compared to the pumped volume. If a significant difference is calculated, or the fluid is totally lost (loss of circulation), efforts are taken to address the issue. Pulling back and swabbing the hole is one of the first actions taken to restore circulation. Adjusting drilling fluid rheology, use of lost circulation materials, and shutting down for a period of time to let the drilling fluid solidify are other measures commonly undertaken. When drilling fluid circulation is lost or significantly diminished, the surface above the profile should be continuously monitored. If extra deformation or inadvertent returns are observed or any of the action triggering events listed in the contingency plans occur, further drilling should be stopped till this issue is addressed.

The drilled profile should be assessed during the drilling, verifying that the deviation from the planned profile is within the acceptable tolerances. If those tolerances are exceeded, the drilling is adjusted, sometimes by pulling back a rod (or more) and re-drilling. It is important to realize that perfectly matching the planned profile is rarely feasible because of equipment limitations and varying subsurface conditions. Those tolerances depend on the application, pipe, landowners' requirements, and the project's size. An error of 1% of the drilled length is not unusual. When the pilot drilling ends,

daylighting at the exit point, the exit point location is compared to the target exit point, and re-drilling is performed if necessary.

If crossing the road is needed for locating the drill bit (walkover tracking), this should be performed as outlined in the transportation management plan. This crossing should be safe for the person carrying the walkover receiver.

B.3.3 Reaming

After completing the pilot drilling, the reamer is attached to the drill string. Its nozzles should be open to allow the passage of the drilling fluid. A log is prepared to document the duration taken to drill each rod, the drilling fluid discharge rate, pull/thrust pressures, and rotary pressures. The reaming is performed as planned (in the number of passes that were planned). The fluid return should be monitored just as in pilot drilling. The fluid return is monitored throughout the reaming. The volume of the return is estimated and compared to the pumped volume. If a significant difference is calculated, or the fluid is totally lost (loss of return), further drilling should be stopped till this issue is addressed. Swabbing the hole can sometimes help with this issue. The surface above the profile should be continuously monitored, and if extra deformation or inadvertent returns are observed or any of the action triggering events listed in the contingency plans occur, further drilling should be stopped untill these issues are addressed and resolved.

B.3.4 Pipe Preparation and Pulling

Casing (or pipe) fusing or welding is usually performed during drilling or reaming in preparation for pullback. Welding or fusing should be performed per specifications, and the casing (or pipe) is tested before being pulled. The casing (or pipe) is preferably fabricated into one continuous segment. A pulling head is welded onto the leading edge of the pull section.

The casing is then laid out next to the exit point. After the reaming ends, a pullback assembly, typically consisting of a reamer and a swivel, is attached to the pulling head of the casing. While pulling or handling, the casing should not be dragged on the ground but rather placed on rollers and/or carried by machinery. Doing so reduces damage to the pipe coating, reduces above-ground friction and therefore reduces the pulling force required, and prevents intolerable deformations and stresses that are commonly incurred during pulling.

The fluid return should be monitored just as in pilot drilling and reaming. Casing pulling is sometimes associated with inadvertent returns since the borehole is mostly occupied by the casing leaving only the annular space for the escape of the fluid and cuttings. Any action triggering events should also be monitored.

Pipe testing requirements during construction are related to the pipe material and applications. More details can be found in the ASCE manual (Skonberg and Muindi 2014).

B.3.5 Site Restoration

After the pipe is pulled, the site should be restored and cleaned. Spoils should be disposed of as planned, in an environmentally friendly method.

B.4 AFTER CONSTRUCTION

B.4.1 Quality Assurance Plan

After completion of the installation, quality assurance may be required to verify that the casing and pipe were properly installed and that the construction did not negatively impact the surrounding ground, structures, or utilities.

B.4.1.1 Pipe Testing

Casing and pipe testing are sometimes required by the owner to verify that the pipe was not damaged during pulling and that it can handle its operating stresses. This might also be required by the state to verify that the casing is continuous and will not result in soil erosion, undermining superstructures. Hydrostatic testing is the most common method of testing in which the pipe is pressurized for a few hours. A constant pressure would indicate a sound pipe or casing, while a loss of pressure would indicate a discontinuity that should be addressed. Another test, mainly for graded lines, includes pouring water, then measuring the outflow to detect if the pipe retained water, indicating some dips, which might be problematic for on-grade sewer applications, for example. A newer method of testing includes passing a camera through the length of the pipe and taking photos of the pipe, which can be used to detect discontinuities.

B.4.1.2 Monitoring

Monitoring of the superstructures and surrounding structures may be required to verify that they were not impacted by the construction. The monitoring plan might include survey measurements, in addition to the deployment of sensors such as accelerometers, crack-gauges, settlement markers, piezometers, etc. The survey measurements before the construction are compared to measurements after (and possibly during) the construction.

B.4.2 Final Delivery Plan

The final delivery package includes the following:

- GPS coordinates of the actual entry and exit points.
- As-built plans.
- Drilling, reaming, and pipe pulling operational logs.

The plans should be submitted to the utility owner and the HDD installation permitting agency (Illinois Department of Transportation).

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APPENDIX C: PROPOSED HDD GUIDANCE SPECIFICATIONS

TABLE OF CONTENTS

USER GUIDANCE 66

C.1 DESCRIPTION 67

C.1.1 Definition of Terms 67

C.1.2 Scope of Work 68

C.1.3 General 68

C.1.4 Policies 68

C.1.5 Responsibilities 68

C.1.6 Utility Permit Requirement 68

C.1.7 Categories 69

C.2 MATERIALS 70

C.2.1 General 70

C.2.2 Product Pipe 70

C.2.3 Detection Wire 70

C.2.4 Filler Material 70

C.2.5 Casing Pipe (if applied) 70

C.3 CONSTRUCTION 72

C.3.1 Site Preparation 72

C.3.2 Crossings 73

C.3.3 Pedestrian Traffic 73

C.3.4 Construction Oversight 73

C.3.5 Construction Timing 73

C.3.6 Electrical Hazards 73

C.3.7 Pipe Handling 73

C.3.8 Product Bore Path 74

C.3.9 Product Locating and Tracking 74

C.3.10 Pilot Hole Drilling 75

C.3.11 Reaming and Pull Back 75

C.3.12 Installation Process 75

C.3.13 Drilling Fluid 76
C.3.14 Equipment Requirement 77
C.3.15 Boring Failure 77
C.3.16 Site Restoration 78
C.4 QUALITY CONTROL 80
C.4.1 General 80
C.4.2 Surety Bonds/Contract Bonds 80
C.4.3 Final Acceptance of Work and Maintenance 80
C.4.4 Survey 81
C.4.5 Product Testing 81
C.5 DOCUMENTATION REQUIREMENT 82
C.5.1 Work Plan 82
C.5.2 Boring Path Report 82
C.5.3 Marked-Up Plan 82
C.5.4 As-Built Plan 83
C.5.5 Damage and Repairs Plan 83
C.5.6 Drilling Logs 84
C.5.7 Contractor Daily Drilling Reports 84
C.6 METHOD OF MEASUREMENT 85
C.7 BASIS OF PAYMENT 86
C.8 REFERENCES 87

LIST OF TABLES

Table 2. Utility Location Contacts 72

USER GUIDANCE

The Proposed Horizontal Directional Drilling (HDD) Guidance Specifications are a combination of both utility permit and construction contract specifications. Not all sections may apply to a given HDD installation project.

This appendix was prepared by combining and editing the relevant parts of the reviewed specifications while benefitting from the lessons learned in the research activities in this project.

Some of the proposed provisions may only be applicable to certain classes of projects, such as project size, and whether it is an IDOT project or a project developed by others and permitted by IDOT. Differentiating the applicability of specific provisions is beyond the scope of this project.

C.1 DESCRIPTION

C.1.1 Definition of Terms

Contract – See Article 101.09 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

Contractor – See Article 101.12 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

"The individual, firm, partnership, joint venture, or corporation contracting with the Department for performance of prescribed work."

Department – See Article 101.14 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

Detection Wire – electronic detection material for non-conductive piping products.

Drilling Fluids – Fluids consisting of water, bentonite, and any approved additives such as environmentally safe polymers, lubricants, and viscosifiers.

Engineer – See Article 101.16 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

Horizontal Directional Drilling (HDD) – A method of installing buried piping by controlled (guided within specified limits), horizontal drilling.

Pavement Structures– See Article 101.26 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

Pilot Hole – The initial controlled drilled horizontal shaft used to guide the enlargement to design size and eventual installation of the product pipe.

Product Pipe – Permanent pipeline for operational use.

Pullback – The pipe installation pulled back by a swivel/pulling head connected behind the reamer, which pulls the prepared product pipe into place.

Reaming – The back-reaming hole opener is attached to the drill pipe and rotated and pulled back through the pilot hole to enlarge the bore in one or more passes to the size needed for product pipe installation.

Structure – See Article 101.45 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

Utility – See Article 101.54 of Illinois Department of Transportation (IDOT) (2016). Standard Specifications for Road and Bridge Construction.

C.1.2 Scope of Work

The Proposed Guidance Specifications document the recommended construction practices, materials, and procedures for Horizontal Directional Drilling (HDD) project on land, property, or interests of the State of Illinois.

C.1.3 General

HDD is a steerable trenchless method to install product pipes. It is a multi-stage process consisting of site preparation, equipment setup, pilot hole boring, pulling product pipe, and site restoration. Proper orientation and tracking systems are applied to accomplish the designed bore alignment. The pilot borehole would be enlarged with back reaming or forward reaming methods for product pipe larger than the pilot hole size. Drilling fluid is introduced into the annular bore space as a soil stabilizing agent to minimize friction and prevent the collapse of borehole. The drilling fluids are selected and designed based on the site-specific soil and groundwater conditions. At the end of construction, the construction site should be restored to preconstruction conditions.

C.1.4 Policies

The Permittee shall adhere to the latest editions of all Illinois Department of Transportation (IDOT) standards, including but not limited to, the following:

- Accommodation of Utilities on Right-of-way of the Illinois State Highway Systems.
- Standard Specifications for Road and Bridge Construction.
- Highway Standards and District Specific Standards.
- Bureau of Design and Environment Manual.
- Bureau of Local Roads and Streets Manual.
- Geotechnical Manual.

C.1.5 Responsibilities

Approval of the utility permit to perform HDD does not alleviate the Contractor from safety regulations during the installation or the operation of the installed utility. The Utility and their subcontractors will indemnify the Department according to Article 107.26 of the IDOT Standard Specifications.

C.1.6 Utility Permit Requirement

The permit application submittal should include necessary information, such as the following:

- Contractors' information, qualifications, and HDD project experience.
- Equipment, machinery, and materials to be used.
- Product pipe properties, including material, diameter, wall thickness, method of jointing, etc.

- Construction site plan, indicating entry and exit pits, proposed bore alignment, depth of cover, Right-of-way (ROW) lines, property lines, public and private roadways, entrances, etc.

- Location and clearances for all existing utility crossings and appurtenances, like Department utilities, drainage systems, foundations, road signs, traffic lights, guardrail posts, etc.

- Soil investigation along the entire boring path to the lowest elevation of the borehole.

    - For borings less than or equal to 6 ft (1.83 m), refer to the United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Web Soil Survey (WSS), and Illinois Water Well Log (ILWATER).

    - For borings greater than 6 ft (1.83 m), provide a geotechnical boring plan and report.

- Transportation management plan (if applicable), which typically requires submission of IDOT forms, BSPE 725 and OPER 2410, a minimum of 21 days before work begins. These forms are required for the traffic control plan's authorization and create the necessary width and other restrictions for oversize load permit routing.

- Damage and Repairs plans, which shows how the damage to any IDOT facility will be remedied when required by the Engineer. These details should be documented and submitted to the Department as discussed in Section C.5.5. When Damage and Repairs plans are required, they must be approved by the Engineer before any work can begin.

- Emergency contingency plan, which specifies the nature of potential emergencies and the intended response by the Contractor. The intended response shall include notification to the Department, first responders, and anyone who may be impacted by the emergency. The plan shall include emergency contacts (name, title, phone number, and email) for Contractor, Utility, Engineer, and IDOT operations personnel all key personnel needed for emergency road closures, detour plan, etc., and a Department-approved BSPE 725 traffic control plan (if applicable).

- Drilling contingency plan, which should address, but not be limited to, general procedures and labor issues for the duration of the project; equipment requirements and the basis of duty/standby arrangement; drilling fluid monitoring and inadvertent drilling fluid returns; time considerations; contract details for the Engineer and any local regulatory bodies that may be affected by the project; waste disposal plans; and public relations requirements.

C.1.7 Categories

The HDD product can be classified based on its carrier content. The categories commonly include pressurized liquid (for water, forced sanitary sewer, etc.), gravity flow liquid (for sanitary sewer, etc.), pressurized gas (for natural gas, etc.), power (for electricity), and telecommunication (for phone cable, fiber optics, etc.)

C.2 MATERIALS

C.2.1 General

Materials are defined as the permanently installed product, which typically includes carrier pipe, conduit, casing, or duct. In addition, the materials also include filler materials, detection wires, and other incidental materials, which are used to install the product pipe in complex subsurface conditions if applied.

C.2.2 Product Pipe

The selection of the product pipe must comply with all applicable IDOT specification sections, listed in Section C.1.4, and ASTM standards. Generally, plastic product pipes, like polyethylene (PE) and polyvinylchloride (PVC), are used for water, sewer, etc.; steel pipes are used for oil and gas installation. There are several different types and pressure ratings of each material available. The selection should consider the location and the project categories, as indicated in Section C.1.7. The used materials should be appropriate for the stresses generated during operation, dealing with the selected equipment and field conditions, and after installation. Ductile iron pipes can be used in cobble and gravel.

The pipe sections need to be joined to ensure that the product pipe has a flush and even inner surface with adequate strength and flexibility to withstand the installation stresses, overburden pressures, and operating pressures. Butt fusion, socket fusion, electrofusion, or welding are typically used for joining plastic pipe segments or metal pipe segments. Mechanical couplings are not permitted. Only skilled operators are allowed to fuse the joints. Unless the product pipe is only used as a sleeve, to pull through a sleeve, or for dry utilities, the Contractor is responsible for the recording of data and time of joint, fusion temperature and pressure, joining/fusion time, and cooling time for each fused joint and for providing the data in the final report of the installation.

C.2.3 Detection Wire

The detection wire is defined as electronic detection material for non-conductive piping products. It is designed for HDD to conductively locate underground utility lines. Each detection wire should be tested for continuity after backfilling of the entrance and exit pits are completed.

C.2.4 Filler Material

The abandoned borings are typically filled with controlled low-strength material (CLSM) without fly ash. For certain diameter pipe/borehole ratios and/or pipe size, annular space between product pipe (or casing) and reamed boreholes should be grouted. The IDOT Standard Specifications for Road and Bridge Construction has specifications for CLSM and grout.

C.2.5 Casing Pipe (if applied)

Casing is typically only used for unjointed pipes for water or sewer in HDD projects. The Department reserves the right to require a warning sign to be placed above ground, per the Manual on Uniform Traffic Control Devices (MUTCD), marking the ends of the casing, which includes, at minimum, the name of Utility, address of the Utility, contents of the carrier pipe, and Emergency phone number(s).

The Utility shall submit the utility permit to the Department with the information of the casing pipe type, length, size, wall thickness, and material specifications.

The casing shall be continuous by one-piece fabrication, welding, or a lock-type jointed pipe that can withstand the stress during installation. Welded steel pipe is a common casing pipe material used in HDD projects. American Water Works Association standard C200 (AWWA C200) recommends wall thickness of welded steel casing pipe based on site subsurface conditions. Field joints shall be either full circumference welded butt joints or integral machined press-fit connections. The joints of the casing pipe shall be rigid and watertight. The ends of the casing shall have an end seal treatment, which prevents the migration of soil into the casing. Carrier pipes that will contain volatile liquids or gases shall have a vent tube installed at both ends of the casing.

There are multiple ways to protect the steel casing pipe, including a galvanic anode system, an impressed current cathodic protection system, galvanizing the casing pipe, and coating the casing pipe with fusion-bonded epoxy.

The use of a plastic casing pipe allows the flexibility necessary to adjust the borehole geometry parameters in response to the anticipated geotechnical conditions. In certain pressure ranges, plastic casings can provide the facility owner with assurance that if in operation the carrier pipe were breached, a plastic casing would effectively contain the fluid and prevent damage to the crossing facility.

C.3 CONSTRUCTION

C.3.1 Site Preparation

Any excavations including, but not limited to, entry, exit, recovery pits, and slurry sump pits should be carried out following the standards listed in Section C.1.4. Drilling fluids are required to be collected in sump pits if vacuum devices are not operated throughout the drilling operation, unless approved by the Engineer.

The work site shall be restored to pre-construction conditions or as specified by the work plans within 48 hours of completing the installation of the product pipes. All excess slurry and spoils from the site shall be cleaned, removed, and disposed of. Exposure of product shall be limited to 3 ft (1 m) and 14 consecutive days, unless approved by the Engineer.

The following steps should be undertaken by the Contractor in order to ensure safe and efficient construction with minimum interruption of normal, everyday activities at the site:

- Notify owners of subsurface utilities along and on either side of the proposed drill path of the impending work. All utilities along and on either side of the proposed drill path are to be located. Most utilities can be located by calling JULIE for downstate projects (outside the limit of the City of Chicago) or DIGGER in the Chicagoland area at the numbers provided in **Table 2**.

- Obtain all necessary permits or authorizations to carry out construction activities near or across all such buried obstructions.

- Expose all utility crossings using hydro excavation, hand excavation, or other approved method (potholing) to confirm depth.

- Arrange construction schedule to minimize disruption (e.g., drilling under major highways and/or river crossings).

- Determine and document the proposed drill path, including horizontal and vertical alignments and location of buried utilities and substructures along the path. It is recommended to use the State Plane Coordinate system or Universal Transverse Mercator coordinate system, measured by GPS, as a reference for the entry and exit point.

Table 2. Utility Location Contacts

Downstate Illinois	Chicagoland Area
JULIE http://www.illinois1call.com/ Call 811 or 800-892-0123	DIGGER https://ipi.cityofchicago.org/Digger Call 312-744-7000

Working in extremely cold weather should be avoided. Below 20°F (-6.7°C), the rig becomes slower as fluids start to freeze. This slowdown might make drilling infeasible.

C.3.2 Crossings

Angles of crossing to highway, road, river, and rail are preferred to be 90 degrees. Variances from this specification must be requested in writing to the Department for review and approval. In the case that 90-degree crossings cannot be made, slight skews have been permitted but nothing over approximately 40 degrees.

C.3.3 Pedestrian Traffic

When and where installations temporarily disrupt the use of a pedestrian way, a safe alternate route needs to be provided in accordance with the IDOT standards listed in Section C.1.4.

C.3.4 Construction Oversight

The Department reserves the right to require construction oversight for the project. If required, the Utility shall submit to the Department the name, company, qualifications, and contact number of any oversight personnel for approval.

C.3.5 Construction Timing

All drilling operations will be conducted at a time of day that reduces the potential for disruption of the traveling public and adjacent property owners. Directional drilling operations shall not be allowed during hours of peak vehicular traffic without an approved road closure permit from the Department or without written approval from the Engineer.

C.3.6 Electrical Hazards

Electrical detection and alarm systems should be equipped on the drilling systems to protect the workers and devices from electrical hazards during the drilling process. In the event an electrical current is detected, all work shall immediately cease until the source of the electrical current has been identified. It is important to notify the Engineer and submit a damage and repairs plan according to section C.5.5.

C.3.7 Pipe Handling

Handling the casing and pipe, especially while pulling, is a stage that should be planned at the design phase. It is highly recommended that the pipe be pulled as one segment (fully welded or fused), which decreases the time of pulling and hence decreases the chances of bore failure and stuck pipes. It is necessary to check that the Right-of-way is sufficient to lay out the pipe and pull it as one segment while designing its profile and location. Pipe handling and pulling machinery and equipment, such as excavators, roller-stands, and swivel, should also be adequately supplied to enable the pulling of the casing and pipe without exceeding stress and deformation limits. The pulling scheme should be designed, and the bending angles should be calculated and checked.

The pipes for installation need to be homogenous and free of visible cracks, holes, and other faults. The Contractor shall transport, handle, and store the pipes in accordance with the manufacturer's recommendations at all times. Materials that are damaged or lost shall be repaired or replaced by the Contractor at no additional cost to the Engineer.

The Contractor should prevent the pipes from being cut, kinked, or damaged. The pipes should be stored on level ground that is free of sharp objects. In construction sites, they can be stored on wooden sleepers with suitable space between supports. The stacking of pipes should be limited to a height that would not cause excessive deformation for lower layers. Ropes, fabrics, or rubber-protected slings and straps shall be used to handle the pipes, while chains or cables with hooks inserted into the pipe ends shall be prevented. In pipe transporting, dragging pipes over sharp objects and dropping pipes onto rocky or unprepared ground shall be prevented.

C.3.8 Product Bore Path

In the design of the borehole path, the Engineer needs to consider the existence of the obstacles, site and soil conditions, space for future projects, and conflicts with existing utilities, to determine the depth of penetration. More importantly, the risks of inadvertent drilling fluid return and surface settlement or heaving should also be included in the considerations. If the risks existed, the depth of penetration should be increased. Typically, this has a minor effect on construction costs, unless more difficult ground conditions are encountered at greater depth.

In the drilling process, the Contractor shall provide methods to control line and grade. The locating and tracking system introduced in Section C.3.9 should be used to accurately locate the pilot hole by the Contractor. The recommended tolerance of both the vertical and horizontal alignment should be within plus or minus 1% of the bore length, and the vertical path of the pilot hole must not establish new high points not shown in the designed path. The Contractor shall include electronic monitoring of horizontal and vertical drilling head location and furnish tabulations of horizontal and vertical alignment to the Engineer at the completion of pilot hole drilling. When the pilot bore deviates from the planned bore path, the Contractor shall notify the Engineer. The Contractor may be required to pull back and re-drill from the location along the bore path where the deviation occurred, if deemed necessary by the Engineer. If conditions warrant removal of any materials installed in a failed bore path, as determined by the Engineer, it will be at no cost to the Department. All voids need to be filled promptly with controlled low-strength material.

C.3.9 Product Locating and Tracking

Locating and tracking systems are used to ensure the proposed installation is executed as intended. The Department recognizes walkover, wire line, wire line with surface grid verification, Magnetic Guidance System (MGS) probe, proven (non-experimental) gyroscopic probe, or any other system as approved by the Engineer as the accepted methods of tracking directional bores.

If signal interference is encountered that significantly affects the ability to accurately track the drill bit, the Engineer may specify the use of a suitable tracking system. If the Engineer informs the Contractor about signal interference or it is reasonable to expect interference at the site prior to bidding, a suitable tracking system without extra cost to the Engineer shall be selected; otherwise, the Engineer shall adjust the contract value and time accordingly. If the Contractor is using a magnetic guidance system, drill path shall be surveyed for any surface geo-magnetic variations or anomalies.

The locating and tracking system should provide information on the depth of the drill head from the transmitter to the surface at any location along the path of the bore. The location of the drill head can be determined from pitch, roll, and clock face orientation.

All facilities need to be installed such that their location can be readily determined by an electronic detection after installation. For non-conductive products, a detection wire should be attached as specified in Section C.2.3.

C.3.10 Pilot Hole Drilling

The Contractor shall verify the loading capacity of the HDD machine before the pilot hole drilling. The size of the entrance and exit pits, controlled by the pipe depth, diameter, and material, should be of sufficient size to avoid a sudden radius change of the pipe and consequent excessive deformation at these locations. The entry hole should be angled so that the curvature of the pilot hole does not exceed the allowable bending radius of the product pipe. After the pilot bore is established, it is important not to push anything from the entry pit to the exit pit.

C.3.11 Reaming and Pull Back

Upon successful completion of the pilot hole, reaming (forward/backward) is usually applied to enlarge the pilot hole when the product pipe size is greater than the pilot hole size. In the reaming process, the selection of reamer type is very important for the success of drilling and safety of the structures above it. A compaction reamer may be used in sands and gravels. It would work by compacting the cut sand and gravel into the periphery of the hole. Using a compaction reamer in clay would not work because clay is not as compressible in short durations. The clay would squeeze around the reamer or stick to it. A fly cutter reamer is preferable for clay.

In the pullback process, the Contractor shall pull the pipe through the borehole during the last step of reaming with the new pipe attached to the back of a swivel connector. Once pullback operations have commenced, it is recommended to continue without interruption and until the pipe is completely pulled through the reamed hole to prevent the slurry from hardening in the borehole. However, when space is limited, it may be necessary to pull a pipe in multiple sections for which a pause in the pull back is needed to join the sections. If a pause in pulling back is unavoidable, the drill pipe shall remain in the bore hole until the product pipe is pulled into place. Pipe pulling through a collapsing borehole is prohibited.

During the pullback operation, the Contractor will not apply more than the maximum safe pipe pull force specified by the pipe manufacturer. The pull section needs to be protected as it proceeds during pull back, so it moves freely and is not damaged. The yield strength of the product pipe can be a controlling factor of the pullback force. Typically, the maximum allowable tensile strength used is 90% of the pipe's yield strength. However, if the pipe is internally ballasted, the maximum pull load of the pipe could go up 3 to 4 times the estimated maximum pull load when pulled empty.

C.3.12 Installation Process

There are two types of installation options for an HDD project: the Cartridge method and the Assembly-line method. The assembly-line method allows the pipe to be pulled in one unit. It requires

a large construction area. The cartridge method assembles a single pipe section, then pulls one section into the bore path sequentially. When the bore path is straight, it is less efficient than the assembly-line method. However, the Cartridge method is effective for limited easement or right-of-way. The assembly-line method can be used for both ductile iron pipe and HDPE pipe, while the Cartridge method usually cannot be used for HDPE pipe.

The Contractor shall ensure the soil cuttings are removed effectively and that the borehole is stable during the process of pilot hole boring, forward/back reaming, and pipe installation. The drilling fluid needs to be monitored, and the pumping rate, pressure, viscosity, and density shall be recorded. When the excess pressure is very high, relief holes might be constructed at locations approved by the Engineer. When the relief holes are to be constructed on IDOT ROW, approval from the Engineer would be needed.

The Contractor shall minimize heaving during the pullback process by selecting a pullback rate that tends to maximize the removal of soil cuttings without building excess down hole pressure. When drilling in suspected contaminated ground, the drilling fluid must be tested for contamination and appropriately disposed of. If in the drilling process it becomes evident that the soil is contaminated, the Contractor shall stop the drilling and contact the Engineer immediately. Approval from the Engineer is required to continue the drilling.

During construction, low-density grout could cause pipe floating. It is recommended to make the grouting operations in multiple lifts to prevent pipe floating. In addition, filling the new pipe segment with water in order to add weight and prevent floatation is also recommended.

C.3.13 Drilling Fluid

In HDD projects, dry boring is seldomly used and may only be used for short-range applications. Drilling fluid is commonly applied. The main purposes of the drilling fluid are to stabilize the borehole, carry away cuttings, reduce friction (pullback and torque on drill rods and product pipe), maintain temperatures of bits and transmitters, clean cuttings from the drill bit and reamers, and control ground water pressure. In fine-grained soils like clays, the fluid could also prevent swelling of the surrounding soil.

The mixture of drilling fluids needs to be designed in a way to perform the preceding functions in the expected soil. The viscosity of the drilling fluid shall be varied to best fit the encountered soil conditions. Fluid segregation can cause the slurry flowing out of the borehole to differ from the fluid remaining in the borehole. The design of the drilling fluid mixture shall prevent fluid segregation from happening.

In suitable ground conditions, water alone should not be used as a drilling fluid, because it may destabilize the hole easily. It is more common to use a mixture of bentonite clay or other approved stabilizing agents, such as polymers, lubricants, and viscosifiers mixed with potable water to create the drilling fluid. Bentonite works best for sandy soils because it has the ability to form a filter cake on the borehole wall. This reduces infiltration of the drilling fluid into the surrounding soils and aids in stabilizing the borehole. Polymers can also be added as additives in drilling fluid for clayey soil.

Any other chemicals or polymer surfactants in the drilling fluid, without written consent from the Engineer, are prohibited from being used. The Contractor shall submit documentation to the Engineer, which certifies that any chemicals to be added are environmentally safe and not harmful or corrosive to the facility. Waste oil or environmentally non-compatible polymers cannot be part of the composition. Fiber additives could increase installation efficiency up to 67% compared to untreated drilling fluid.

The source of water for mixing the drilling fluid should be identified before construction. Any water source used, other than a potable water source, may require a pH test. The water shall be from a clean source. Water of a lower pH or with excessive calcium shall be treated with the appropriate amount of sodium carbonate or equivalent. Approvals and permits are required for obtaining water from such sources as streams, rivers, ponds, or fire hydrants. Hard water may be treated with soda ash to reach the required pH value. In conclusion, the water source for HDD construction should have a pH value between 7.5 and 10. Additionally, it should be free of chlorine with calcium, sodium chloride, or chlorine.

Before HDD construction, the contractor shall provide detailed information about drilling fluid and fluid mix in the work plan. More information can be found in C.5.1.

C.3.14 Equipment Requirement

The directional drilling machine needs to consist of a power system to rotate, push, and pull back hollow drill pipe into the ground at variable angles, while delivering a pressurized fluid mixture to a guidable drill head (bit). It should have sufficient strength to drill the pilot hole, ream the hole to adequate diameter, and pull the carrier pipe through the hole for the length and pipe diameter indicated through a leak-free hydraulic system.

The drill rig is anchored to the ground to withstand the pulling and rotating pressure. Depending on the diameter and length of the product pipe being installed, the capacity of the drill rig and its auxiliary equipment need to be adequate for the installation, especially for installing dual force mains.

The employed drill rig shall be capable of exerting a pullback force of at least two times that of the total anticipated pulling force required to complete the installation of the pipe specified.

C.3.15 Boring Failure

In HDD construction, boring failure happens when the drilling equipment cannot proceed. In this instance, the Contractor shall cease the operations to allow the ground-induced hydro-lock effect to subside. Then, if the drilling equipment remains stuck on re-commencement of the operations, the Contractor shall notify the Engineer immediately. The Engineer and the Contractor shall discuss the appropriate equipment recovery plan (e.g., open cut) to allow the drilling to continue. If the encountered obstruction can prevent installation from being as designed, the drilling pipe can either be taken out of service or left in place with approval from the Engineer. The pipe left in place should be filled with excavatable flowable fill immediately. A new installation procedure and revised plans should be submitted to the Engineer for approval before resuming work at another location. In the

case of permit work, the Department shall be notified of the boring failure and approve the damage and repairs plan.

Hydraulic fracturing could happen when the soil layer is insufficient to hold down the mud pressure. Drilling under the shallow part of a sloping surface could easily cause hydraulic fracturing. Using conductor casing, using pressure relief holes, and increasing cover depth are effective ways to reduce the risk of hydraulic fracturing. Hydraulic fracturing is also common when drilling through loose and highly permeable soil like sand, silty sand, or clayey sand. In this case, the drilling fluid shall be adjusted properly.

Hydro-lock and hydraulic fracturing could be noticed by monitoring the drilling fluid pressure. If the pressure goes abnormally high, the Contractor shall ensure that the contingency plan is implemented. The Engineer and the Contractor will discuss and implement additional options as needed.

If the pilot bore deviates from the planned bore path, the Contractor shall notify the Engineer. The Contractor may be required to pull back and re-drill from the location along the bore path where the deviation occurred, if deemed necessary by the Engineer.

C.3.16 Site Restoration

The Contractor should restore the site to its original conditions or better at no additional cost to the Department. The restoration shall include but not be limited to paved and unpaved surfaces, structures, shrubbery, landscaping, trees, and all else encountered. Any damage caused by heaving, settlement, separation of pavement structures, or escaping drilling fluid due to the drilling operations shall be repaired by the Contractor. If, during construction, damage is observed to the IDOT facility, cease all work until a plan of action for restoration is obtained and approved by the Engineer to minimize further damage.

The Contractor should backfill and compact all excavations, including subsurface exploration borehole, entry and exit pits, relief holes (if applied), etc. The subsurface exploration boreholes shall be sealed in accordance with IDOT Geotechnical Manual Section 4.4.2.1. Before sealing the annulus space, the Contractor shall allow the installed product pipe to cool and relax from the heat generated during the pull-back process due to friction and high-tension stresses. Before backfilling the entry and exit pit, the Contractor shall ensure that the product pipe is properly connected, installed, and supported by suitable material and approved by the Engineer, in order to avoid sagging after backfilling and compaction.

Any excess material shall be removed upon completion of the bore. All drilling fluids need to be disposed of or recycled in a manner acceptable to the appropriate local, state, or federal regulatory agencies. All drilling fluid and fluid additives shall be disclosed. Excess drilling fluid shall be confined in a containment pit at the entry and exit locations until recycled or removed from the site. Precautions shall be taken to ensure that drilling fluid does not enter roadways, streams, municipal storm, sanitary sewer lines, and/or any other drainage system or body of water. The unintended surfacing of drilling fluid shall be contained at the point of discharge and recycled or removed from the site.

Drilling fluids that are not recycled and reused shall be removed from the site and disposed of at an approved disposal site.

C.4 QUALITY CONTROL

C.4.1 General

The Contractor and the Utility who fully understand the project scope, equipment, boring operation, and Department procedures must be present at the job site during the entire installation and address immediate concerns and emergency operations. The Engineer shall be notified 48 hours in advance of starting any work. Installation can only begin when the Engineer is present at the job site and agrees that proper preparations have been made. For permit work, the Department shall be notified 48 hours in advance of work.

C.4.2 Surety Bonds/Contract Bonds

Surety Bonds required for Utility permit work shall follow the Surety Bond requirements outlined in TITLE 92: TRANSPORTATION, CHAPTER I: DEPARTMENT OF TRANSPORTATION, SUBCHAPTER f: HIGHWAYS, PART 530 ACCOMMODATION OF UTILITIES ON RIGHT-OF-WAY of the Illinois Administrative Code.

Contract Bonds are required for all the Department's construction contracts per Article 101.09 of Illinois Department of Transportation (IDOT) (2016) Standard Specifications for Road and Bridge Construction. A Contract Bond is a surety bond, and it is defined in Article 101.10 of Illinois Department of Transportation (IDOT) (2016) Standard Specifications for Road and Bridge Construction as "The approved form of security furnished by the Contractor and his/her surety as a guaranty that the Contractor will execute the work according to the terms of the contract."

C.4.3 Final Acceptance of Work and Maintenance

The work performed by the Utility/Contractor shall be free from failure, shifting, settlement, erosion, roadway damage, facility damage, etc. Any removal, replacement, repair, or disposal of any unauthorized or defective work or material shall begin within a period as specified by the Department following written notice by the Department to the Utility/Contractor.

For the Department's construction contracts, final acceptance of work does not bar the Department "from requiring the removal, replacement, repair, or disposal of any unauthorized or defective work or material or from recovering damages from any such work or material" per Article 109.08 of Illinois Department of Transportation (IDOT) (2016) Standard Specifications for Road and Bridge Construction. "Repairs to work subject to the approval required due to defective materials or workmanship or caused in whole or in part by Contractor operations or negligence, shall be performed at no additional cost to the Department" per Article 107.30 of the Illinois Department of Transportation (IDOT) (2016) Standard Specifications for Road and Bridge Construction.

Utility permit work performed within the ROW shall follow cleanup and restoration per Section 530.250 of TITLE 92: TRANSPORTATION, CHAPTER I: DEPARTMENT OF TRANSPORTATION, SUBCHAPTER f: HIGHWAYS, PART 530 ACCOMMODATION OF UTILITIES ON RIGHT-OF-WAY of the Illinois Administrative Code, which states that "The right-of-way shall be returned to a condition which is at least as good as it was before the permitted work took place, in a timely manner. This

includes restoration of entrances and side roads. Restoration of roadway surfaces will be made using Department approved materials and methods (see Section 530.30 'Department Approved')." Then, the utility shall be maintained and repaired as outlined in Section 530.290 of the TITLE 92: TRANSPORTATION, CHAPTER I: DEPARTMENT OF TRANSPORTATION, SUBCHAPTER f: HIGHWAYS, PART 530 ACCOMMODATION OF UTILITIES ON RIGHT-OF-WAY of the Illinois Administrative Code. If the need arises, the Department reserves the right to require that the utility be removed, relocated or modified as outlined Section 530.310 of the TITLE 92: TRANSPORTATION, CHAPTER I: DEPARTMENT OF TRANSPORTATION, SUBCHAPTER f: HIGHWAYS, PART 530 ACCOMMODATION OF UTILITIES ON RIGHT-OF-WAY of the Illinois Administrative Code.

C.4.4 Survey

Utility survey, geotechnical survey, and other evaluations are needed to reduce potential construction impacts when installing long-distance and segmented pipes. The geotechnical survey shall follow the procedures in IDOT Geotechnical Manual.

C.4.5 Product Testing

The Contractor shall conduct appropriate pipe joint testing methods and ensure the joints follow ASTM C828, ASTM C1103, and ASTM C969. The test records shall be provided to the Engineer as part of the As-Built Plan.

If there is any indication that the installed product has sustained damage, work must be stopped, and the Engineer must be notified. The Engineer may require exploratory investigations or testing and reserves the right to be present during this work. In these conditions, a pressure test is typically required by the Engineer to be performed after the installation of the product pipe. The Engineer shall review the test results and determine whether the product installation satisfies the specifications. Non-compliant installations may need to be filled with controlled low-strength material backfill.

Further testing may be required to ensure the pipeline (including joints) is leak-proof. For example, watertight configurations are usually required for the product pipes installed beneath any pavement structures, including sidewalks and shoulders.

C.5 DOCUMENTATION REQUIREMENT

C.5.1 Work Plan

Prior to beginning work, a Work Plan should be prepared to detail the procedure and schedule to execute the project. The work plan will be detailed, realistic, and based on actual working conditions for this project. The work plan documents the planning required to successfully complete the project. The work plan includes complete descriptions of proposed plans, procedures, equipment, personnel, and, if applicable, supporting material for the following:

- Project design plots including a profile of the crossing plotted at the proper scale, site layout including entry and exit points and surface survey plots, pipe stress, and pullback calculations.
- Drilling operation plan illustrating the plan of the pilot hole drilling procedure, the reaming operation, and the pullback procedure.
- Equipment list and setup plan including drilling rig, drill bit, back-reamer(s), mud mixing, pumping systems, guidance system with calibration records, and rig safety system.
- Drilling fluid management plan including drilling fluid types and specifications, drilling fluid pressure calculations, procedures of cleaning and recycling equipment, estimation of flow rates, procedures for minimizing drilling fluid escape, and the procedure for final disposal of waste drilling fluids with the location provided.
- Other plans, including pipe storage and handling details, pipeline assembly and installation procedures, Safety Data Sheets (SDS) of any potentially hazardous substances to be used, contingency plans based on risk analysis, and personnel qualifications.

C.5.2 Boring Path Report

The Contractor needs to submit a Boring Path Report to the Engineer within seven days of the completion of each bore path. The Boring Path Report shall include (a) location of the project, project number, and contract number or permit number; (b) name of the person who collected the data (title, position, company name); (c) investigation site location (using station number in contract plans or reference to a permanent structure within the project right-of-way); (d) identification of the detection method used; and (e) elevation and offset dimensions as required.

C.5.3 Marked-Up Plan

At the completion of the HDD product pipe installation, the Contractor shall provide the Engineer a Marked-Up plan noting all deviations from the plans in the design phase that result in a change of the location, material, type, or size of work guided by the boring operations and guidance system log. The mark-ups shall include pipe final alignment, entry and exit pit, pipe connection joints, and any lateral service connections. The Marked-Up plan is commonly provided in a hand-written form.

C.5.4 As-Built Plan

Upon completion of HDD installations, the Permittee shall provide IDOT with As-Built plans and any supporting documents within 60 days of project completion. As-Built plans are preferred in common software formats (like: MicroStation, Geopak, AutoCAD, etc.) but may be submitted in paper form. The plans must show appropriate elevations and be referenced to a Benchmark (mean-sea level) or to a U.S. Geological Survey (USGS) grid system and datum. Plans must be the same scale in black ink on white paper, of the same size and weight, as the permitted plans. As-Built plans shall be derived from the tracking data and operator logs. Specific contents may include but not be limited to the following:

- Drawings that indicate the centerline location of each facility installed and abandoned (if applicable). Notes should be added to indicate the final bore path diameter, product diameter, drilling fluid composition, the composition of any other materials used to fill the annular void between the bore path and the product, or facility placed out of service. If the product is a casing, the size of the casing and product pipe placed within the casing should be noted.

- Construction plan, including size, capacity and arrangement of drilling equipment, type of used steering and tracking equipment, location and size of entry and exit pits, method of installing detection wire, method and equipment to fuse pipe, and boring procedure (including water source for drilling, method to control slurry, etc.).

- Detection of surface movement. The pre-construction and post-construction elevations of the Department facilities at maximum 10 ft (3 m) intervals along all roadway shoulders, lane edge lines, and centerlines shall be reported. The limits of the as-built plans shall be a minimum of 100 ft (30.5 m) on each side of the bore line or as directed by the Engineer.

- Cross-section for each bore path. The ground or pavement structures surface and crown elevation along each facility installed or installed and placed out of service should be indicated to an accuracy of 1 in. (2.54 cm). On profile plans for bore paths crossing the roadway, show Department roadway centerline stationing at the crossing on the plans.

- Drawings showing the top elevation, diameter, and material type of all utilities encountered and physically observed during the subsurface exploration. For all other obstructions encountered during a subsurface exploration or the installation, the type of material, horizontal and vertical location, as well as top and lowest elevation observed should be indicated. It is also necessary to note if the obstruction continues below the lowest point observed.

C.5.5 Damage and Repairs Plan

All potentially affected work areas shall be visually inspected to assess and document conditions prior to any work being conducted. Once occurring during the construction, all incurred damage and repairs should be documented in a Damage and Repairs Plan and submitted to the Engineer for approval.

If there is a boring failure, as discussed in Section C.3.15, during construction, the failed bore path should be shown in the plan along with the final bore path. The failed bore path should be noted as "Failed Bore Path - Taken Out of Service." The name of the Utility, location, the length of the drill head, and any drill stems not removed from the bore path should be indicated in the Plan.

C.5.6 Drilling Logs

The Contractor should maintain detailed drilling logs during the pilot hole drilling process and the production hole. The drilling logs typically need to provide: (1) drill bit location (both horizontally and vertically) at selected intervals along the drill path, (2) the duration required to drill the length of each rod, (3) the drilling fluid pressure, (4) the drilling fluid discharge rate, (5) the drilling thrust and rotary pressures, and (6) notes relative to drilling behavior. The Contractor shall provide the Drilling Logs to the Engineer at the end of drilling.

C.5.7 Contractor Daily Drilling Reports

The Contractor should keep daily drilling reports, and submit to the Engineer at the end of each day. The daily drilling reports shall note the drilling behavior throughout each (1) drill pass, (2) back ream pass, or (3) pipe installation pass. Relevant drilling behavior includes but is not limited to: (1) drilling fluid pressure, (2) drilling fluid flow rate, (3) drill thrust pressure, (4) drill pullback pressure, and (5) drill head torque.

C.6 METHOD OF MEASUREMENT

There are multiple methods of measurement that can be employed. One possible method is described in this section.

The selection of measurement methods should be based on the length of the product in place along the surface of the ground. The measurement would be made in place from center-to-center of small appurtenant structures, connection points, or between open ends inclusive of lengths of pipe bends and branches. Measurement of horizontal bore installed pipe, completed in place, will be made to the nearest foot along the geometrical center of the pipe.

The Engineer will not make additions or deductions for sweeps in either the vertical or horizontal direction to complete the installation. Specifically, deductions will not be made for catch basins, inlets, or manholes that are 6 ft (2 m) or less across, measured in the direction of flow.

When there are authorized changes during construction or appreciable errors in the contract quantity, the final measurement will be made. Revision or correction will be computed and added to or deducted from the contract quantity. The length of the structure may be increased by no more than 3 ft (1 m) as necessary to avoid cutting the pipe, but such increased length will not be included in the contract quantity for payment.

C.7 BASIS OF PAYMENT

The price and payment shall include the cost of furnishing all labor, materials, and equipment (including dewatering if required) necessary to satisfactorily complete the work. The basis should account for furnishing and installing product from the planned point of beginning to the planned point of ending at the planned depth, removal of excavated materials and spoils, removal and disposal of drilling fluids, backfilling, and complete restoration of the site.

Bundled product in a single bore will be paid for as a single bore based on the equivalent outside pipe diameter (not restrained joint diameter). Separate payment shall not be made for individual products in a bundle.

The cost to populate the installed product (such as wires, pipes, or carriers in conduit/casing/ducts) will be made under a separate pay item.

The installation and attachment of tracking conductors (wire or tape) will be included in the cost of the bore and will not be paid for separately.

No payment will be made for failed bore paths, injection of excavatable flowable fill, products taken out of service, or incomplete installations.

No payment will be made for directional boring until a Bore Path Report has been delivered to the Engineer.

C.8 REFERENCES

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APPENDIX D: PROPOSED PERMIT SUBMITTAL CHECKLIST

User guidance:

Some of the proposed items may only be applicable to certain classes of projects such as project size, and whether it is an IDOT project, or a project developed by others and permitted by IDOT.

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1. Project Description

2. Site Investigation
   IDOT will have the decision on such requirements, e.g., reference the Geotechnical Manual.

3. Design:
   - □ Pipe, casing, and hole diameters and lengths
   - □ Pipe and casing materials
   - □ Drawings:
     - □ Cross-section showing:
       - □ entry and exit points and angles and depth below ground at all locations
       - □ maximum profile curvature angles
       - □ location of the entry and exit pits
       - □ existing utility locations (with clearance measurements)
       - □ nearby structures' locations (with clearance measurements)
       - □ locations of pressure relief holes (if any)
     - □ Plan showing:
       - □ entry and exit points
       - □ location of the entry and exit pits
       - □ utility locations (with clearance measurements)
       - □ nearby structures' locations (with clearance measurements)
       - □ locations of pressure relief holes (if any)
     - □ Entry and exit pits shoring plans (if deeper than 6 ft [1.8 m])
   - □ Calculations:
     - □ Pipe/casing installation and operating loads and stresses and pull load
     - □ Downhole pressure analysis:
       - □ Minimum allowable pressure
       - □ Estimated in-hole pressure
       - □ Maximum allowable pressure

4. Contractors' Information, Qualifications, and Experience:
   - □ Contractor name, address, phone number, email
   - □ Summary of the experience of the contractor

- □ List of the last five projects of similar size and length done by the contractor using HDD, including contact information for the owners and main person of contact of these five projects (required for installations > 12 in. (30.5 cm) in hole diameter and > 50 ft (15.24 m) in length → divide HDD projects into 3 or 4 levels with increasing requirements with size and length and shallowness)
- □ List of contractor's personnel involved in the project including at least one experienced inspector

5. Equipment, Machinery, and Materials to be used:
   - □ List of Machinery and Equipment:
     - □ Rig type and catalog
     - □ Fluid mixing machine and water tank
     - □ Fluid recycling system (if any)
     - □ Tracking system
     - □ Drilling bit(s)
     - □ Reamer(s)
     - □ Centralizers (if any)
     - □ Pipe/casing pulling equipment
     - □ Pipe/casing fusing/welding/connecting equipment
     - □ Conductor casings (if any)
   - □ List of Materials:
     - □ Pipe/casing type and connection type
     - □ Pipe/casing coating type and thickness (if required)
     - □ Fluid mix with Material(s) Safety Data Sheets

6. Execution:
   - □ Site Layout showing:
     - □ Location of Machinery
     - □ Location of equipment
     - □ Location of materials including pipe/casing
   - □ Fluid Mix Testing Plan (if required)
   - □ Pilot Drilling Plan, including pilot holes for larger diameter installations
   - □ Reaming Plan
   - □ Pipe/casing Fusing/Welding Plan (if required)
   - □ Pipe/casing Pulling Plan:
     - □ The trajectory of pipe/casing during pulling
     - □ Calculation of maximum angles that pipe/casing will experience
     - □ Tracing wire
   - □ Grouting plan (if required)
   - □ Heavy Machinery Movement plan (See Article 107.16 of IDOT Standard Specifications)
   - □ Site Restoration:

- □ Spoils handling and disposal
- □ Ground-level restoration

□ Schedule:
- □ Beginning and end dates
- □ Daily work hours

7. Public Safety:
   - □ Transportation Management Plan (required if traffic modification [e.g., detour, lane closure, or traffic staging] is needed).
   - □ Safety Management Plan
   - □ Contingency Plans:
     - □ Action in case of frac-out
     - □ Action in case of inadvertent returns
     - □ Action in case of sink-hole
     - □ Action in case of excessive deformation of ground or structures
     - □ Action in case of stuck equipment
     - □ Action in case of loss of return
     - □ Action in case of intolerable deviation from planned profile
     - □ Action in case of failure of pipe during or after pulling
     - □ Action in case of hitting an underground obstacle or utility
   - □ Environmental Plan (if required):
     - □ Noise Management (e.g., IDOT Standard Specifications)
     - □ Contaminated Soil Management Plan (required if contaminated soil is present)

8. Quality Assurance Plan:
   - □ Pipe Testing:
     - □ Hydrostatic testing
   - □ Monitoring Plan:
     - □ Road/IDOT assets deformations
     - □ Utility deformations

9. Final Delivery Plan:
   - □ GPS coordinates of the entry and exit points
   - □ As-Built Plan
   - □ Drilling logs
   - □ Boring Path Report

10. Acknowledgment of state and federal regulations and IDOT HDD specifications:
    - □ IDOT Accommodations of Utilities on Right-of-Way of the Illinois State Highway System
    - □ Traffic Control Standards
    - □ Identify other relevant governing local, state, and federal regulations

APPENDIX E: PROPOSED INSPECTOR CHECKLIST

User guidance:

- The inspector shall have a copy of the approved permit and all supporting material. Changes to the plans and details approved in the permit require prior approval by the Illinois Department of Transportation (IDOT) before proceeding with the horizontal directional drilling (HDD) installation. In this checklist, the term "permit" refers to either a "utility permit" or IDOT construction contract plans and specifications.

-The Contractor's responsibility for proper execution of the work is per Article 107.30 of the IDOT Standard Specifications. The presence of the inspector and the contractor's obligations are per Articles 105.12 and 106.04 of the IDOT Standard Specifications.

Prior to construction:

1. Check that the equipment, machinery, and materials to be used on site match those specified in the permit [take photos]:
    - □ List of Machinery and Equipment:
        - □ Rig
        - □ Tracking system
        - □ Reamer(s)
        - □ Pipe/casing pulling equipment
        - □ Pipe/casing fusing/welding/connecting equipment
        - □ Drilling fluid mixing and recycling system
        - □ Clean up equipment
    - □ List of Materials:
        - □ Pipe/casing and connections
        - □ Fluid mix materials
        - □ Water source

2. Transportation Management Plan: Check that the traffic plan being implemented matches the plan specified in the permit and that all signage was deployed [take photos].

3. Safety Plan: refer to Article 107.28 of the IDOT Standard Specifications.

4. Site Preparation [take photos]:
    - □ Check whether all utility locations and depths were identified and that clearances exceed or are equal to the minimum acceptable clearances.

- □ Check that the points of entry and exit are marked by a surveyor before the commencement of construction. The coordinates of those points should match the coordinates in the permit.

5. Pre-construction Site Inspection and Survey [take photos]:
    - □ Take photos of the site, including all IDOT structures. Look for existing cracks in pavement and structures.
    - □ Ensure Contractor conducts pre-construction survey of relevant IDOT assets (as identified in the permit).

During construction:

1. Check that the above-listed machinery, equipment, and materials are being used. Make sure that changes suggested in the field are reviewed and approved by the Engineer (or other agency issuing the utility permit) before being implemented.

2. Check that the execution plan matches the plan approved in the permit:
    - □ Vehicles and machinery movement on the pavement needs to follow Article 107.16 of IDOT Standard Specification to protect the pavement from damage.
    - □ Pressure relief holes (if any) were installed.
    - □ Exit point after pilot drilling is within the approved tolerated range from the planned exit point.
    - □ Depth below IDOT structures, including pavement, is within approved tolerance.
    - □ Reaming scheme implemented matches the plan specified in the permit.
    - □ Pipe/casing pulling scheme implemented matches the plan specified in the permit. Also, check that the pipe/casing is not subjected to intolerable bend angles or dragged on the ground.
    - □ Grouting of the annular space around the casing/pipe was performed (if required).
    - □ Handling and disposal of the spoils matches the plan specified in the permit (IDOT projects only).
    - □ Maintenance of traffic plan is implemented throughout construction.
    - □ Safety plan refer to Article 107.28 of the IDOT Standard Specifications.

3. Prepare **daily reports** and include the following [take photos]:
    - □ Time of start and end of pilot drilling, reaming stages, swabbing, and pipe pulling.
    - □ Developments in distance drilled and speed of drilling (time per rod).
    - □ Fluid return.
    - □ Any other developments, issues, or problems.
    - □ Photos of work and site.
    - □ Weather conditions.
    - □ Inspector arrival and departure times.

4. Look for any contingency triggering events and ensure that they are dealt with as approved in the permit. If those events are not addressed, notify the contractor to address the issues and, if necessary, request a damage and repairs plan be developed and submitted to the Engineer [take photos]. The contingency triggering events may include:
    - □ frac-out
    - □ inadvertent return
    - □ sink-hole
    - □ excessive deformation
    - □ stuck equipment
    - □ loss of return
    - □ intolerable deviation from planned profile
    - □ hitting an underground obstacle or utility
    - □ Other

After construction:

1. Site Restoration [take photos]:
    - □ Check that all the pits are closed (for IDOT projects/property).
    - □ Check that the site is restored after construction (for IDOT projects/property).

2. Post-construction Site Inspection and Survey [take photos]:
    - □ Take photos of the site, including all IDOT structures. Look for additional cracks in pavement and structures.
    - □ Ensure Contractor conducts a post-construction survey of relevant IDOT assets (as identified in the permit).

3. Check that the pipe/casing testing is performed as specified in the permit. Acquire a copy of the testing results and include them in the daily report.

4. Acquire the following from the Contractor and include in the daily report:
    - □ GPS coordinates of the entry and exit points
    - □ Contractor daily drilling report
    - □ Marked-Up plans
    - □ Drilling logs (at the end of drilling)

5. Acquire Boring Path Report and As-Built Plans at the end of the project.

6. Check that all damage incurred was fixed per the damage and repairs plan as approved by the Engineer [take photos].

7. Submit all reports and close out the permit.

APPENDIX F: LITERATURE REVIEW

TABLE OF CONTENTS

F.1 INTRODUCTION 98

F.1.1 History of HDD 98

F.1.2 Advantages of HDD 99

F.1.3 Applications of HDD 104

F.2 ENVIRONMENTAL ASPECTS OF HDD 106

F.3 MANAGEMENT AND PLANNING OF HDD PROJECTS 107

F.3.1 Contracting 107

F.3.2 Planning 111

F.3.3 Productivity 111

F.3.4 Risk and Risk Management 113

F.3.5 Training of HDD Operators 121

F.4 HDD DESIGN AND CONSTRUCTION 125

F.4.1 Overview of the HDD 125

F.4.2 Site Investigation 126

F.4.3 Geometric Design 130

F.4.4 Pipe Design 131

F.4.5 Fluid Design 137

F.4.6 Construction Equipment 150

F.4.7 Alternative Construction Methods 157

F.5 PERFORMANCE AND QUALITY CONTROL 164

F.5.1 Impact on Ground and Structures 164

F.5.2 Ground Surface Movement Monitoring 167

F.5.3 Pipe Performance 168

F.5.4 Tunnel-induced Deformations 173

F.6 CASE HISTORIES 173

F.6.1 Overview 173

F.6.2 Selected Case Histories 173

F.6.3 Case History Summary Table 176

F.7 CODES, GUIDELINES AND SPECIFICATIONS SUMMARY 225
F.8 REFERENCES 268

LIST OF FIGURES

Figure 15. Chart. Average percentage of delay (representing on average 40% of total project time) of each of the identified risks—modified from (Murray, Osbak, and Bayat 2013)..... 118

Figure 16. Photo. The training system as shown in Wang et al. (2013). 125

Figure 17. Figure. Horizontal directional drilling process (Yan et al. 2018)..... 126

Figure 18. Photo. Barolift fiber additive (Ariaratnam, Lueke, and Anderson 2004). 149

Figure 19. Photo. N-Seal fiber additive (Ariaratnam, Lueke, and Anderson 2004)..... 150

Figure 20. Photo. Compaction drill head (Ariaratnam and Allouche 2000). 151

Figure 21. Photo. Mud motor assembly on HDD rig (Ariaratnam and Allouche 2000)..... 151

Figure 22. Photo. Walk-over tracking device (Ariaratnam and Allouche, 2000). 152

Figure 23. Photo. Reamer used in clayey soils (E. Allouche, Ponnam, and Shu 2012)..... 154

Figure 24. Photo. Reamer used in sandy soils (E. Allouche, Ponnam, and Shu 2012). 154

Figure 25. Photo. Typical reamer used in rock formation (Allouche, Ponnam, and Shu 2012). 155

Figure 26. Figure. Centralizers used to limit the subsidence of heavy reamers (Zhu and Yi 2018)..... 156

Figure 27. Photo. An HDD project employing the cartridge method (Maidani, Fergerson, and Carpenter 2006)..... 158

Figure 28. Schematic. Bore salvage method (Orton 2008)..... 159

Figure 29. Schematic. Pullback assist method (Orton 2008). 159

Figure 30. Schematic. Conductor barrel method (Orton 2008)..... 159

Figure 31. Schematic. Buoyancy control using PE pipe filling with water (Kong et al. 2013)..... 160

Figure 32. Schematic. Difference between (a) back reaming, (b) front reaming (Shu and Zhang 2018). 162

LIST OF TABLES

Table 3. HDD Rigs Manufactured and Sold Worldwide 99
Table 4. Comparison of Costs 102
Table 5. Costs Comparison 103
Table 6. Average Productivity in Various Soil Types 112
Table 7. Rank and Weights for Factors Affecting the Productivity of HDD 113
Table 8. Summary of Case Histories 177
Table 9. Summary Table for Codes, Guidelines, and Specifications 226

F.1 INTRODUCTION

This appendix provides an extensive literature review of HDD. It includes a review of guidance documents as well as published papers. Readers are referred to the original sources for further details. The following sections quote extensively from reviewed literature. When the quoted text includes dimensions in either SI or conventional English units, we provided the complementary dimensions in the other unit. The added text and units are underlined to indicate that this is added to the text extracted from the original source.

F.1.1 History of HDD

Directional drilling was invented in 1933 when a giant oilfield near Conroe, Texas, was leaking, and inclined wells had to be drilled to stop the leakage. It took the combined efforts of oilfield technology innovators George Failing of Enid, Oklahoma, and H. John Eastman of Long Beach, California, to save the Conroe (AOGHS 2005). The press celebrated this breakthrough: "*Only a handful of men in the world have the strange power to make a bit, rotating a mile below ground at the end of a steel drill pipe, snake its way in a curve or around a dog-leg angle, to reach a desired objective"* (Gleason 1934, 40-50).

Horizontal directional drilling (HDD), in which rigs are operated from the ground surface rather than operating from within caissons, is said to be invented by Martin Cherrington, who enhanced the available directional drilling technology and experimented with different downhole drilling tools and entry angles to execute the first reported river crossing using directional drilling under the Pajaro River near Watsonville, California, in 1971 (Cherrington 2000). By the early 1990s, Cherrington held 13 patents on the process and the equipment he developed for the industry (Farr 2012).

Allouche, Ariaratnam, and Lueke (2000, 68) report that: "*Currently* (year 2000)*, in North America alone, there were 17 manufacturers of HDD rigs and accessories and thousands of horizontal drilling rigs that are owned and operated by several hundred dedicated HDD contractors as well as utility companies and large pipeline outfits. Nearly 20 million meters of product line were installed across North America in 1998 alone, using approximately 6,000 directional drilling rigs.*" In addition, Kirby et al. (1996, 692) point out that *"The horizontal drilling industry in North America has grown from 12 operational units in 1984 to a multibillion-dollar industry with more than 2,000 units operating in 1995.*" Baik, Abraham, and Gokhale (2003) state that approximately 17,800 HDD units were manufactured and sold during the period between 1992 and 2001 in North America, according to R Carpenter (2002). Table 3 from Mohmd Sarireh, Najafi, and Slavin (2013), citing R Carpenter (2011), presents the number of rigs manufactured and sold worldwide.

Table 3. HDD Rigs Manufactured and Sold Worldwide

Year	Number of HDD rigs manufactured and sold worldwide
1992-1195	3,435
1996-2000	13,347
2001-2005	5,427
2006-2011	9,926
Sum of rigs manufactured worldwide	32,132
Sum of rigs manufactured in the USA (~80%)	~ 25,700

The survey conducted by Allouche, Ariaratnam, and Lueke (2000), which received 49 responses of HDD contractors from the United States (32 respondents) and Canada (17 respondents), demonstrates that 85% of contractors indicated that they were considering the purchase of new equipment, 84% indicated that they were considering the hiring of new personnel, and 74% intended to increase their region of business in the near future. Allouche, Ariaratnam, and Lueke (2000) claim that this rapid growth may be attributed, at least partially, to escalating costs involved in the installation of utility conduits in urban areas (e.g., traffic control, restoration costs, the need to dig around existing utilities), increased awareness of social costs (e.g., traffic delays, disruption of business activities), and increasing environmental regulations (e.g., placement of pipelines across rivers, wetlands, and other environmentally sensitive areas).

Allouche, Ariaratnam, and Lueke (2000, 68) give more details on the development of the technology: "*The equipment and installation techniques used by HDD contractors evolved by merging technologies from the utility, oil field, and water well industries. Relatively complicated and inaccurate steering and navigation systems may be partially attributed to the relatively slow acceptance of the technology during early years. The early 1980s were marked by a rapid advancement of the equipment's mechanical, hydraulic, and electronic systems. Drilling rigs were built smaller and made to drill greater distances. New systems and navigation tools were developed resulting in easier operation and decreasing capital investment. Consequently, HDD became a cost-effective method for the installation of conduits in congested urban areas and the method of choice by many utility and pipeline companies for the crossing of buried and surface obstacles.*" HDD was used for installing pipes thousands of meters long under rivers and lakes (Ma et al. 2010).

F.1.2 Advantages of HDD

Trenchless technologies have many advantages over the traditional open-cut methods, which can be identified by a broad comparison of the costs of both methods. Gangavarapu, Najafi, and Salem (2003) list the elements of the life-cycle cost of a project according to Iseley, Najafi, and Tanwani (1999):

- *Pre-construction, land acquisition, easements, permits, design fees, planning, and legal costs.*
- *Construction costs: direct costs, indirect costs, and social costs.*
- *Post construction costs: operation and maintenance.*
- *Decommissioning or renewal costs.* (Gangavarapu, Najafi, and Salem 2003, 1715)

F.1.2.1 Social Costs

According to Stein, Möllers, and Bielecki (1989), till the year 1989, "*the impact of construction works on the environment was not an issue for most utilities and their designers. Traditionally, utilities have avoided bearing the whole cost of their installation. The direct cost is born by the utility, whereas the community has to bear the cost of disruption, delay, or damage*" (quoted in Tighe et al. 1999, 45).

Downey (2006) reports that The Transport Research Laboratory and Jason Consultants found that secondary and social impacts of trenching in the UK can cost at least as much as the direct engineering works, by a number of overseas studies, works, and that this has been endorsed in Brady, Burtwell, and Thomson (2001).

Social costs of open cut methods, according to McKim (1997a) and Gangavarapu, Najafi, and Salem (2003), citing Boyce and Bried (1998) and Budhu and Iseley (1994), include the following:

- Traffic disruption and inconvenience to the public due to extra traffic on the detour route.
- Damage to the road, adjacent utilities, adjacent structures, and detour roads (due to heavier traffic loads and volumes).
- Noise, vibration, and air pollution.
- Risks to pedestrian safety.
- Business or trade loss (businesses lose driving and walk-in customers due to lack of convenient access from the road and due to noise and clutter).
- Damage to detour roads.
- Citizen complaints.
- Environmental impacts.

Traffic disruption results in other social costs according to McKim (1997a) and Gangavarapu, Najafi, and Salem (2003), citing Bush and Simonson (2001):

- Time duration of the project.
- Cost of fuel.
- Cost of travel time.
- Vehicular wear.
- Delays to emergency vehicles.

- Loss of revenue and sales tax (municipalities lose tax revenues due to business losses reducing business tax, and federal governments lose income taxes due to reduced revenues).

Tighe et al. (1999) claim that it is becoming apparent that the traditional open trench methods are not always suitable when social costs and reinstatement costs would be significant. According to Tighe et al. (1999), the three basic variables associated with traffic capacity analysis are volume or the rate of flow, speed, and density. The delays will consist of two parts: (1) slowing delays caused by reduced speed through the affected area and (2) queuing delays due to the congestion when traffic demand exceeds capacity. Tighe et al. (1999) studied three representative plans for controlling traffic while construction in the road is occurring, then developed equations to estimate the traffic disruptions associated with those plans in terms of user delay costs. Those models enable quantifying the delays and the costs of the delays, thus including them in the comparison between trenchless and trenched methods. McKim (1997a) even suggests including the social cost in the bid.

Tighe et al. (2002, 751) indicate that "*(1) approximately 30% reduction in pavement life can be expected once an excavation is made in a road; (2) increased maintenance and rehabilitation costs for excavating 1-year-old pavement were determined to be approximately Can$146/m2, and the costs for excavating 7-year-old pavement vary from Can$85 to $140/m2; and (3) the use of trenchless technology with good construction practices has the potential to significantly reduce road maintenance and rehabilitation costs and user-delay costs.*"

F.1.2.2 Environmental Costs

Onsarigo, Atalah, and Roudebush (2014) describe the concept of Environmental Value Engineering (EVE), an environmental life cycle analysis methodology that evaluates the environmental impact and contribution of built alternatives in terms of solar energy through ten phases in the life cycle of a project. It is an assessment methodology that can be used to compare the environmental impact of alternatives competing for the same resources. The paper cites the findings of Rehan and Knight (2007), whose analysis shows that the use of trenchless construction methods can result in 78% to 100% lower greenhouse gas emissions than open-cut pipeline installation methods, and the findings of Goduto and Atalah (2013), which compares the design and construction costs of installing a 16 in. (40.6 cm) waterline underneath I-75 in Bowling Green, Ohio, using four potential alternatives: open-cut with detouring traffic, postponing the installation until resurfacing the interstate to install the line by open-cut, horizontal directional drilling, and auger boring. The study concludes that it could cost $604.50, $134.50, $57.47, and $173.44 per linear foot to install the pipe using Auger Boring, Horizontal Directional Drilling, incorporating the water line into the design of the highway reconstruction with the project delayed, and open-cut with detouring traffic, respectively. Onsarigo, Atalah, and Roudebush (2014) conclude that the open-cut construction method has a 66.22% greater impact than that of horizontal directional drilling on the environment, making HDD more environmentally friendly.

F.1.2.3 Comparison of Costs

Trenchless methods may save costs, especially social costs. Najafi and Kim (2004) made a qualitative cost comparison between open-cut and trenchless construction methods. A summary of this comparison is presented in Table 4.

Table 4. Comparison of Costs

Cost Factor	Open Cut	Trenchless
Preconstruction costs		
Field Survey Work and Plan Preparation	Major	Minor
Engineering and Design	Major	Major to Minor
Legal Issues	Major	Minor
Working Area Requirements	Major	Minor
Subsurface Investigation Requirements	Minor	Major
Preparation of Bid Documents	Major	Minor
Direct Costs		
Mobilization and Demobilization	Major	Minor
Shoring and Sloping Trench Walls	Major	Minor
Dewatering	Major	Minor
Spoil Removal	Major	Minor
Cost of Detour Roads	Major	Minor
Backfill and Compaction	Major	Minor
Reinstatement of Surface	Major	Minor
Construction Equipment Costs	Major to Minor	Major to Minor
Labor Costs	Major	Minor
Material Costs	Minor	Major
Social Costs		
Road Damage (Reduction in Life of Pavement)	Major	Minor
Damage to Adjacent Utilities	Major	Minor
Damage to Adjacent Structures	Major	Minor
Noise and Vibration	Major	Minor
Dust and Air Pollution	Major	Minor
Vehicular Traffic Disruption	Major	Minor
Pedestrian Safety	Major	Minor
Business and Trade Loss	Major	Minor
Damage to Detour Roads	Major	Minor
Site Safety	Major	Minor
Environmental Impact	Major	Minor
Citizen Complaint	Major	Minor
Post-Construction Costs		
Operation	Major	Minor
Maintenance	Major	Minor
Loss of Revenue due to Emergency Repairs	Major	Minor

Table 5 from McKim (1997a) summarizes the social costs of 14 construction projects documented in Thomson, Sangster, and New (1994) and McKim (1996).

Table 5. Costs Comparison

Method	Project #	Estimated Construction Cost (1000$)	Estimated Social Cost (1000$)	Percentage of Social Cost to Construction Cost (%)
Open Trench	1	189	134	70.9
	2	20	98.5	492.5
	3	39	22.5	57.7
	4	20	30.8	154
	5	2	2.1	105
	6	20	14	70
	7	6	6.4	106.7
	8	30	110	366.7
	9	1073	680	62.4
	10	4.5	2	44.4
	Mean	115.9	122.3	78.4
Trenchless	10	26.8	0	0
	11	5	0.3	6
	12	1665	50	3
	13	4.5	0.5	11.1
	Mean	567.1	16.9	3

Kramer and Gary (2000) describe the feasibility study performed for the replacement of around 13,000 ft (4 km) of water mains in a leaking water distribution system in Texas. The feasibility study was performed by two independent teams and concluded that horizontal directional drilling would save around 33% of the cost compared to the open-cut method.

F.1.2.4 Advantages of HDD over Other Trenchless Methods

According to Allouche, Ariaratnam, and Lueke (2000, 69), "*in comparison with other trenchless technologies, HDD offers several advantages: (1) No vertical shafts are required as drilling commences from the surface; (2) relatively short setup time; (3) the borehole alignment does not necessarily have to be straight, as HDD makes it possible to change the borehole alignment and elevation to avoid striking existing utilities and other underground obstacles along the path; and (4) the single drive installation length exceeds that of any other non-man entry trenchless method.*"

Sarireh, Najafi, and Slavin (2013) cite the American Society for Trenchless Technology HDD Good Practices Guidelines (Bennett and Ariaratnam 2008), claiming that HDD is the most widely used trenchless technology construction method for the following reasons:

- *Its ability to accommodate both small and large diameters (from 2 in. to 60 in. [5 to 152 cm]) based on the site and project conditions.*
- *Its ability to install pipes of different materials including HDPPE, PVC, steel, and ductile iron.*

- *Its compatibility with a variety of soil conditions, including loose sand to solid rock.*
- *It requires relatively little auxiliary equipment.*
- *It satisfies environmental guidelines (especially in wetlands).*
- *It causes minimal traffic disruptions and associated social costs considering the long installation drives.*
- *It is applicable to pressure (water, gas, oil, force main), electrical, and telecommunication conduits and, in some cases, gravity pipelines.* (Sarireh, Najafi, and Slavin 2013, 1850)

F.1.3 Applications of HDD

F.1.3.1 Utilities Pipe

HDD is used for various applications. Current applications range from the installation of telecommunication lines, natural gas distribution systems, and power cables to the placement of gravity sewers, water mains, horizontal water wells, and diversion channels for hydroelectric projects (Allouche, Ariaratnam, and MacLeod 2003; Sarireh, Najafi, and Slavin 2012).

The survey conducted by Allouche, Ariaratnam, and Lueke (2000) shows that 89% of the contractors surveyed are currently involved in underground utility installation, 74% in municipal applications, 63% in pipeline installation, and 28% in the environmental market. The number of contractors that indicated having more than 5 years of experience in a given application was 70% for underground utility installation, 53% for pipeline, and 52% for municipal applications.

F.1.3.2 Sewer Pipes

Gunsaulis and Levings (2008) describe three methods for using HDD for gravity sewers, and reports that although less commonly used, gravity flow sewers, given favorable soil conditions, a patient drilling unit operator, and external magnetic interference at a reasonable level, may be installed with HDD at grades down to -.5%. Some successful installations have been reported at even shallower grades (Griffin 2003b, 2003a). For this application, Gunsaulis and Levings (2008) suggest using a single reaming pass to open the hole to the desired diameter, claiming that on multiple pass back-reaming operations, with each successive pass, the centerline of the borehole tends to drop unless a centering device is used in front of the reamer to force its centerline to stay in the middle of the hole.

Tucker and Scanlan (2018) describe the installation of 1960 ft (597 m) of a 16 in. (40.6 cm) diameter fusible polyvinyl chloride (FPVC) force main next to the Harmar Lift Station and very near the confluence of the Ohio River in Ohio. The pipeline was designed to be installed using HDD in a bedrock layer at a maximum depth of approximately 90 ft (27 m).

Barnard et al. (2018) describe the installation of a 2500 ft (762 m) of a 12 in. (30.5 cm) diameter fusible polyvinyl chloride (FPVC) force main in the city of Frisco, Texas, located just north of Dallas. The installation included a compound curve and was installed mostly in rock under a road surrounded by short buildings.

F.1.3.3 Grouting

Blakita (2000) describes the usage of HDD for Tube-a-Manchette (TAM) grouting and its advantages and disadvantages. Kummerer, Falk, and Gularte (2012) state that directional drilling is the only technique to create curved drillings as well as "straight" drillings, and it can substitute a large number of ineffective inclined linear drillings. The paper presents two case histories where TAM grouting via HDD was used to stabilize structures before tunnel boring machine (TBM) machines pass below them.

Mair (2008) describes the use of HDD for compensation grouting under a bridge pier, required before the construction of twin tunnels of diameter 9.1 m (30 ft). "*Initial calculations showed that the tunneling was expected to generate large settlements, typically around 20 mm but potentially up to 50 mm for volume losses of 1%. Such settlements would have induced excessive distortions of the viaduct, which was a cause of concern, particularly as suspension of train services was not permitted. There were also major concerns about potential cracking of the masonry arches, some of which were already cracked. Compensation grouting was therefore implemented*" (711).

F.1.3.4 Environmental Applications

Allouche, Ariaratnam, and Biggar (1998) list some of the environmental applications of HDD. Environmental remediation methods used in horizontal wells in North America include (1) soil vapor extraction (SVE), (2) groundwater extraction for pumping and treatment, (3) air sparging, (4) enhanced bioremediation or bioventing, and (5) free product recovery. Another application of HDD is in the evaluation and monitoring of suspected contaminated sites. HDD technology can be used for the collection of soil samples beneath existing facilities (e.g., landfill cells) or the installation of leak detection instruments. The paper presents three case histories where HDD was successfully used for environmental remediation.

Allouche, Ariaratnam, and Biggar (1998) conclude that (1) horizontal environmental wells can be cost-effective in the remediation of contaminated soil and groundwater, (2) horizontal well technology offers several advantages over vertical well technology, including larger contact area, greater accessibility, reduced disruption to daily operations, and potentially lower project life-cycle costs, (3) shortfalls of horizontal well technology include higher installation costs, lack of experienced contractors, and the absence of design and construction specifications, and (4) future research efforts should concentrate on reducing direct drilling costs, developing criteria for well technology selection, and the development of standard operating procedures for well installation and completion. Ariaratnam and Allouche (2000a) further explain the advantages, limitations, design, construction, equipment, and tools for remediation of contaminated sites using HDD.

F.1.3.5 Soil Sampling

Allouche et al. (1997) describe how horizontal drilling can be used to sample soil. Locating a vertical drilling rig directly above a soil deposit to be characterized is not always possible. *"Also, in environmental investigations vertical drilling has the risk of penetrating impermeable layers, potentially causing cross-contamination between aquifers. Many of these limitations can be overcome using horizontal directional drilling technology"* (24). A sampler, called the PunchMaster 2000, *"is capable of cutting a 50 mm (2 in.) diameter by 1.5 m (5 ft.) long"* undisturbed vertical or horizontal

samples from soft to medium soils (19). *"The sampler works on a principle similar to a split-spoon or a Shelby Tube core sampler. First a blind borehole is drilled up to the target area"* (19). A significantly smaller and lighter sampler was developed by Ditch Witch in the mid-1990s.

Allouche et al. (1997) developed a multiple-port soil sampler which is claimed to significantly reduce costs and duration associated with horizontal sampling projects. However, the authors mentioned the need for laboratory and field evaluations in order to establish parameters such as punching force requirements and sample quality for various types of soils.

Allouche et al. (1997, 24) conclude that "*horizontal site characterization tools present a new dimension in the field of site investigation. New applications for this technology are likely to arise as more cost-efficient tools are developed and practicing professionals become aware of its advantages."*

Boden et al. (2018) describe a technique called horizontal directional coring, in which coring methods are employed from the surface, just like in HDD, to investigate the ground conditions along proposed alignments of planned tunnels.

F.2 ENVIRONMENTAL ASPECTS OF HDD

Muindi (2013, 895) describes how trenchless technology methods can be adapted and used successfully to bypass contaminants or minimize the potential for migration of contaminants during construction: "*Key benefits derived from Trenchless Technology (TT) modifications that address potential contaminants include: 1) prevention of groundwater migration that can exacerbate existing contaminants which could occur between different soil strata and independent aquifers or along the tunnel alignment 2) reduction of excavated quantities of soil and groundwater requiring special handling. Launch and receiving shafts and pits can be constructed so as to isolate TT operations and optimize soil removal 3) Protection of completed works from harm (modifications remain in place such as casing pipe or shaft support).*"

The paper suggests three methods for dealing with contaminated soils:

1. *Starter Casing*

   Starter casing (SC) has been used in cases where bore collapse or hydro-fractures might occur during HDD operations. Other applications include use of SC to isolate and protect existing utilities, bypass near-surface obstructions, and manage drilling fluid. Starter Casings can be used to protect equipment and product from the contaminated soil.

2. *Cofferdam*

   Cofferdams (shafts or pits) can be constructed to allow for removal and isolation of contaminants, thereby creating a favorable environment for trenchless activity. The cofferdam also allows associated works such as conduit connection or manholes to be constructed in suitable ground conditions.

3. Seals

Ground improvement (GI) methods can be applied outside the cofferdam. This is quite commonly used in micro-tunneling at the exit and entry (break- in/break-out) locations of the cofferdam – normally used to prevent soil and groundwater movement into the cofferdam and also provide support for the microtunnel boring machines (MTBM) allowing for maintenance of line grade. Examples of GI include chemical grouting, excavation and replacement with flowable fill, and soil mixing. (Muindi 2013, 896-897)

Muindi (2013, 897-899) presents a case study of a river crossing where the fill at the entry point was contaminated: "*This project involved the trenchless design and installation of three parallel HDD river crossings within a tight easement. Each crossing had a length of about 1,650 feet and consisted of a bundle of seven, 8-inch HDPE conduits. The minimum reamed hole size for each bore was set at a diameter of about 36 inches. the HDD entry side had a documented history of industrial chemical storage, spills, and waste disposal practices that resulted in heavy contaminant impacts to soil and groundwater. The contaminants were primarily found in the urban fill soils. A 90-foot-long by 60-foot-wide steel-sheeted cofferdam was the selected solution at the entry side to isolate the constructed works from the highly contaminated soil and groundwater. In addition to this protection, the cofferdam served to control the quantity and associated premium cost of managing and disposing of the contaminated materials. A flowable fill seal was specified to be installed outside the cofferdam in the area of sheeting penetration. A starter casing was incorporated into the design for each of the three entry-side bores."*

F.3 MANAGEMENT AND PLANNING OF HDD PROJECTS

F.3.1 Contracting

The survey conducted by Allouche, Ariaratnam, and Lueke (2000, 70-71) showed that "*on average, 67% of the projects undertaken by the survey participants were for private clients, 24% for municipal clients, and 9% for federal clients. Seventy four percent of the contractors surveyed obtain between 75 and 100% of their work through a competitive bidding process. Projects not obtained through competitive bidding typically fall under two categories: work that is highly specialized, and work obtained through strategic alliances. The survey revealed that the most common type of contract used in the directional drilling industry is unit price. Approximately 98% of the respondents had utilized the unit price contract in their operations. The second most common type of contract utilized was lump sum with 75% of the respondents indicating its utilization. Per diem, or daily rate, 35% of the respondents indicated that they had worked under this type of contract. Only 29% of the contractors indicated they had operated under an hourly contractual arrangement.*"

Kramer and Meinhart (2004) describe some of the conventional design bid build processes:

- *The Design Bid Build Process:*
  1- Engineer prepares 100% design documents.
  2- Owner or owner's representative obtains competitive bids based upon the 100% design documents.

3- *Owner and/or owner's representative evaluates bids and awards construction contract to a contractor.*
4- *Contractor mobilizes, orders materials and constructs project.*

- *The Modified Design-Build Process:*
  1- *Engineer prepares less than 100% complete design documents. Typically, it will range from 50% to 75% complete design documents.*
  2- *Owner or owner's representative obtains qualifications and/or price proposals from contractors based upon the design documents.*
  3- *Owner and/or owner's representative evaluates qualifications and price proposals and selects contractor.*
  4- *Design Engineer and selected Contractor work as a together as a team to complete the design documents to 100%.*
  5- *Team seeks to find methods to generate cost savings, schedule reductions and improvements in constructability.*
  6- *Contractor may order long-lead materials prior to completion of 100% design documents.*
  7- *Contractor may modify his final price based upon the completed design if bid items have changed.*
  8- *Contractor constructs project.*
- *The Design-Build Process:*

  In the design build process, the Contractor and Designer work together as a single team as described below:

  1- *Owner or Engineer prepares partial design documents. Design documents may range from as little as 10% to 50% complete or more.*
  2- *Owner or owner's representative obtains qualifications and/or price proposals from contractors (possibly teamed with an engineering firm) based upon the partial design documents.*
  3- *Owner and/or owner's representative evaluates qualifications and price proposals and selects contractor.*
  4- *Design-Build team completes design and begins construction. Construction may begin prior to completion of 100% of the design.*
- *Engineer/Procure/Construction (EPC) and Engineer/Procure/Construction Management (EPCM):*

  Using EPC or EPCM, the Contractor/Engineer are responsible for the design and construction process.

  1- *Owner or Owner's representative prepares request for qualifications for proposed project.*
  2- *Owner and/or owner's representative evaluates qualifications and selects Contractor/Engineer.*
  3- *Contractor/Engineer prepares design documents to the extent required to construct the project. Design may first be completed for long lead items.*
  4- *Contractor prepares procurement packages for all or some of the bid items.*

5- *Contractor obtains competitive bids and selects subcontractors to perform construction activities. Contractor may elect to submit prices on procurement packages and self-perform some or all of the construction activities.*
6- *Prices for construction are now set.*
7- *Contractor serves as construction manager and oversees construction.* (Kramer and Meinhart 2004, 2-3)

Kramer and Meinhart (2004) then identify some considerations when evaluating the appropriateness of alternative methods:

- *Are there any laws that prevent the use of alternative contract delivery methods?*
- *Depending on the method, is the owner willing to release project control to the contractor earlier in the life of the project (e.g., Design-Build or EPC)?*
- *Does the owner need to accelerate the schedule?*
- *Is the owner seeking additional innovation that may lead to cost savings?*
- *Does the owner accept loss of control over final design documents?*
- *Can the owner or his representative develop performance criteria that meet his requirements?* (Kramer and Meinhart 2004, 3-4)

The paper then lists the advantages and disadvantages of each of the listed design bid build processes:

- *Design-Build or Modified Design-Build*
    - *Advantages:*

        - Owner can select contractor based upon qualifications, potential design and cost savings.

        - Contractor/Engineer Team can develop innovative solutions that can be incorporated into final design documents.

        - Long-lead items can be procured prior to completion of final design.

        - Potential for claims due to design issues may be reduced or transferred to the Design-Build team.

    - *Disadvantages:*

        - Owner's management role may increase until design-build Team is selected.

        - For modified design-build and sometimes for design-build, final construction cost may not be known until completion of design documents.

- *EPC or EPCM*
    - *Advantages*

- Owner has reduced administrative burden once Contractor is on-board.

- Contractor takes responsibility for all aspects of the project including contract administration, control of costs, schedules, design and quality.

- Contractor can immediately order long-lead items with the potential for reduction in the overall schedule.

- Construction may begin on early lead items such as site preparation and utility location/relocation prior to completion of design.

- *Disadvantages*

- Depending on when the job is bid, final construction cost may not be known until completion of design documents.

- Owner may need assistance in developing contract documents and how to manage new relationship with Contractor. (Kramer and Meinhart 2004, 4)

Kramer and Meinhart (2004) then present four case histories which illustrate that each of the alternative delivery methods can be beneficial in the right environment:

1- *The first project was delivered with a conventional contract delivery approach. It was imperative that the potential bidders were provided with thorough subsurface information including qualitative analysis of the rock corings which enabled them to prepare a responsive bid and limit the potential for change orders on the City's behalf. The specifications required contractors with appropriate prior experience in similar conditions. Construction documents were prepared that allowed flexibility in the construction process. Each of the described steps led to a successful project that was completed several weeks ahead of schedule and $200,000 under budget.*
2- *The second project was delivered with a design-build delivery approach. Means for the design-build team to create innovative solutions to challenges were created, which resulted in a reduction in overall project schedule and construction cost.*
3- *The third project was delivered with a modified design-build delivery approach. The project team was able to significantly reduce the design and construction schedule as compared to a conventional approach.*
4- *The fourth project was delivered with an EPCM delivery approach. The project schedule was reduced by approximately two months when compared to a traditional design-bid-build approach.* (Kramer and Meinhart 2004, 5-10)

Francom, Asmar, and Ariaratnam (2014) investigate the cost performance of trenchless construction projects delivered with APDM (Alternative project delivery methods), particularly DB (design-build) and CMAR (construction management at risk) water and wastewater projects. The analysis shows that APDM trenchless projects exhibit an average cost savings of 27%.

Deering, Bardin, and Pollak (2001) describe the addition of a 4000 USD/day early completion bonus in the HDD contract for the installation of a 1100 ft (335 m) long, 27.6 in. (70 cm) diameter HDPE force

main and how that helped in completing the work 16 days ahead of schedule, which was initially planned to take 49 days. The pipe profile was planned to reach a maximum depth of 39 ft (12 m) in soft soils. Some hydro-fractures were caused by the HDD including one at the middle of the bore at 39 ft (12 m) depth.

F.3.2 Planning

McKim (1997b) developed a model to facilitate selecting the trenchless construction method for repair and upgrade of existing utilities or installation of new ones. The model considered flow, geometric, material, and other design requirements. Allouche, Ariaratnam, and MacLeod (2003) present a computer program designed to assist trenchless contractors in tracking their direct operating expenditures as well as making financial and estimating decisions. The key elements for the program are the utilization of data normally collected by many firms, maximization of the number of applications for which the data are utilized, and ease of use facilitated by the program's simple structure and user-friendly interface.

Baik, Abraham, and Gokhale (2003) discuss the development of the framework for a decision support system (DSS) to assist in the selection of the appropriate equipment for HDD projects based on seven primary criteria: economic attractiveness, site conditions, diameter of pipe, depth of installation, drive length, soil conditions, and pullback load. The DSS also provides information about different types of pipes and drilling rigs as well as the estimated slurry volume, pullback load, and productivity for HDD operations. The paper presented two case studies in which this system was used.

F.3.3 Productivity

In the survey conducted by Allouche, Ariaratnam, and Lueke (2000), contractors were asked to list concerns that they commonly considered when entering an environmental or a utility project:

> *These concerns are listed below in order of importance.*
>
> *For utility projects:*
>
> *1- Location of existing utilities*
> *2- Soil conditions*
> *3- Safety conditions on site (e.g., traffic)*
> *4- Accessibility*
> *5- Reliability of client (e.g., payment, soil data provided)*
> *6- Type of product*
> *7- Containment and disposal of drilling fluid*
> *8- Length of bore*
> *9- Time of the year*
> *10- Quality of design*
>
> *For environmental projects:*
>
> *1- Type(s) of contamination*
> *2- Soil conditions*

3- *Location of buried obstacles*
4- *Location of plume*
5- *Method and site for disposal of drilling fluids/cuttings*
6- *Contract and local regulations*
7- *Level of risk/public exposure*
8- *Expected level of performance*
9- *Site hydrogeological conditions*
10- *Accessibility*

The survey shows that:

- *Productivity tends to decrease when product diameter increases.*
- *The highest productivity is attained while drilling in clay and silty clay.*
- *Lower productivity is expected while drilling in cobble and gravel.*
- *Reasonably satisfactory advancement rates can be achieved in sand and sandstone formations* (Allouche, Ariaratnam, and Lueke 2000, 73)

Table 6, modified from Allouche, Ariaratnam, and Lueke (2000), provides a summary of the average productivity rates in various soil types.

Table 6. Average Productivity in Various Soil Types

Diameter mm	*Clay m/day*	*Silty Clay m/day*	*Sand m/day*	*Gravel m/day*	*Cobbles m/day*	*Hardpan m/day*	*Sandstone m/day*	*Bedrock m/day*
50-100	*180*	*221*	*133*	*80*	*38*	*95*	*149*	*103*
150-200	*128*	*131*	*100*	*49*	*23*	*41*	*80*	*69*
250-300	*102*	*-*	*90*	*41*	*23*	*35*	*45*	*45*
>300	*67*	*-*	*65*	*40*	*23*	*23*	*45*	*23*
Diameter in	*Clay ft/day*	*Silty Clay ft/day*	*Sand ft/day*	*Gravel ft/day*	*Cobbles ft/day*	*Hardpan ft/day*	*Sandstone ft/day*	*Bedrock ft/day*
2-3.9	*591*	*725*	*436*	*262*	*125*	*312*	*489*	*338*
5.9-7.9	*420*	*430*	*328*	*161*	*75*	*135*	*262*	*226*
9.8-11.8	*335*	*-*	*295*	*135*	*75*	*115*	*148*	*148*
>11.8	*220*	*-*	*213*	*131*	*75*	*75*	*148*	*75*

Zayed and Mahmoud (2013, 69) analyzed the responses of professionals trying to estimate the time and cost of new pipe installations using Horizontal Directional Drilling (HDD): "*Approximately, 220 questionnaires are sent to TT professionals in North America with a response rate of 12% (28 projects). All replies represent the new pipe/cable installations using HDD in clay, sand, and rock soils. Around 20% of the data was excluded from the modeling phase in order to be used for validation purposes."* They "*considered 13 factors: crew/operator skills, drilling bit capabilities, safety regulations, machine conditions, slurry flow rate, steering problems, soil type, unseen buried obstacles, site and weather conditions, pipe diameter, pipe length, pipe depth, and pipe type" (66).*

Table 7 presents the results of the analysis ranking the factors affecting HDD productivity from the most to the least important.

Table 7. Rank and Weights for Factors Affecting the Productivity of HDD

Factor	*Rank*	*Weight*
Operator and Crew skills	*1*	*0.1024*
Soil Type	*2*	*0.0988*
Pipe Diameter	*3*	*0.0905*
Drilling Bit Capacitites	*4*	*0.0875*
Steering Problems	*5*	*0.0854*
Machine Condition	*6*	*0.0852*
Slurry Flow Rate	*7*	*0.0785*
Unseen Obstacles	*8*	*0.0702*
Pipe length	*9*	*0.0635*
Safety Regulations	*10*	*0.0623*
Site/Weather conditions	*11*	*0.0604*
Pipe Type	*12*	*0.0578*
Pipe Depth	*13*	*0.0575*
	Total	*1.0000*

Adel and Zayed (2009) suggest using fuzzy logic integrated with neural networks to predict productivity (meter/hour) of HDD projects. The literature review, as well as the industry experts' input, identified thirteen major factors affecting HDD productivity: operation/crew skills, safety regulations, rig size, machine condition, slurry flow rate, steering problems, soil types, unseen obstacles, site/weather conditions, pipe diameter, pipe length, pipe depth, and pipe type. The paper focuses on analyzing the relationship between activities cycle time and the eight most relevant factors: operation/crew skills, pipe diameter, rig size, machine condition, unseen obstacles, pipe length, and the site/weather conditions, as well as identifying their relevant impact on productivity. The model was trained then tested using 8 data points that were not included in the training set, and an average validation of 96% was obtained, hence indicating good productivity prediction capability of the model. Zayed and Mahmoud (2014) present a similar study.

F.3.4 Risk and Risk Management

Ariaratnam, Allouche, and Lueke (1998, 21) indicate that "*HDD can have a higher magnitude of risk, compared to open cut. Potential risks for an HDD contractor include failure to complete the bore successfully, safety of workers, environmental issues, damage to structures, and hitting other underground utilities or structures.*" HDD has lower risks in other directions such as safety of workers and chance of encountering utilities at greater depths (Woodroffe and Ariaratnam 2008).

According to O'Reilly and Stovin (1996, 33), *"Risk studies enable a complex multi-faceted project to be understood in the light of the uncertainty to which it is (or is believed to be) subject. Risk identification, analysis and the consideration of potential response strategies allow decision-makers*

to choose rationally between competing schemes. The consideration of risk prior to commencing work enables positive steps to be taken to adjust the risk on the project."

F.3.4.1 Risk Identification

Kramer et al. (2002) classify project risks into the following three groups: technical risks, financial/contractual risks, and third-party risks. Kramer et al. (2002) give some examples of risks that may be encountered on a trenchless project:

1- *Technical Risks:*
   - *Ground movements or settlement during micro-tunneling, directional drilling or pipe bursting*
   - *Pipe or manhole settlement after construction*
   - *Movement of structures after completion of tunneling, directional drilling or pipe bursting due to groundwater displacement or other causes*
   - *Failure of pipe or liner during or after the installation process*
   - *Slow production or stoppage of equipment due to natural or man-made obstructions, or varying/different geology than that are indicated in the contract documents*
   - *Failure of temporary works such as shafts or by-pass pumping during construction*
   - *Inadequate or inappropriate equipment and methods selected by the contractor based on inadequate contract documents Subsurface contamination or hazardous material conditions!*

2- *Contractual/Financial Risks:*
   - *Risk of performance (Does the system perform as specified/required? For example, are the flow or capacity requirements satisfied?)*
   - *Penalties for failure to meet owner or court ordered deadlines for completion*
   - *Unlimited liability for failures or problems (no financial or time limitation due to problems or failure of installed system)*
   - *Unpredictable consequential damages (no financial limitation from third party claims impacted by project construction)*
   - *Extended guarantees or warrantees (warranty period outside of industry practice)*

3- *Third Party Risks:*
   - *Disruption to residents and loss of public amenity*
   - *Disruption to businesses and commerce*
   - *Disruption to traffic and increased accident levels*
   - *Disruption to adjacent utilities*
   - *Environmental impacts (e.g., noise and vibration)* (Kramer et al. 2002, 4)

Murray, Osbak, and Bayat (2013) provide a quantitative HDD technical risk identification summary from the assessment of 100 HDD projects. In the paper, 21 risk events were identified based on unplanned schedule delays as recorded in daily work record sheets. The frequency of occurrence, schedule impact, and risk index for each risk event was determined. The paper presents the average overall schedule impact based on the accumulated schedule delay for each project:

> *The average overall schedule impact is 40 percent of the final construction schedule. The subsurface risk events contribute approximately 33 percent of the average schedule impact,*

while the surface risk events provide the remaining 7 percent. There are three subsurface risk events that provide the greatest contributions to overall schedule impact and have the highest risk index values: reduced drill cuttings return, loss of circulation; and waiting on owner. The identified risk events are listed below:

Subsurface Risks:

- *E1 – Hydraulic Fracturing: Drilling fluid that escapes the borehole annulus and is released to the surface required a stop in production, cleanup activities were initiated, and decisions made on how to proceed given the location of the fluid release.*

- *E2 – Collapsing Soil / Lost Hole: Soft cohesive soils can squeeze into the borehole annulus or loose granular soils can fall into the borehole annulus bridging off the borehole. Drilling production was stopped and mitigative measures established to prevent more risk events from occurring, such as losing drilling fluid circulation, hydraulic fracturing or having the drill rods become stuck in the hole.*

- *E3 – Loss of Circulation: Drilling fluid is pumped from the drill rig at surface through the drill stem to the cutting tool at the bottom of the hole, then returns to the drill rig via the borehole annulus to be cleaned of cuttings and re-circulated. When the volume returning to the drill rig at surface is reduced or completely lost into the subsurface, drilling production is stopped and mitigative measures are required to attempt to gain circulation such as modifying the drilling fluid properties, applying lost circulation materials (sawdust, magma fibre, etc.), grouting the thief zone or applying conductor casing.*

- *E4 – High Annular Pressure: The downhole annular pressure is monitored during pilot hole drilling and is maintained within empirical thresholds. When annular pressures approach or exceed allowable pressures, the drilling stops and mitigative measures are required.*

- *E5 –Abnormally Slow Production: Subsurface conditions that contribute to slow production and require that the drilling/reaming assembly be checked at surface.*

- *E6 –Reduced Drill Cuttings Return: Drill cuttings that are not effectively removed from the borehole annulus require a stop in normal production and require mechanical cleaning of the borehole by resizing the annulus with the cutting tool as it is removed from the borehole. Cutting beds and/or a restriction of the borehole annulus diameter may be developed as a result of subsurface conditions that promote swelling or result from circulation loss. Drilling operations reacting to the subsurface conditions such as rate of penetration, drilling fluid condition and volume of material cut may also contribute to reduced drill cuttings return.*

- *E7 – Drill String Stuck in Hole: Drilling progress is halted as a result of the drill pipe being stuck in the borehole due to subsurface conditions. This risk event is often precipitated by any/or E1-E6 occurring.*

- *E10 – Down-hole Tooling Malfunction/Damage: A stop in production resulting from a rapid or catastrophic degradation of the downhole drilling assembly caused by subsurface conditions and does not represent normal wear and tear.*

- *E12 – Wait on Owner: When a subsurface risk event occurs that stops production, the contractor informs the Owner of the risk event and events leading to the risk and assists in developing mitigation strategies. Production is stopped due to the time required for the Owner or Owner's representative to arrive at a decision or seek authorizations in developing or implementing mitigation strategies as a result of a subsurface risk event.*

- *E14 – Pilot Hole Deviations: Schedule delays resulting from a segment of the pilot hole that is outside of the specified tolerances of the planned drill path. The HDD contractor pulls-back and re-drills from the location along the bore path before the deviation to remain within specified tolerances. The subsurface conditions will promote a deviated bore path.*

- *E15 – Flow to Exit: A schedule delay results when remedial action is required to respond to drilling fluid flowing to exit, such as using a vacuum truck to clean up the drilling fluid. Subsurface conditions and an elevation differential from entry to exit can promote fluid flow to the exit.*

- *E16 – Drilling Fluid/Solids Control Work: Non-scheduled delays to production resulting from building or modifying drilling fluid, or until drill cuttings have been cleaned out of a holding area. This risk event is precipitated by other subsurface risk events. For example, a loss of circulation event will result in building additional drilling fluid and/or building and applying loss circulation materials in an attempt to seal the loss circulation zone. Encountering formations that react negatively with the drilling fluid result in schedule delays due to modifications/additives required to the drilling fluid. Solids control work results in a schedule delay caused by removing excessive drill cuttings from a holding area resulting from tripping out of the borehole to clean the borehole annulus.*

- *E18 – Water Production: The borehole can produce formation water as a result of artesian conditions or when drilling above entry elevation through a perched water table. During these occurrences, drilling fluid clean-up and modification is required and was recorded as a risk event within the construction process.*

- *E19 – Conductor Casing Delays: Through drilling operations, such as wash-out at the end of the casing or buoyancy of the drill pipe or product line, instances may occur*

where the drilling assembly or the product line will not enter the casing resulting in delays to mitigate the issue.

- *E20 – Damaged Product Line: Instances where the product line or product line coating has become damaged to the point that remedial action must be taken were documented as a risk event. Protective coatings on the product line can be damaged during product installation due to excessive pull-back forces involved and by contact with abrasive soil/bedrock present in the bore hole.*

- *E21 – Product Line Stuck in Hole: Similar to Risk Event, E7, the product line can become stuck in the hole and cannot be pulled to the entry point for installation. A stuck product line results from a caving borehole annulus or from an annulus that has not been sufficiently cleared of cuttings.*

Surface Risks:

- *E8 –Wait on Vacuum Truck: A stop in production resulting from the clean-up of drilling fluid using a vacuum truck. The stop in production was often due to waiting for the vacuum truck to arrive on site or as a result of safety protocol as it worked around the HDD equipment. Drilling fluid clean-up/recovery was implemented as a result of drilling fluid released to the surface (E1) or drilling fluid migrating to the exit side (E15) or as a result of water production (E18).*

- *E9 – Wire-line Malfunction/Damage: A schedule delay resulting from a broken or damaged wire-line connection causing an interruption to the flow of power to the downhole steering and/or annular pressure tools. The contractor was required to trip out of the borehole to locate and repair the malfunction to the wire-line to allow for steering and annular pressure monitoring.*

- *E11 – Surface Equipment Malfunction/Damage: A stop in production resulting from a component of the surface equipment such as the drilling fluid recycling system, drill rig or exit side equipment requiring repair, replacement or unscheduled maintenance.*

- *E13 - Wait on Equipment/Services: A time delay preventing production due to the requirement of necessary equipment or services. Often, HDD site locations are remotely located, and a time delay resulted from acquiring necessary equipment/services such as delivery of water, drilling additives and equipment components.*

- *E17 – Weather Delay: Inclement weather can directly result in non-scheduled delays to production such as heavy or extensive rainfall, thunderstorms and particularly in Canada, this is often due to extremely cold temperatures (below -30° C [-22° F]) and blizzard conditions*

Approximately half the risk events have a frequency of occurrence greater than 25 percent. Four risk events have a frequency of occurrence greater than 50 percent and include

subsurface risks, E3, E6 and E12 and surface risk E11. The average schedule impacts with the greatest values are attributed to subsurface risk events E21, E20, E10, E7, E18, E2 and E6 with values exceeding 10 percent of the average schedule impact. The highest average schedule impact, 29 percent, corresponds to E21, where the product line became stuck in the borehole. The average schedule impacts for the surface risks ranged from 0 to 6 percent. Results indicate that the overall schedule impact varied from 2 to 85 percent of the final construction schedule. The average impact of overall risk is 40 percent of the final project construction schedule, with a standard deviation of 20 percent. [Figure 15] shows the average percentage of delay of the identified risks. If the preconstruction schedule was based solely on the cost for normal HDD construction with no allocation for potential risk impacts, then the schedule overrun due to the average aggregate risk could be significant. (Murray, Osbak, and Bayat 2013, 1058-1061)

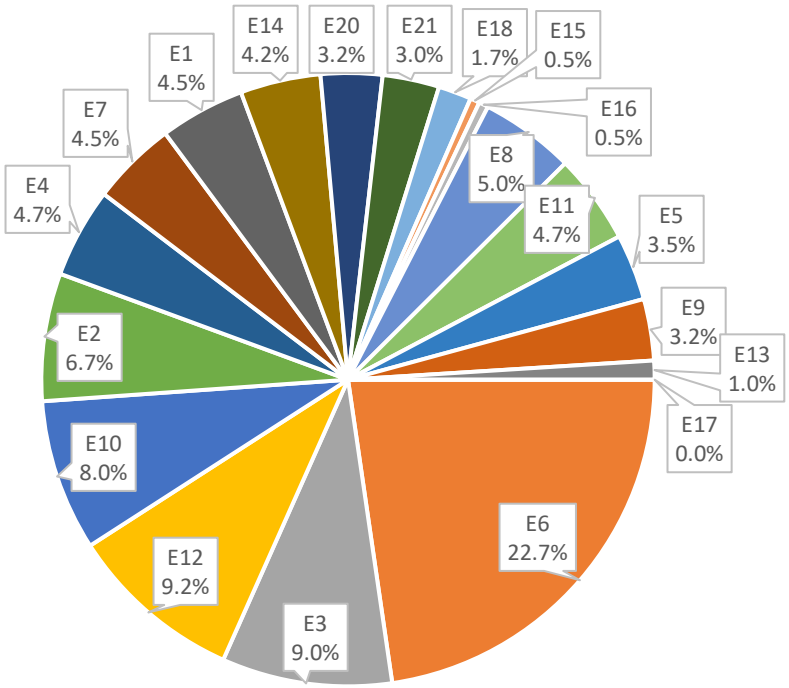


Figure 15. Chart. Average percentage of delay (representing on average 40% of total project time) of each of the identified risks—modified from (Murray, Osbak, and Bayat 2013).

Onsarigo, Adamtey, and Atalah (2014) conducted a survey and received 19 responses and interviewed 5 HDD professionals. The study shows that the risks with the highest probability of occurrence are in order: mixed soil conditions, hydro-fracture, loss of circulation, loss of formation, obstructions, hitting unknown utilities, and down hole tooling failure. The risks with the highest impact on cost are in order: hitting unknown utilities, the collapse of product pipe, stuck pipe, down hole tooling failure, loss of depth, heave of surface, obstructions, and loss of formation.

F.3.4.2 Risk Mitigation

Woodroffe and Ariaratnam (2008) suggest methods to mitigate some of the major technical risks:

1- *Geotechnical Data:*
Geotechnical data must be much more accurate for HDD than open cut. To help minimize risks of an unsuccessful drill, an extensive soils report should be conducted to reduce the chances of unforeseen materials or debris in the drill path.

2- *Selection of drilling equipment:*
Choosing the proper drilling equipment for an HDD project is much more complicated than equipment on an open cut project. Selecting the proper HDD drill rig is essential for completing a successful project. Excessive bending of the rods, hard or sharp objects encountered in the bore, and using poor quality or improperly-sized tooling can contribute to the risks in completion Bennett et al. 2004.

3- *Loss of drilling fluid:*
When drilling fluid circulation is lost from the bore hole and surrounding soil formation is resistant to fracturing or absorption, hydro-lock will occur. Hydro-lock can be controlled by maintaining constant circulation flow return of the drilling fluids and also by excavating relief holes to reduce excessive fluid pressure along the drilling path.

4- *Soil Collapse:*
Soil collapsing within the borehole may occur when drilling through various soil compositions. Soft or loose soils pose particularly high risks of collapse during drilling, thereby preventing drill fluid circulation and resulting in increased rotary torque. To overcome these obstacles, it is recommended to adjust the drilling fluid mixture to match the encountered geology, pull back and re-drill to regain circulation, and drill relief holes along the pipe alignment to establish a path of least resistance.

5- *Collapse or Subsidence on the surface:*
Another risk that HDD poses on existing infrastructure is the risk of collapse or subsidence on the surface. This is a serious problem caused by over-excavation and consolidation above the bore and may cause soil above the utility to cave in. There is a potential risk for hydro-fracture of drilling fluid. Hydro-fracture creates pooling of drilling fluid on the ground surface, a very undesirable outcome that increases restoration costs. According to Najafi 2005, the cost of double handling soil and the amount of work required for resurfacing can be up to 70% of the total costs on an open cut project. (Woodroffe and Ariaratnam 2008, 87-88)

Kramer et al. (2002) describe the typical methods for minimizing and managing risks associated with the installation of new pipes and the rehabilitation of conduits using a trenchless technology method during the design process, bidding process, and once the construction phase begins. Those methods include:

1- *Geotechnical Baseline Reports and Environmental Baseline Reports:*
A Geotechnical Baseline Report (GBR) possibly combined with an Environmental Baseline Report (EBR) is one tool that should be considered as part of the contract documents if micro-tunneling, horizontal directional drilling (HDD), or open cut excavation is to be used on a project. (Kramer et al. 2002, 5)

2- *Dispute Resolution Boards:*
There are several methods that could be used for dispute resolution, should a dispute between the owner/sponsor and the contractor occur during a project. Traditionally, these include claim and change orders, arbitration and litigation. For trenchless and other underground projects, alternative methods such as Dispute Review Boards (DRB's) and Escrowed Bid Documents have been used to more effectively manage the risk associated with these projects. (Kramer et al. 2002, 5-6)

3- *Contractual Methods for Handling Obstructions:*
The three methods most commonly used for contractually handling obstructions are identified below.
   a) *The contractor is responsible for handling all obstructions. This method shifts the risk to the contractor, and generally, results in higher bid prices, and claims for changed subsurface conditions.*
   b) *The owner/sponsor of the project assumes the risk for handling obstructions by for example, specifying the number of obstructions to be removed, the minimum requirements for the capabilities of the trenchless method (e.g., micro-tunneling machine or directional drilling rig), and mandates that the contractor submit a unit price to handle each obstruction. This method shifts some of the risk to the owner by providing a mechanism for the contractor to be reimbursed for the costs of handling obstructions. Contractors generally put a high price on each obstruction removal to cover his risk. If more obstructions are encountered than specified by the owner, the cost to the owner can become substantial.*
   c) *Contractual language is placed in the contract documents requiring a shared risk approach. A shared risk approach will result in a more equitable result for both the owner and the contractor. The shared risk approach requires the contractor to submit an auditable unit cost (after award of the contract) for down time of specified equipment and manpower if stoppage during the installation process is required due to a possible obstruction.* (Kramer et al. 2002, 7)

4- *Field Monitoring and Instrumentation Program During Construction:*
The response of structures, utilities and other points of concern to the construction operations can be monitored by establishing a baseline pre-construction survey of critical locations, structures, and utilities by using settlement markers and then monitoring their movement during trenchless operations. In addition, inclinometers, seismic (vibration) monitors, borros points (i.e.- steel rods extending from road boxes at surface to one or two pipe diameters

above the pipe) and groundwater observation wells can also be used to establish baseline conditions prior to the start of construction, and to detect changes during construction. The deformation points, inclinometers, seismic (vibration) monitors, borros points, and ground water observation wells are then monitored during trenchless operations. As the equipment approaches a specific location, the monitoring points in the area of the location should be more frequently monitored to provide data to evaluate ground movements and the cause of ground movement during operations. If the data indicate changes that approach or exceed the range of estimated values or predetermined tolerable values often defined by the threshold and limiting values (yellow and red flags), trenchless operations should be halted until it is determined what is causing the potential problem. (Kramer et al. 2002, 8-9)

5- *Contractual Methods for Managing Risks due to Obstructions:*
Other contractual tools, including pre-qualification of specialty contractors, contractor incentive programs, and partnering should be considered for trenchless technology projects. (Kramer et al. 2002, 10)

Kramer et al. (2002) present two case studies where some of those tools were used.

F.3.5 Training of HDD Operators

Ariaratnam, Najafi, and Morones (2002) present an overview of a 3-day training program on HDD conducted to train 125 resident engineers and permit inspectors for the California Dept. of Transportation, 54 utility inspectors, 16 consultants, and 26 city/county inspectors in the State of California between July 1999 and February 2000:

The first and third days involved classroom instruction, while the second day provided field site demonstrations of the equipment and techniques used in HDD construction. The education level of the participants was broad: high school diploma 37%, bachelor's degree 37%, associate degree 14%, and graduate degree 12%. A pretest was administered on the first day, prior to any instruction, followed by a final test administered at the end of the last day. The description of the training program is shown below:

- *Day One (Classroom Instruction):*

  The first day of the academy presented the basic operational and safety procedures involved in HDD. Prior to any instruction, a 50-min pretest was administered to evaluate the current level of understanding in HDD practices of the participants. The pretest consisted of 111 multiple-choice questions divided into 6 areas: locating and tracking, contracts and specifications, drilling fluids, project management, permit specifications; and pipe calculations. Upon completion of the pretest, an entire day of classroom instruction was conducted on the following topics:

  - *Introduction to HDD Technology, Capabilities, and Limitations: This 50-min instructional block presented: the various types of drilling rigs currently available on*

the market; the basic operational procedures, including types of drill bits, back reamers, and tracking devices; and limitations of various drilling rig types due to maximum size capacity. An academic, extensively involved in HDD research activities, provided instruction.

- *Location and Clearance of Utilities, Tracking, and Radius of Curvature: This 80-min instruction was provided by two manufacturer representatives. This included presentation of the tracking equipment in locating the drill bit during drilling operations. The participants were instructed on how to read and interpret the tracking receiver to determine the exact location of the drill bit below the surface. In addition, instruction was provided on methods for calculating a safe radius of curvature so as to reduce the chance of overstressing the new pipe during installation;*

- *Description and Operation of Locating Equipment: A 60-min block presented the methods of locating existing subsurface utilities. Utility locating is a crucial activity and must be conducted prior to initiation of any HDD installation. A representative from a utility locating manufacturer provided instruction;*

- *Importance of Soil Analysis: An 80-min block was dedicated to instruction on geotechnical aspects of HDD. One of the leading causes of disputes during HDD operations is compensation for unforeseen geotechnical conditions. A geotechnical engineer provided instruction on the importance of soil analysis, basic principles of soil classifications, various field tests available to evaluate soil types, and special considerations for highway crossings; and*

- *Effects of Fluids/Mud Technology, Viscosity & Mixing of Drilling Fluids. Drilling fluid considerations are perhaps the leading cause of failures in HDD operations. A 100-min block was dedicated to an introduction to drilling fluids, types of material, mixing ratios, applications, troubleshooting, and basic field tests for quality. A representative from a drilling fluid manufacturer provided instruction.*

- *Day Two (Field Session):*

  The second day of the academy provided field demonstrations of HDD. Drilling equipment and material were brought to a field demonstration site. The participants were divided into four groups that spent 2 hours at each of four different field stations. The field demonstration emphasized the lecture material from the first day in a practical real-world environment.

  - *Station A: Drilling Fluids Technology: Participants were given additional instruction on drilling fluids technology in an outdoor field laboratory setting. Instruction was more in-depth than that provided during the classroom lecture. Additionally, each person was given the opportunity to perform several basic field tests for quality of drilling fluid composition. These included testing for density, sand content, and gel strength. This is*

valuable information for permit inspectors and engineers to utilize when they are performing inspection of HDD projects.

- *Station B: Tracking and Locating: Two different manufacturers of tracking and locating equipment provided hands-on instruction on using the equipment during HDD operations. The participants were further subdivided into two groups, each spending an hour learning about each manufacturer's equipment. Each of the participants was involved in the actual tracking and locating of an HDD installation. Additionally, the instructors demonstrated how the equipment may give incorrect information due to interference from nearby electrical lines and buried metal objects.*

- *Station C: HDD Rig 1: At this station, the participants were shown actual drilling operations. An experienced HDD contractor explained the various types of drilling bits and their applicability for various soil conditions. The class observed an actual pilot bore over a 50 m section. In addition, safety issues related to the operation of the HDD rig were addressed.*

- *Station D HDD Rig 2: An experienced HDD contractor discussed the various types of back reamers used during the installation of a new pipe and explained the applicable soil conditions for each type. The participants observed a pullback operation in which a 50 mm high density polyethylene pipe was installed over a 50 m horizontal distance.*

- *Day Three (Classroom Instruction):*

  The final day of the academy involved a second day of classroom instruction with an emphasis on the engineering, contracts, and project management aspects of HDD.

  - *Job Setup and Operation: An 80-min block was provided for instruction on job setup and operation considerations from the contractor's perspective. An experienced HDD contractor addressed aspects of preplanning, boring, pullback, cleanup, and safety;*

  - *Permit Package Submittal and Plan Sets: A 60-min block was assigned for instruction related to elements contained in the permit submittal package to Caltrans. Sections from the Guidelines and Specifications for Horizontal Directional Drilling Installation booklet were discussed. Adherence to this document is a requirement for any HDD project on California State rights-of-way. A consulting engineer experienced in HDD projects provided instruction;*

  - *Question and Answer Period: A 75-min. block was provided to solicit questions and answers from the participants related to any of the topics covered with a focus on the field instruction. All of the field instructors were present as panelists for the session;*

  - *Pipe Calculation Considerations. A 60-min block was provided to demonstrate the methodology used in calculating and designing for: pipe tensile loads; external collapse loads; friction; and wall thickness. It is imperative that pipes with the correct standard*

dimension ratio (SDR) be specified. SDR is the ratio of outside pipe diameter divided by wall thickness. Incorrectly specified pipes risk postconstruction collapse or failure during construction. Instruction was provided by an engineer experienced in designing of HDD projects;

- *Safety, Project Closeout, and Documentation. A 55-min block was provided to further illustrate the importance of safety during HDD operations and examine safety protocol. Additionally, an academic who teaches this topic at a university-level discussed project management aspects of HDD projects;*

- *Contract Administration and Overview of Different Types of Specifications. A 110-min block was provided for instruction on the various aspects of contract administration and an overview of specifications. The participants were instructed on different types of contracting mechanisms available and the potential risks involved with each. Additionally, sections from the Encroachment Permits, Guidelines and Specifications for Horizontal Directional Drilling document were examined. Various specification clauses were explained and examined in detail. Instruction was performed by an academic who was directly involved with the development of the Caltrans HDD Guidelines and Specifications; and*

- *Final Test:*

  - *A final 60-min test was administered to each of the participants. A final grade of 70% or higher was required to pass the academy and receive certification the average pretest score was 55.61% compared to an average final test score of 75.27%.* (Ariaratnam, Najafi, and Morones Jr. 2002, 66-68)

Due to the risk associated with horizontal drilling on the expensive drilling rigs machines and equipment, and since the drilling experience is one of the major parameters determining the success of HDD projects, Li et al. (2011) created a platform for virtual-reality-based training of rig operators which enables training of a large number of operators, while significantly reducing the cost of training. The platform merges simulation and visualization software with actuators that are very similar to the actual rig controllers. The trainees use those actuators to control the simulation and can see the effects of their moves on the screen, which provides them with the feedback loop necessary for learning. Wang et al. (2013) provide updates on the system demonstrated in Li et al. (2011) and provide a photo of the system as presented in Figure 16.



Figure 16. Photo. The training system as shown in Wang et al. (2013).

F.4 HDD DESIGN AND CONSTRUCTION

F.4.1 Overview of the HDD

A typical HDD execution is composed of three main stages: pilot bore drilling, reaming, and pipe pulling, as presented in Figure 17. Given the geometric design of the installation profile, the rig is placed at the entry point, and the drill bit is attached to the drill pipe. The drilling starts inclined and is steered, using the drill bit, to follow the target profile till it exits at the exit point. The steering is guided by a tracking system that gives the drilling tool's location, depth, and orientation using a tracking sensor installed near the drill bit. After the drill bit exits at the exit point, it is replaced by a reamer which is pulled to enlarge the bore. Reaming could be done using reamers of different sizes till the target bore diameter is reached. Then, the pipe is connected to the reamer via a swivel and pulled back through the bore. During those three stages, drilling fluid is injected under pressure to stabilize the hole by creating the filter cake and to suspend and transport cuttings. The used drilling fluid is either disposed of or recycled. Different pipe types are used for HDD and are selected based on the application.

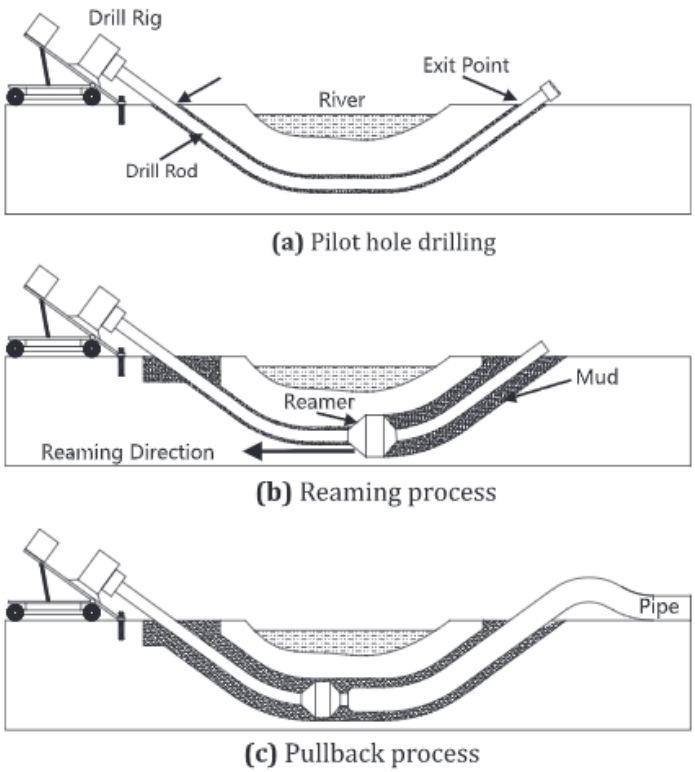


Figure 17. Figure. Horizontal directional drilling process (Yan et al. 2018).

HDD projects typically start with a site investigation of the site and a study of its constraints and challenges, which guide the initial geometric design of the installation profile. The corresponding pull loads and fluid pressures are calculated in an iterative process which also includes fluid design, flow, and drag calculations. A suitable fluid system is selected. The product pipe is designed and may be coated. Suitable steering, tracking, and reaming systems are selected. The capability of the drill pipe to handle the installation loads is sometimes checked. Depending on the site conditions and limitations, special construction methods and technologies might be employed. Before, during, and after its completion, the HDD process and results should be inspected.

F.4.2 Site Investigation

Geotechnical investigation is a necessary step that is used to confirm the suitability of HDD and to guide its design.

F.4.2.1 Locating Utilities

According to Skonberg and Muindi (2014, 6), "*horizontal and vertical positions of existing utilities should be determined accurately if possible, especially when the HDD alignment is to pass within 10-ft of those utilities. One method of obtaining utility data is to contact the local 'One Call' locating service which can be reached by dialing 8-1-1 from anywhere in the United States. In areas where One Call assistance is not provided during the design phase of work, municipalities and private utility companies should be contacted to obtain the required information. Additional research is often*

necessary, however, because not all utilities belong to the One Call Network and One Call Locates are not always clear with respect to depth of utilities. Methods of confirming subsurface utility locations include pipe locators, ground-penetrating radar, probing, manual excavation, vacuum excavation, and seismic survey."

According to Ariaratnam and Proszek (2006, 352), "*Damages to underground facilities by contractors often lead to costly litigation and legal consequences. Contractors can greatly reduce incidents of utility strikes during horizontal directional drilling installations by following good practices. Prebore site assessment is recommended to identify and verify underground, surface, and overhead hazards. Walking along the intended installation path with the locating receiver in the 'on' position can help to identify potential sources of interference prior to drilling. This enables the contractor to employ measures to address these interferences. Maintaining records on a driller's logbook is a prudent practice. This information is one of the first pieces of information requested by lawyers investigating utility strikes.*"

F.4.2.2 Geotechnical Investigation

The ASCE HDD Pipeline Design Manual (Skonberg and Muindi 2014) provides some guidelines for geotechnical investigation for HDD projects:

> *A typical geotechnical survey consists of taking exploratory borings to collect soil samples for classification and laboratory analysis. Methods utilized in the survey of underground utilities can also be incorporated into the geotechnical survey. The number, location, and depth of exploratory borings should be determined taking into account site-specific conditions such as the general geology of the area, availability of access, availability of existing data, cost, etc. Borings should be located off the drilled path centerline to reduce the possibility of drilling fluid inadvertently surfacing through the borings during HDD operations. The borings should penetrate to an elevation 20 to 30 ft (6 to 9 m) below the depth of the proposed drill path to provide information for design modifications and anticipated pilot-hole deviations during construction. Areas of geologic transition and/or significant contrast in physical ground properties can present unique challenges to HDD construction and should be carefully scrutinized with greater frequency of investigation. Where rock is encountered, it should be cored to the maximum depth of the boring. Because the drilling operations produce spoil materials that require handling and disposal, soil and/or groundwater samples should be examined by both visual and olfactory means to determine if potential hazardous materials exist. Samples should be taken and analyzed in accordance with applicable state and EPA regulations and methods. When hazardous materials or contaminated soils are encountered, special consideration should be given to selecting an appropriate pipe material for these conditions.* (Skonberg and Muindi 2014, 9-12)

The most important soil properties to be identified are highlighted by M.M. Gelinas and Mathy (2004):

1- ***Soil Grain Size Distribution:*** *Particles which are too large or heavy to be suspended in the drilling fluid can sometimes be physically displaced by the reaming tools or the product*

pipe itself but can also collect to form an impenetrable blockage within the bore hole. Hence, knowledge of the grain size distribution of bore path soils is critical to evaluating the feasibility and efficiency of HDD construction. Cobbles and boulders present an obvious, high risk for HDD: their size and weight make them virtually impossible to remove from the bore hole. Soils containing greater than 50% gravel size or larger particles present a high risk for HDD, while soils containing 30 to 49% gravel size or larger particles present a risk, but which is often mitigatable.

In porous formations or formations with interconnected fractures and/or discontinuities it can be very difficult, if not impossible, to prevent drilling fluids from flowing out of the bore hole and into the formation. Drilling fluid loss is generally only of a concern for clean, coarse-grained soils (i.e., sands and gravels containing less than 12% fines). Where clean, coarse-grained soils are identified along a project bore path, detailed grain size analysis is required to determine if HDD is feasible.

In coarse-grained soils, the ability to maintain bore hole stability (i.e., the ability to prevent bore path soils from uncontrollably running or flowing into the bore hole) is often of significant concern. Bore hole stability is also of concern in formations identified as containing oversize materials such as cobbles or boulders due to the sheer weight of the materials. In fine-grained, firm to stiff soils (with the exception of saturated, non-plastic silts) bore hole stability is generally of lesser concern.

2- ***Soil Plasticity:*** *Plasticity of fine-grained soils is important as it relates to the soil's tendency to swell when in contact with water, which is present in HDD drilling fluids. The tendency of fine-grained soils to swell effects HDD in two general ways: It can cause the bore hole to constrict, effectively "choking" the bore hole, reducing the drilling fluid flow area and making insertion of the product pipeline difficult. It can also cause cuttings drilled from the formation to swell during transport out of the bore hole, thickening the cuttings slurry, increasing bore hole pressures, and increasing the likelihood of a bore hole blockage. The swelling tendency of fine-grained soils can normally be overcome by the addition of polymers to the drilling fluid (which inhibit the transfer of water from the drilling fluid into the drilled soil formation), and by ensuring that adequate drilling fluid volumes are used. In general, greater volumes of drilling fluids are required for coarse, dense, and/or porous formations and for dry, highly plastic, and/or very stiff formations.*

3- ***Soil Density/Consistency:*** *The density (coarse-grained soils) or consistency (fine-grained soils) of bore path soils can have a significant impact on HDD. Soil density/consistency is generally correlated to standard penetration test blow counts. In general, stiff (i.e., high blow count) fine-grained soils have a higher tendency to swell than soft (i.e., low blow count) fine-grained soils, while stiff or dense (i.e., high blow count) soils generally require larger volumes of drilling fluids than soft or loose (i.e., low blow count) soils.*

The amount of passive resistance that can be generated by a drill bit is directly related to its surface area. As a result, in loose or soft soil formations, contractors may elect to use a broader-faced tool in order to generate greater amounts of passive resistance, and therefore make more precise steering adjustments. For reamers, tool selection is more dependent on the plasticity and grain size rather than its density/consistency. In fine-grained soils, the object of the reamer is to chop the formation into suspendable pieces, which can be entrained within the drilling fluid and transported out of the bore hole. In clayey soils, however, the soil often tends to stick to the reamer, greatly reducing its effectiveness. Thus, when drilling in clayey soils, many contractors prefer reamers which have lower surface area and larger diameter or a greater number of fluid nozzles. In coarse-grained soils, the formations are generally non-reactive, allowing a greater variety of reamer designs to be used.

4- ***Stratigraphy:*** *Knowledge of stratigraphy is critical to the rational design of an HDD bore path. Alluvial soils are particularly likely to vary significantly in composition and consistency over short vertical and lateral distances. Where problematic soils are identified, the bore path should be designed to either avoid them or minimize the length of bore path within them. This can be accomplished by either moving the bore path higher or lower (vertical adjustment) or changing the plan location of the bore path (lateral adjustment). Knowledge of the vertical and lateral distribution of soils is also critical to identifying where changed and mixed face conditions may exist along a proposed bore path, allowing design countermeasures to be put in place to minimize their impact on construction. A changed face condition occurs when a bore path moves from one soil formation to another. A mixed face condition occurs when a bore path moves along the interface between two different soil formations. The effect that changed and mixed face conditions will have on HDD construction depends on the relative difference in properties between the two soil formations (i.e., loose/soft soils vs. very dense/hard soils), but may include steering difficulty, bore path deviation, etc.* (Gelinas and Mathy 2004, 4-6)

Jeyapalan (2010) describes a lake crossing HDD project, which was awarded for 1.74 million dollars with a timeframe of 90 days but ended up costing more than 6 million dollars and 1000 days. According to the paper, the large-diameter pipe installed using HDD ran over cost because of problematic soil conditions (loose sands, gravel, and cobbles). The design was based on incomplete information on soil conditions. The paper also describes some of the complications that resulted from ambiguous contracts highlighting the limits of authorities of the different entities.

Lueke et al. (1998) describe the soil improvement performed before installing a 2296 ft (700 m) long crossing for a high-pressure pipeline after realizing that the proposed path will pass through coal mines containing exposed seams of coal that were extensively mined creating unstable slopes. According to the paper, *"An extensive geotechnical investigation was planned and executed which included seismic tomography to determine the potential for voids and presence of existing mine*

works. A ground improvement plan was developed and executed with a total of 105 grout holes. The strength characteristics of the grouted zone was designed to be similar to that of the natural surrounding bedrock. Borepath design, hydrofracture, and pipe stress analysis were supplemented with a parametric study using the finite element method to optimize the pipe wall thickness within the limits of the ground improvement zone. The stress calculations were completed based on the Pipeline Research Council Institute model. Hydrofracture calculations of the installation were completed based on the extensive geotechnical information collected by the 24 boreholes" (39).

F.4.3 Geometric Design

Once enough site investigation results are available, the geometric design of the installation profile can be done. The drilled path can be typically be defined by six parameters: entry and exit points, entry and exit angles, radius of curvature, and depth of cover (Watson 1995).

Watson (1995) provides general guidelines related to those parameters:

- *The entry and exit points are the end points of the drilled profile. The drilling rig is positioned at the entry point. The pipeline is pulled into the exit point and back to the entry point. The relative location of the entry and exit points, and consequently the direction of pilot hole drilling, reaming, and pulling back, should be established by the site's geotechnical and topographical conditions. When choosing the relative locations of the entry and exit points, it is important to note that steering precision and drilling effectiveness are greater close to the drilling rig. Where possible, the entry point should be located close to anticipated adverse subsurface conditions. An additional consideration is the availability of workspace for pull section fabrication. It is preferable to have workspace in line with the drilled segment and extending back from the exit point the length of the pull section plus 200 feet (61 m). This will allow the pull section to be prefabricated in one continuous length prior to installation. If space is not available, the pull section may be fabricated in two or more sections which are welded together during installation. However, welding during installation slows the process and will increase costs. A slow installation also increases the chances of getting the pipe stuck.*

- *Entry angles should be held between 8º and 20º with horizontal. These boundaries are due chiefly to equipment limitations. Horizontal drilling rigs are typically manufactured to operate at 10º to 12º. Exit angles should be designed to allow easy breakover support. That is, the exit angle should not be so steep that the pull section must be severely elevated in order to guide it into the drilled hole. This will generally be less than 10º for larger diameter lines.*

- *The depth of cover should be governed by the definition of the obstacle. Adequate cover should be provided to maintain crossing integrity over its design life. Geotechnical drillability factors may also be considered when selecting the vertical position of the pipeline. A minimum depth of cover of 15 feet (4.6m) should be maintained in designing drilled profiles. This aids in reducing inadvertent returns, provides a margin for error in existing grade elevation, and allows for future changes in grade elevation.*

- *The design radius of curvature in feet for steel pipes used in HDD installations is determined by the following formula: Radius (feet) = 100 x Pipe Diameter (inches). This relationship has been developed over a period of years in the horizontal drilling industry and is based on experience with constructability as opposed to any theoretical analysis. Larger radii can be used for more flexible pipes such as HDPE or fusible PVC pipes.* (Watson 1995, 34-35)

On the issue of the radius of curvature, the ASCE HDD Pipeline Design Manual (Skonberg and Muindi 2014, 16) reports "*The cold bending radius for HDPE pipe in HDD and other pull-in applications is usually limited to 40 to 50 times the diameter. The preferred installed radius for full-length, flexible restrained joint DIP is 100 ft per in.-diameter; however, the flexible restrained joint is capable of significantly reduced values. In these cases, the lower limit of radius is generally controlled by the capabilities of the drill pipe being used. However, reduction in radius increases bending stress and pulling load on steel pipe. For flexible restrained joint DIP bending stress is not an issue, but a similar increase in pulling load is encountered."*

Avoiding hydraulic fracture is an important criterion when selecting the depth of the alignment. Other criteria include avoiding problematic soils or utilities, reducing surface settlement or heave, etc. This is especially essential for important structures, for which a depth of cover no less than 40 ft (12 m) is sometimes suggested (Hair and Associates 2008). More details on this issue are presented in later sections.

Many computer programs were created to assist HDD design including *DrillPath, Atlas Bore Planner, PLEXCALC II, FieldCalc, MDrill,* BoreAid, and PPI-BoreAid, which provide tools for selecting the profile, estimating pipe stresses, estimating fluid pressures limits, estimating settlements, and assisting in tool selection (Bayat, Knight, and Lawrence 2009; Lawrence et al. 2011).

Reamer size is usually increased to allow the escape of fluid pressure. The connection between geometric design and the reamer size needs further research.

Peters, Lloyd, and Tatum (2018) describe the installation of a 2,300 ft (701 m) long 30 in. (76.2 cm) FPVC force main via HDD in eastern Volusia County, Florida. The geometric design was conducted with the assistance of the BoreAid® software. A conductor casing was used to contain the mud at the entry point. Multiple hydro-fractures occurred near the entry and exit points.

F.4.4 Pipe Design

During HDD installation, a continuously fused or welded pipeline segment is subjected to tension, bending, and external pressure as it is pulled through a pre-reamed hole. The stresses and failure potential of the pipe are a result of the interaction of these loads (Skonberg and Muindi 2014). Based on the calculated installation and operating loads, pipes sections are selected or suggested pipe sections are verified.

F.4.4.1 Installation Loads

The pullback load balances the resistance forces during pipe installation using HDD. It is a key parameter for selecting a drill rig with appropriate pullback capacity and evaluating the stresses

during product pipe installation. In addition to the submerged weight of the pipe, the main resistance forces, according to Yan et al. (2018), are the following:

- *resistance force between pipe and ground surface and borehole wall (caused by gravity and buoyancy of pipe): When the product pipe is pulled into the borehole, it incurs a reverse friction force as a result of the interaction between the pipe and ground surface. The ground friction is maximum at first, but then decreases as more pipes are pulled into the borehole. In practice, constructors usually use rollers, slings or even water ditches to minimize friction. The interaction between the pipe and borehole wall produces a resistance force that counters movement of the pipe.*
- *resistance force at the curves (caused by Capstan effect and bending/stiffness effect): When the product pipe is pulled crossing a curve section, the direction of the pull force changes, resulting in an increase in the contact pressure between the pipe and borehole wall. The increase in frictional force at the curve section is referred to as the Capstan effect. In addition, because of the flexural rigidity of the product pipe, the increasing bending stress will also result in an increase of normal force between the pipe and borehole wall during crossing of curve sections. The frictional force increases and is referred to as the bending/stiffness effect.*
- *drag force of drilling fluid (caused by its viscosity): When the product pipe is pulled through the borehole, the relative movement between pipe and viscous drilling fluid produces a drag force* (Xufeng Yan et al. 2018, 163)

Different methods were proposed to estimate the pull load. Currently, the ASTM F1962 model (ASTM 2011) and the Pipeline Research Council International (PRCI) model (Huey, Hair, and McLeod 1996) are the most widely used estimation models (Yan et al. 2018). The ASTM F1962 model considers the Capstan effect but ignores the bending/stiffness effect and the ground surface friction. Although the ASTM method is explicitly intended for use with polyethylene (e.g., HDPE) pipe, and the PRCI method was initially developed for steel pipe, accounting for the relatively high bending stiffness of this product, both procedures have been used for estimating HDD pull loads for pipes of various material (Slavin and Scholl 2014).

Other common methods include Driscopipe (Driscopipe 1993) and Drillpath (Drillpath 1996), which do not account for mud drag and bending/stiffness effects (Baumert and Allouche 2002).

Slavin, Najafi, and Skonberg (2011a) present an extension of the ASTM F1962 method to account for the case where the entry and exit points are of different elevations, which affects the drag force. Slavin, Najafi, and Skonberg (2011b) account for this elevation difference when anti-buoyancy measures (e.g., water ballast) are employed.

Rabiei et al. (2016) propose a general method for estimating pullback force applied on polyethylene (PE) pipes during horizontal directional drilling (HDD) installations based on adapting the Capstan equation to a PE pipe negotiating a curved bore. This method supports any bore geometry. The paper claimed that this method and the ASTM method yielded more accurate results in comparison with the PRCI method.

Slavin and Scholl (2014) claim that it appears, based on the reported performance of pipes, that both the ASTM F1962 and PRCI methods are capable of providing reasonable results for design purposes for maxi-HDD installations. Based on two crossings, one using a steel pipe and the other using a PE pipe, Cai et al. (2017) compared six methods for pull load calculation: PRCI, ASTM F1962, Driscopipe, DrillPath, the PipeForce method (Cheng and Polak 2007), and the NEN 3650 method (Netherlands Standardization Organization), and found that the Driscopipe method and Drillpath method underestimate the maximum pulling forces in both cases, and the ASTM F1962 method underestimates the maximum pulling force in steel pipe cases, while the PRCI method and NEN 3650 method overestimate the maximum pulling force in polyethylene cases. It suggests that the PRCI method, NEN 3650 method, and PipeForce V1 method are suitable for steel pipe cases, while the ASTM F1962 method and PipeForce V1 method are acceptable for polyethylene pipe cases.

Ariaratnam and Botteicher (2009) evaluate the installation load on fusible PVC pipes from seven pipe installations and found that the estimations made using the ASTM F1962 model were in excellent agreement with the actual pull loads, measured using an inline load monitoring device, with the error ranging from around 0.6 to 22.5%.

In Baumert, Allouche, and Moore (2004), installation loads during 19 commercial horizontal directional drilling (HDD) installations were monitored using new in-hole monitoring cell technology. Fifteen of these installations were part of a 27,000 ft (8300 m) section of 8 in. (20.3 cm) diameter by 0.16 in. (0.4 cm) wall thickness steel gas distribution line. All data collected showed an approximately linear relationship between the length of pipe inserted and the increase in pulling force, except for local peaks that tended to dissipate quickly. The resistance to pipe advancement in the bore is strongly influenced by the characteristics of the surrounding soil, with pockets of well-graded sand and gravel causing a significant increase in recorded loads compared with those monitored in silty clay.

Moore et al. (2011) examined, through field and laboratory measurements and numerical modeling, the effect of cyclic pulling force histories on HDPE pipes pulled into place using directional drilling and found the following:

- Cyclic stress history results in steady increase in tensile axial strain at the end of each pulling cycle.

- Reasonable estimates of these tensile axial strains can be obtained by calculating creep under a constant axial pulling force.

- The ability of the HDPE pipe to survive those installation forces could be made by comparing that strain value with the short term (e.g. 24 hours) strain capacity of the material.

- Axial tension in the center of the pipe immediately after the end is released is about half the peak value that developed during installation; this value decreases with time, dropping in this example to about 1/3 of the peak after it is fixed, and down to 1/4 or less of the peak after 3 years.

- The use of current practice restricting short-term axial stresses in HDPE pipes to 9 MPa (1305 psi) should ensure that long-term axial stresses remain below the long-term allowable limits.

F.4.4.2 Operating Loads

According to Skonberg and Muindi (2014, 25), "*the operating loads imposed on a pipeline installed by HDD are not significantly different from those imposed on a conventionally installed pipeline. As a result, existing procedures for calculating and limiting stresses can be applied. However, unlike a cut-and-cover installation in which the pipe is bent to conform to the trench, a continually welded or fused pipeline installed by HDD contains elastic bends. Flexural stresses imposed by elastic bending should be checked in combination with other longitudinal and hoop stresses to evaluate if acceptable limits are exceeded. Those loads include internal pressure, bending, thermal expansion and external pressure*." Equations for calculating those loads are also presented in Skonberg and Muindi (2014).

F.4.4.3 Pipe Size

According to Allouche, Ariaratnam, and Lueke (2000, 70-71), "*72% of the total pipe product installed by HDD during 1995-1996 was 100 mm (3.9 in) or smaller in diameter. Products in this diameter range are typically utilized in telecommunication (e.g., fiber-optic), electrical conduits, and natural gas distribution systems. Sixteen percent of the total product line installed was in the range of 150–300 mm (5.9-11.8 in). Pipe and conduit over 300 mm (11.8 in) in diameter account for approximately 12% of all projects under-taken. The material of choice for horizontal drilling installations without doubt is HDPE, which accounts for approximately 62% of the total length of pipe installed. The second most common material indicated was steel, accounting for 23% of the total length of pipe installed. The utilization of steel pipe was found to be more common in the larger pipe sizes representing 31% of all pipe products installed in the 150–200-mm (5.9–7.9-in) diameter category and 92% of all pipe with 250-mm (9.8-in) or larger diameter. PVC pipe accounts for 15% of the total length of pipe installed during 1995-1996. 97% of all PVC pipe installed had diameters equal to or smaller than 100 mm (3.9-in).*"

F.4.4.4 Pipe Material

Steel and HDPE pipes have been used for HDD crossing projects for decades (Yan et al. 2018). Yan et al. (2018) describe the advantages of the relatively newer restrained joint ductile iron pipe (DIP) and fusible polyvinylchloride pipe (FPVCP™) which, according to the paper, have provided owners and designers with feasible alternative material options:

- *DIP requires a smaller curvature radius and site space than other pipes due to the ability to cartridge load the drill string rather than string out the entire fused or welded pipe string. The diameters of DIP installed by HDD range from 100mm (3.9-in) to 900mm (35.4-in) with achieved crossing distances over 500m (1640-ft). Joint strength is the key parameter in determining the maximum allowable pullback load of DIP; however, there currently exists no theoretical solution for different joints to accurately estimate pullback loads.*

- *Different from the classic PVC pipe, which is connected by bell or spigot joints increasing the diameter at the connection parts compared to the pipe body, FPVC™ provides restrained joints without a diameter change and the same tensile capacity of the pipe post-fusion. As a result of*

no increase in profile at the fusion joint, a smaller diameter borehole can be achieved, resulting in a smaller diameter backream and use of less drilling fluid. The high tensile strength of joints leads to a higher allowable pullback load, which is determined by the minimum tensile stress of PVC (48.26 MPa, 7000 psi) and a safety factor of 2.5. It maintains properties of PVC pipe such as corrosion resistance, high resistance to chemicals, high Hydrostatic Design Basis (HDB) and tensile strength, and no material relaxation time. Compared to HDPE, FPVC™ requires a larger bend radius. (Yan et al. 2018, 168-169)

Maidani, Fergerson, and Carpenter (2006) compare HDPE and ductile iron pipes (DIP):

- *The material strength of ductile iron is elastic under stresses up to the yield point (42,000 psi, 290 MPa) and not time dependent like HDPE which is a viscoelastic material where strength decreases with time.*

- *Temperature has no impact on the strength of ductile iron pipe unlike HDPE which is de-rated at temperatures exceeding 74 °F (23.3 °C).*

- *Ductile iron has more than 24 times the tensile strength of HDPE and 12 times more impact strength.*

- *Ductile iron pipe's larger inside diameter results in significantly more energy savings than HDPE pipe.*

- *HDPE pipe is permeable and should not be laid in soils contaminated with hydrocarbons.*

- *HDPE pipe fusion welding requires a highly skilled technician.*

- *The 40' (12.2m) and 50' (15.2m) lengths assembled into an assembled line of HDPE pipe can create logistical and equipment challenges in the field. Thermal expansion and contraction problems are not uncommon with HDPE pipe.*

- *HDPE fittings are most often fabricated and manufactures typically recommended a de-rating factor of 25% for any fabricated fittings.*

- *HDPE pipe is difficult to locate from the surface therefore requiring metallic tracing wire*

- *Based on 7 HDD installations, a cost comparison showed that HDPE pipes were more expensive because they required to be fused into a single assembled-line prior to pull back. This requires a substantial, unobstructed linear lay-down area for pipe that, on project sites. In contrast to the assembled-line method used with HDPE pipe, flexible restrained joint ductile iron pipe can be installed using the "cartridge" method*. (Maidani, Fergerson, and Carpenter 2006, 6-7)

Horton (2007), citing Carpenter and Conner (2003), lists more of the advantages of DIP over HDPE:

- *Liberal, allowable joint deflection with simultaneous joint restraint.*

- *No significant residual bending stresses that could adversely affect future serviceability remain in the pipe after pull-back.*

- *No significant "recoil" and minimal pipe movement after installation due to thermal expansion.*

- *Lack of movement and the inherent strength of ductile iron eliminates potential for shearing of tapped lateral outlets or breakage of pipe due to thermal expansion and contraction*. (Horton 2007, 3)

In addition, Horton (2007, 4-13) studied the corrosion of DIP pipes when using four commercially available drilling fluids: "*While previous corrosion studies in saltwater have shown the corrosion rate of unprotected DIP in this environment to typically be between 0.003 to 0.006" per year (0.008 to 0.015 cm per year), none of the drilling fluid "pure" mixtures (i.e. not mixed with soils) evaluated in this study would be considered corrosive to DIP. Average weight loss corrosion rates in all mixtures were less than 0.001" per year (0.003 cm per year) over the one-year test period. Results indicated the additions of corrosion inhibitors did not change corrosion rates on blasted coupons. However, they did result in significant improvement regarding attack on the asphaltic shopcoat.*"

Some examples of large-diameter pipe installations that employed ductile iron pipes were presented in Ehrin and Carpenter (2006) and Carpenter, Schwarzlose, and Whitaker (2005). Some examples of large-diameter pipe installations that employed FPVC pipes were presented in Shae, King, and Botteicher (2010) and Price, Olson, and Staheli (2015). In the latter, the paper mentions that the use of a plastic casing to incapsulate the 10 in. (25.4 cm) FPVC carrier pipeline, instead of a steel casing pipe, was a variance from the standards; however, its use allowed for deepening of the HDD bore path, which passed below a railroad, due to the smaller bend radius of plastic pipe versus steel pipe.

F.4.4.5 Pipe Coating

Hair (2002) experimentally examines the relationship between steel pipe coating wear and rock properties. The study concluded the following:

- *Coating loss due to abrasion from soil and very soft rock is not a critical problem in HDD installations. Initial tests were run in the rotary tester using soft rock samples (i.e. shale, mudstone). No coating wear resulted and the rock samples broke down during testing indicating that testing with very soft rock should be discontinued.*

- *Coating loss will occur during HDD installations through hard abrasive rock (i.e. granite, quartzite, hard sandstone). This loss has been conservatively quantified and can be mitigated by specifying the appropriate thickness of one of several available protective coating systems.*

- *The length and type of rock to be penetrated should be taken into consideration when specifying protective coating thickness. In general, bedrock with high unconfined compressive strength and Mohs hardness can be expected to be abrasive and cause coating wear.*

- *Point loads from sharp rock fragments and gravel will gouge coating. The depth of these gouges appears to be limited and coating integrity can be preserved by specifying the appropriate thickness of one of several available protective coating systems*. (Hair 2002, 8)

Hu, Xu, and An (2014) report the performance of epoxy glass fiber reinforced plastic coating in protecting HDPE pipes from damage due to sharp edges when drilling through stone. Although the coating was scratched, it remained intact, hence protecting the pipe.

F.4.5 Fluid Design

According to ASTM D6286-98, *"Water without additives is not effective as a drilling fluid for two reasons, first, it does not have any cuttings-carrying capacity, having a Test Method D6910 Marsh-funnel viscosity of only 26 s, and secondly, it does not possess any gel-strength properties for building a mud rind on the borehole wall, allowing for borehole wall collapse, differential sticking of the drill tools to the borehole wall, and creation of 'draining chimneys' due to fluid invasion and internal erosion of the borehole wall (Driscoll 1986; Shuter and Teasdale 1989). Also, water containing only natural clays should not be used as a drilling mud. This fluid mixture, containing only natural clays and water, will make only a heavy, clay-laden fluid that will not have the capacity (viscosity) to carry the drill cuttings uphole and will not make a thin mud rind on the borehole wall to inhibit its collapse (lack of gel strength). Instead, it will allow washouts of the borehole wall, fluid, and clay penetration into the borehole wall, and perhaps, cause differential sticking and loss of the drill tools in the borehole. Channeling and chimneys of sand also can result in the borehole wall allowing preferential seepage paths close to the borehole"* (8).

According to Ariaratnam and Allouche (2000b, 142), *"during the boring process, drilling fluid is injected under pressure ahead of the advancing bit. Drilling fluid is composed of a carrier fluid (typically water) and solids (clay or polymer). The carrier fluid carries the solids down the borehole, creating a mud cake along the perimeter of the borehole, thereby stabilizing the borehole and reducing friction during the pull-back operation. Drilling fluids also function as coolant for the electronics at the drill head and to suspend and transport drill cuttings to the surface and reduce the shear strength of the soil to enable easier displacement during the pull-back operation."*

Ariaratnam and Beljan (2005, 118) define the general guidelines of fluid design: *"For HDD, the proper drilling fluid mixture is heavily dependent upon the soil encountered. It must be formulated for the anticipated geological conditions. When drilling through sand and gravel, a drilling fluid needs to serve two important functions: stabilization of the borehole and suspension and transportation of cuttings. When drilling through clay, the same functions need to be performed; however, an additional requirement of the fluid is to retard swelling and reduce sticking of the soil to the downhole tooling and product line being installed. Geological conditions may vary between fine and coarse soils; consequently, different combinations of drilling fluid additives will be needed to perform the required functions under actual conditions. In general, for coarse soils, bentonite should be used, while for fine soils, polymers (possibly added to a bentonite base) are recommended."*

The main rheological properties of drilling mud that have been defined and can be measured include (1) funnel viscosity, (2) plastic viscosity, (3) yield point, (4) apparent viscosity (effective viscosity), (5) flow index, (6) consistency index, and (7) gel strength (Shu, Ma, and Lan 2014).

F.4.5.1 Fluid Modeling

There are three main rheological models that are most widely used when dealing with drilling fluids and include the following according to Ariaratnam et al. (2003):

- *Bingham Plastic Model: The Bingham Plastic Model has a linear relationship between shear rate and shear stress. It is the simplest rheological model and assumes true plastic behavior. This model has a yield stress that must be overcome before the fluid will flow. It assumes a flow index of n = 1, which is generally not the case in reality. The slope of the shear stress/rate curve is the fluid's plastic viscosity. This model has been adopted by the American Petroleum Institute (API 2010) to determine the circulating pressure in oil well drilling, but it can also be applied to HDD (Rostami 2017).*

- *Power Law Model: The Power Law Model is useful in describing drilling fluids that have a yield stress of zero. As a result, this model is well suited for representing polymer-based drilling fluids. This model is also accepted by the American Petroleum Institute (API 2010). This model is not as common as the Bingham model. It requires a six-speed viscometer device instead of two-speed viscometer device to calculate the rheological parameters of the drilling fluid (Rostami 2017).*

- *Herschel-Bulkley (H-B) Model: The Herschel-Bulkley (HB) or Yield Power Law (YPL) is a much more complex and sophisticated model. This model combines the features of both the Bingham Plastic and Power Law Models. When n =1, the YPL model reduces to the Bingham Plastic Model, and when the fluid yield stress is zero, the YPL model becomes the Power Law Model.* (Ariaratnam et al. 2003, 1336-1337)

Shu, Ma, and Lan (2014) build on those models and propose a refined model.

F.4.5.2 Fluid Drag

One of the forces that acts on the pipe, resisting its movement and hence increasing the required pull load, is the fluid drag. Fluid (viscous) drag is the amount of resistance to pipe movement due to slurry flow in the borehole. It results from viscous shear stress on the outer surface of the pipe, which is created by the interaction between the viscous fluid and the pipe within the bore (Faghih et al. 2015). According to Faghih et al. (2015, 1-2), "*Different methods vary in the method of calculation of this force. In early models of pullback force estimation, such as Driscopipe and Drillpath, the fluid drag is assumed to be negligible. ASTM F1962 assumes a hydrokinetic pressure estimated by considering a balance of the forces acting on the fluid annulus in the bore hole due to the hydrokinetic pressure and the lateral shear forces acting on the pipe and walls of the bore hole. In the PRCI model, the total fluid drag between the slurry and the pipe is estimated by a fluid coefficient of friction (μ_{mud}) multiplied by the external area of the pipe.*"

Baumert, Allouche, and Moore (2005) review many case histories of drag calculations and conclude that the current method used in HDD design for calculating annular frictional pressure loss, based on the assumption of Bingham plastic flow in a concentric annulus, is overly conservative. The paper reported that the calculation of fluid drag using PRCI method or ASTM F1962 is overly conservative, by as much as 1–2 orders of magnitude. The paper suggested characterizing annular flow in HDD with low shear rate drilling fluid rheology parameters and considering the effect of eccentricity in reducing annular frictional pressure loss.

Faghih et al. (2015) propose a new method to calculate the fluid drag, validate it using two case studies, and conclude the PRCI method overestimates the fluid drag. Rabiei, Yi, Bayat, Cheng, et al. (2016) also proposed a new method to estimate the fluid drag. The method takes into account factors such as product-pipe and drill rod eccentricities and is applicable to muds characterized as Herschel-Bulkley (H-B) fluids. For solving the problem of eccentric annular flow, the finite volume method (FVM) has been implemented to solve the fluid equation of motion numerically as a part of the procedure to determine the drilling fluid's return pattern through a bore. The new method was validated using two case studies and showed closer matches to the measured loads compared to the PRCI method, which showed a significant overestimation. Rabiei et al. (2017) proposed a new method for evaluating the hydrokinetic pressure and fluidic drag changes during the pullback operation in HDD pipe installation projects, assuming the slurry is a power-law fluid. The method was validated using the same case studies as in Rabiei, Yi, Bayat, Cheng, et al. (2016) and yielded slightly better results. Rabiei et al. (2018) suggested a series of simple methods for estimating the fluidic drag component of pullback force during HDD pipe installation operations, which are applicable to both Power law and H-B drilling fluids. The paper reported that the fluidic drag changed linearly with in-bore pipe length and concluded that the current PRCI equation can be followed, but a new fluidic drag coefficient, as presented in this paper, must be used. The fluidic drag coefficient is for the hydrokinetic pressure with a value of 350 Pa (0.05 psi) taken from the Dutch Standard NEN 2650, Requirements for Pipeline Systems (NEN 1992), as recommended by Rabiei et al. (2018).

F.4.5.3 Fluid Pressure

According to Rostami (2017, 30), *"Circulation of the drilling fluid through the annulus leads to pressure developing inside the borehole. Increase in the annular pressure arises from a clogged borehole annulus or a change in material properties of the drilling fluid. When the annular pressure is excessively high, it can cause shear or tensile failure of the surrounding soil, loss of drilling fluid circulation, and the inadvertent return of mud to the ground surface. The inadvertent return of drilling fluid to the ground surface is considered a critical risk to HDD projects due to the negative environmental and operational impacts."*

According to Sparks, Snider, and Sauls (2010, 1291-1292), *"Hydraulic fracture typically occurs when the drill path passes through relatively weak cohesive soils with low shear strength or loose granular soils. In general, very loose to loose sand, and soft to medium stiff silt and clay typically have a high hydraulic fracture potential. Medium dense to very dense sands and very stiff to hard silts and clays typically have a low to moderate hydraulic fracture potential. Inadvertent returns occur when drilling fluid emerges at the ground surface. In practice, inadvertent returns most often occur near the entry and exit points where soil cover is thin. Inadvertent returns can also occur along preexisting fractures*

or voids, at exploratory boring locations, or along the sides of existing structures such as piles or utility poles. Not all inadvertent drilling fluid returns are hydrofractures. In fact, true hydrofracture occurs in a small percentage of inadvertent fluid returns." The probability of a sudden increase in annular pressure is much higher during pilot drilling compared to other stages, primarily due to the small area of the annulus and cutting bed development at the bottom of the borehole, which increases the risk of hydraulic fracture (Rostami 2017).

According to Skonberg and Muindi (2014), the following can increase the risk of inadvertent returns:

- *Highly permeable soils such as gravel;*
- *Soils consisting of loose sands or very soft clays;*
- *Soil and bedrock materials with very low permeability but jointed or fractured (slickensided clays or rock fractures);*
- *Clay soils that have a tendency to swell in the presence of fluids;*
- *Considerable elevation differences between either the entry or exit point and ground elevations along the HDD alignment;*
- *Disturbed soils such as fill or in soils adjacent to piles or other structures;*
- *Areas along the HDD alignment where depth of cover is less than 40 ft (12.2 m);*
- *Locations along the HDD alignment where significant variations in density and/or composition of ground conditions are encountered (i.e., overburden/bedrock contact and other types of mixed-interface transition zones); and*
- *Use of inappropriate downhole tooling or drilling practices.* (Skonberg and Muindi 2014, 50)

Skonberg and Muindi (2014) note that predicting hydraulic fracture may identify areas of relatively higher risk and that, although drilling fluid and pumping parameters can be adjusted to reduce the risk of inadvertent returns, their possibility cannot be eliminated.

Studies have revealed that the two primary factors affecting hydraulic fracturing in soil are fluid pressure in the borehole and depth of cover. Fluid pressure in an open borehole is determined by the weight and resistance to flow of the drilling returns and is proportional to the bored length (Ariaratnam et al. 2003).

To prevent hydraulic fracture, two quantities must be calculated: the failure pressure at which hydraulic fracture occurs, and the fluid pressure through the borehole. At any point, if the fluid pressure approaches the failure pressure, hydraulic fracture is expected to occur, so maintaining the pressure at all points below the failure pressure helps prevent hydraulic fracture.

Failure Pressure

There are two common mechanisms of failure around the borehole (cavity) according to the shear strength of soil and initial stresses in the soil medium: tensile failure is a common type of fracture in cohesive soil at greater depths, and shear failure occurs in low-cohesive and frictional soils at shallow depths (Rostami 2017).

Luger and Hergarden (1988) propose the first model applied to predict the maximum allowable pressure of the drilling fluid following the shear failure assumption, which is known as Delft's method. The method assumes small strain, axial symmetric conditions, and linear elastic isotropic homogenous material behavior till yield is determined by the Mohr-Coulomb failure criterion (Rostami 2017).

Many drawbacks of the Delft's method are described by Yan et al. (2018, 166): "*Soil usually acts as anisotropic or transverse isotropic medium and hence the Delft equation could over-estimate the strength of normal consolidated soil, and provide a risk estimation of allowable fluid pressure during HDD. Additionally, soil properties and behaviors are quite different between clay and sand. The sand is purely frictional material (considered tensile strength is 0) with large grain and high hydraulic conductivity, and the mud can intrude and filtrate into the sand around the borehole. Therefore, it is necessary to analyze borehole instability mechanisms of clay and sand separately. The Delft equation attempts to predict maximum allowable pressure with a uniform equation for all soil mediums.*"

Yu and Houlsby (1991) propose an alternative large-strain cavity expansion derivation with the same assumptions. In the elastic zone, small strain was assumed, and, in the plastic zone, large strain was assumed.

Kennedy, Skinner, and Moore (2004) performed finite element method (FEM) analyses assuming a linear elastic behavior of soil to study the effect of the variation of the coefficient of earth pressure K_0 on the failure pressure. The paper considers the tensile mode of failure, which the Delft's equation does not consider. An equation for the failure pressure, alternative to the Delft's equation, is proposed. Based on its results, the paper concluded that the Delft equation generally provides unconservative estimates of failure pressure because of the assumptions on K_0 and mode of failure.

Large-scale laboratory experiments performed by Elwood and Moore (2008) showed that for uniform sand, the maximum internal mud pressures are well estimated employing either the solution described by the Delft solution or a finite element analysis model with reasonably accurate soil parameters. Other methods (Yu and Houlsby 1991) were found to overestimate the maximum internal pressures significantly. For a two-layer configuration, the Delft solution was found to underestimate the maximum pressure by around 33%. With a similar testing method and setup but different cover depths and lengths of the test borehole, Xia (2009) found that the Delft solution overestimated the maximum allowable mud pressure by 160% to 180%.

Xia and Moore (2006) propose a method to estimate the failure pressure in cohesive soils, which considers maximum plastic radius growth and different lateral earth pressure coefficients. Xia (2009) proposed an approximate closed solution for cohesive soil based on theoretical and numerical analyses as well as a design equation for sand based on the numerical analysis. Both equations, referred to as the Queen's equations, considered the anisotropic stress condition, rather than the isotropic condition used in the Delft equation (Shu 2018).

Lan (2018) distinguishes tensile failure (hydro-fracture) and shear failure (blow-out), as in Kennedy, Skinner, and Moore (2004) and Xia and Moore (2006), and mentions that the failure mechanism considered by the Delft Equation is the shear failure. In the study, the two failure mechanisms are

explicitly distinguished by new criteria that relate the ratio of undrained shear strength over effective vertical stress (S_u/σ_v') to K_0: "*For tensile failure, fracture initiation is defined as when effective (rather than total) hoop stress reaches tensile strength. Therefore, pore pressures (hydrostatic and excess pore pressure) should be considered. For shear failure, the Mohr-Coulomb failure criterion is used. Theoretically, hydro-fracture is likely to occur in brittle material (heavily over-consolidated clay or soil with Liquidity Index (LI)<0) while blow-out normally governs in plastic material (normally consolidated or lightly overconsolidated clay, or soil where LI>0). Several examples from the literature involving these two failure mechanisms were used to provide support for the criteria*" (Lan 2018, 552).

In the same study (Lan 2018), a series of medium-scale laboratory tests were performed in a 6.6 x 6.6 x 6.6 ft (2 x 2 x 2 m) pit, which was filled with hydro-sand and sandy-gravel. A hole was made into the sand body, and mud was pumped under pressure into the hole. Different burial depths to hole diameter (H/D) were tested and are classified accordingly into shallow, medium, and deep. The mud pressure history and radial, hoop, and axial stresses were recorded. Some of the most important conclusions are listed here:

- *The failure pressure increases with increasing burial depth.*

- *The Delft equation consistently overestimated allowable mud pressures at all burial depths, no matter whether $Pmax$ was found by calculating cavity expansion when yield (shear failure of the soil) reached two-thirds of the way to ground surface (the conventional approach used widely by consultants and contractors) or half-way to the ground surface. For the modified 'Delft Equation' (where the mud pressure limit is estimated as that which induces hoop strain around the borehole of 5%), $Pmax$ was overestimated at shallow depths (i.e., H/D < 10) but underestimated at the deep cover (where H/D >20) in these experiments.* (Lan 2018, 556)

- *Three pump rates were used in a set of experiments having similar H/D values. It was found that $Pmax$ is independent of pump rates. For the tests at the lowest pump rate, the post-peak phase was longer which indicates that more mud infiltrated into the soil surrounding the borehole, and the observed ground movements were the smallest. For the test at the highest pump rate, the failure consequence was dramatic and the number, width and depth of the cracks on the ground surface were the highest among the tests, likely because mud did not have time to infiltrate into the soil around the borehole and so contributed more to borehole expansion and ground uplift.* (Lan 2018, 556)

- *Three different thicknesses of loose sand layers were employed in tests having similar H/D values as the control (uniform dense sand) test. When the thickness of loose layers increased, the peak mud pressure decreased. Three different thicknesses of dense sandy gravel layers were used in tests having H/D similar to the control test. The trends in the peak mud pressure were then opposite to those tests involving loose sand layers: peak mud pressure increased as the amount of dense sandy gravel increased.* (Lan 2018, 557)

- *Small ground movements were observed near the maximum mud pressure $Pmax$ (values were usually less than 0.5 mm [0.02 in.]). However, the patterns of surface movement indicate that shear planes had developed in the soil prior to reaching that peak pressure. As further mud*

was pumped into the borehole and mud pressure decreased from P_{max}, ground movements began to increase significantly, with maximum ground movements occurring just before mud flowed out onto the ground surface. Once mud appeared on the surface, ground movements decreased from the maximum values. (Lan 2018, 562)

In Rostami, Yi, and Bayat (2016), the effectiveness of estimating the maximum allowable annular pressure during horizontal directional drilling (HDD) in non-cohesive soils by using two theoretical cavity-expansion solutions (Yu and Houlsby 1991), data of small-scale laboratory tests from Elwood and Moore (2008), and large-scale laboratory tests from Xia (2009) were used for validation. The limit pressures calculated using the two cavity-expansion solutions were higher than the measured failure pressures as a result of the assumption of uniform expansion to infinity. The Delft method was overestimating the pressure by around 2 times while the method of Yu and Houlsby (1991) was overestimated by 3.3 times, although the latter had a better correlation with the measurements, but with a factor of 3.3. The method of calculating parameters used to obtain those results are explained in Rostami, Yi, and Bayat (2016).

In Rostami (2017, 36), an experimental test setup was designed to simulate the formation of the cake on the surface of the sand during HDD: "*The results of the permeability test showed that the coefficient of permeability drops rapidly when using 2%, 3%, and 4% bentonite drilling fluid. During pumping, the flow rate of the drilling fluid with a constant head starts to increase at the initial stage when the drilling fluid fills the voids of the sand specimen; the flow rate then drops rapidly when the cake forms, thus preventing further penetration of the drilling fluid. UU triaxial shear tests showed that the shear strength of the specimen only slightly changed. The results implied that the formation of the cake prevented the drilling fluid from further infiltrating the sand specimen; thus, negligible amounts of bentonite particles were trapped in the sand specimen, which did not greatly impact the shear strength of the soil.*"

According to Shu (2018, 2), "*As HDD has expanded its application from soil and sand to bedrock, it has been noticed that the failure mechanism of surrounding bedrock is substantially different from that of surrounding soils. Buenker (2015) found the infeasibility of using the original Delft equation in bedrock, so he used the Hoek-Brown criterion in the cavity expansion theory and derived some analogous equations of the Delft equation for bedrock. These equations are still based on the cavity expansion theory, and the problem is that it is yet unknown whether the cavity expansion theory is suitable for bedrock or not due to the significant difference of material mechanical properties between soil and rock.*"

Fluid Pressure

Drilling fluid is pumped to the drill bit (or reamer) via the drill rod, is released into the borehole through nozzles, and then flows back to the entry or exit point with cuttings through the annular space (Shu and Ma 2016). Therefore, the maximum fluid pressure in the borehole occurs near the drill bit (or reamer) and decreases gradually along the borehole (Yan et al. 2018).

The fluid pressure is usually estimated using the models described in the previous section (F.4.5.1).

Rostami et al. (2015) and Rostami (2017) estimate the plan annular pressure using the Bingham and Power Law flow models with rheological parameters determined from a six-speed viscometer with varying shear rate ranging from 3 to 600 RPM. In Rostami (2017), the estimated pressures were compared to pressures from two HDD projects measured via wireline using an annular pressure tool sensor located within the orienting sub behind the mud motor:

> *For the Bingham model, which is the most widely-used model, the comparison indicated favorable results for the Bingham model at the low shear rate range of 100-200 RPM. Conversely, the results at high shear rate ranges of 200-300 and 300-600 RPM overestimated the measurement up to 30 percent on average along the drilling path and approximately 110 percent near the exit pit. Therefore, it is suggested that Bingham rheological parameters determined at low shear rate ranges, e.g. 100-200 RPM, be used for the prediction of annular pressure during pilot boring in HDD. This overestimation of fluid pressure is claimed to be too conservative, resulting in design costs increases of HDD projects. The study suggested to investigate other fluid models (e.g. Power Law model) in future studies.* (Rostami 2017, 81-82)

> *Using the Power Law model, the estimated pressures calculated with the five shear rate ranges from 3 to 600 RPM generally show a good agreement with the annular pressure measurements, and the best prediction is achieved by the range of 6–100 RPM. This range is very close to the recommendation (3–100 RPM) by API (2009). It is concluded that the Power Law method is more accurate in predicting circulating pressure since it accounts for the nonlinear relationship of the shear stress and shear rate (shear thinning behavior) and it also considers lower shear rates compatible with those of the fluid inside the borehole. Nevertheless, more validation using field measurements is needed before this method can be confidently applied to the industry.* (Rostami 2017, 32-33)

According to Yan et al. (2018, 167-168), "*Shu and Ma (2016) remarked that: because of the high ratio of boring diameter to the drill pipe diameter in large-bore HDD projects, the flow of the drilling fluid is laminar, and the rotation of drill rod has minimal impact on the fluid flow behavior. Subsequently, pressure loss in the borehole can be calculated, which is also the maximum mud pressure around the drill bit (or reamer). However, the borehole profile is often not a concentric circular shape and the roughness of borehole wall is difficult to determine. Accordingly, Yan et al. (2016) established a new method to calculate the maximum pressure in the borehole considering that the pumping pressure balances the circulating pressure and keeps the mud flowing, which can be measured on the ground, and that the circulating pressure is the sum of pressure losses in the drill rod through the bit nozzles and in the annulus. According to the paper, calculation of pressure losses in the drill string is accurate because of the uniform circular cross-sections of the drill rod and bit nozzles. Therefore, the method to predict maximum fluid pressure in the borehole by pumping pressure and pressure loss in the drill string provides a more accurate estimation than other approaches."* However, the calculated pressures in the case history presented in Yan et al. (2016) are significantly above the failure pressure estimated by Delft equations and the Queen's equations, which is questionable.

Construction procedures are an important factor influencing when and where drilling fluid loss occurs. If the contractor operates with inadequate pump volumes, inadequate drilling fluid

properties, or improper penetration rates, the annulus may become blocked through an accumulation of drill cuttings falling out of suspension; if the accumulation creates a blockage downhole, the annulus may become over-pressurized, leading to hydraulic fracturing and inadvertent returns (Sparks, Snider, and Sauls 2010). Adherence to good practices and preparing and following a surface spill and hydraulic fracture contingency plan can be very effective for reducing risks of inadvertent fluid return incidents and reducing potential consequences (Bennett and Wallin 2008).

If the hydraulic fracture evaluation indicates that high risks of hydraulic fracture exist at certain locations or segments of the HDD bore, Bennett and Wallin (2008) suggested employing measures such as relief wells, piezometers, conductor casings, and monitoring drilling fluid returns at the drill rig.

Mitigating Failure Risk

According to Skonberg and Muindi (2014), where HDD installations face a significant impact from inadvertent returns, the following may be considered:

- *Pressure while drilling (PWD) tool: This tool provides real-time data of annular pressures behind the drill bit. The tool can indicate sudden increases in annular pressures, which may indicate annular blockage or other problems.*
- *Drilling fluid testing: Frequent testing of drilling fluids being pumped downhole and returning to the surface provides relevant data to analyze for comparison with annular pressure calculations and to identify trends.*
- *Drilling practices: Drilling methods to increase the likelihood of maintaining drilling fluid returns during pilot-hole drilling include swabbing (retracting and reinserting each drilled joint) and the use of weeper subs, which introduces drilling fluid to the annulus along the drilled profile.*
- *Proper contingency planning is critical for an effective response to inadvertent returns. It is important not to delay or affect the HDD operations, particularly during prereaming or pull back. Planning should include:*
    - *Identifying methods of rapid detection (access to the drill alignment and associated areas);*
    - *Having suitable containment materials (silt curtain, hay bales, sandbags, excavation tools, plywood sheeting, etc.) at the HDD site to contain an inadvertent return in the event it occurs;*
    - *Identifying the length of time before cleanup begins (if in a traveled street then it is most likely immediate; however, it may be more suitable in other areas to allow the bentonite gel to set and dry);*
    - *Listing regulatory agencies that should be notified in the case of an inadvertent return event;*
    - *Establishing ingress/egress routes and methods into environmentally sensitive areas to minimize disturbance from equipment and personnel; and*
    - *Determining short- and long-term monitoring requirements, if any, for areas of inadvertent fluid release that are not accessible and where mitigating measures are*

impractical or not feasible (i.e., flowing waterways, inaccessible wetlands, etc.). (Skonberg and Muindi 2014, 50-51)

Burnam et al. (2002) describe the installation of a 100 ft (30.5 m) long 30 in. (76.2-cm) steel force main: "*A minimum depth beneath Trout Creek was established by performing a hydro-fracture analysis, based on cavity expansion theory. With the soils in close proximity to the bore path, a minimum depth of 7.6 meters (25 feet) below the creek was established. This minimum depth was specified, allowing the contractor to deepen the alignment at their choice. The pull-back forces, bending forces, and external hoop stress was then analyzed to determine the appropriate wall thickness of the pipeline. These calculations were based on the guidelines prepared by the Pipeline Research Committee of the American Gas Association (1995)*" (4). A hydro-fracture occurred near the exit point.

Performing pressure calculations (borehole stability analysis) might save a project from complications by reducing the chances of hydro-fracture. Gelinas et al. (2010) present a project where a hydro-fracture caused the authorities to change the construction method, preventing the completion of the bore with HDD. The design of the 771 ft (235 m) long, 15.7 in. (400 mm) diameter HDPE water pipe was to be installed at an invert depth of 14.1 ft (4.3 m).

Another example where pressure calculations were performed and the actual pressures measured is presented in Shell et al. (2012).

F.4.5.4 Fluid Carrying Capacity

The carrying capacity of drilling fluid represents the ability of the drilling fluid to transport cuttings. According to Shu and Zhang (2018),

> *The ability of the fluid to return transporting cuttings is very important for a successful HDD because:*
>
> - *If the cuttings cannot be transported out of the borehole in time the way of drilling fluid might be blocked, thus the drilling mud pressure in the borehole may dramatically increase, and hydraulic fracturing may occur due to the excessive mud pressure*
>
> - *The accumulation of cuttings at the borehole will increase the rotation torque of drill bit or reamers such that the drill bit or reamer may eventually get stuck in the borehole*. (Shu and Zhang 2018, 1)

Zeng et al. (2018) conducted a set of lab experiments to investigate the effects of different fluid parameters on its cuttings bearing performance. It was found that increasing the Yield Point and flow rate of mud results in a remarkable rise in transport distance of cuttings. The testing results indicated that once cuttings settle down and form a cuttings bed in the invent of the borehole, it is hard to clean up the borehole by increasing the Yield Point of mud or pump volume in both of directional and inclination HDD borehole. The study also found that the rotating drill rod can break and inhibit the

cuttings bed from forming in the HDD reaming process and increase the feasibility of large size cuttings transport in large diameter HDD projects.

F.4.5.5 Fluid Return

The fluid pumped is expected to flow back to the entry or exit point; however, the drilling fluid flows in the path of least resistance which can results in loss of circulation (seepage of fluid into the surrounding soil) or inadvertent return (seepage of fluid to the surface) (Watson 1995).

Shu and Ma (2016) studied the return of the drilling fluid and presented procedures based on a simplified borehole condition to estimate the mud returns to be expected on the job site. The study showed that "*the drilling mud can return to both exit and entry points of the drill path at the same time, while the percentages depend on the reamer, location of the reamer, and flow index. The location of the balance point, at which the volumes of drilling mud returning to the exit and entry points are equal, is not at the middle of the drill path but typically somewhat closer to the entry point. It is important to realize that during the pipeline pullback stage, most of the drilling muds return to the entry point, because this may be useful to understand the fluidic drag portion of the total pull force. In practical situations, the exit and entry points may be at different elevations which can affect the drilling mud return significantly. When the location of entry point is higher than the exit point, most of the time, the drilling mud only returns to the exit point and vice versa. It is possible that all the drilling mud only returns to the exit point or the entry point during the whole reaming process if the elevation difference is large enough*" (11).

Shu and Zhang (2018) studied the effect of the difference of elevation between the entry and exit points on the cuttings transport distance. The study developed an equation to calculate the cuttings transport distance was obtained based on the theoretical analysis and derivation. It found that "*the pump volume and the consistency index are the two main factors that affect the cuttings transport distance. The larger the pump volume, the larger the average drilling mud velocity in the annulus, and the longer the cuttings transport distance. It also showed that the higher the consistency index, the longer the cuttings transport distance. The flow index n has less effect on the cuttings transport distance; however, a small n value is very good to the cuttings transport because it can introduce a low settling velocity when the drilling mud circulation slows down or stops*" (7).

F.4.5.6 Fluid Recycling

Fluid recycling system design is critical to the successful implementation of HDD, especially for large-scale HDD projects. Shu et al. (2011) listed the considerations for designing the pump volume of mud recycling systems in the drilling and reaming process:

- *Mud volume should be enough to dilute the cuttings generated in the drilling or reaming process, so that the annular mud density is not too high, or else the drill bit or reamer may get stuck in the hole.*

- *Cuttings should be transported efficiently out of the hole, so the velocity of mud in the annuli is supposed to be of an applicable value.*

- *The pump volume may also depend on the stratum because different stratum generates cuttings with different diameter and density.*

- *The bigger the diameter of the reamer, the bigger the pump volume needed.* (Shu et al. 2011, 2052)

Shu et al. (2011) concluded the following:

- *Drilling mud in large-diameter and long-distance HDD projects is much more important than those in medium and small HDD projects, since the consumption of bentonite may up to several thousand tons.*

- *The volume of drilling mud needed in drilling or reaming processes is still not available precisely and the theoretical research on that is not well done, so an empirical equation is used to get an approximate value which is much smaller than the practical value. (Shu et al. 2011, 2057)*

F.4.5.7 Fluid Mix Design

The fluid design may be adjusted to account for difficult ground conditions. Ariaratnam, Lueke, and Anderson (2004, 165) pointed out that "*For HDD, the proper drilling fluid mixture is heavily dependent upon the soil encountered. It must be formulated for the anticipated geological conditions. For simplicity, soil conditions may be defined as either a coarse soil (sand and gravel) or a fine soil (clay, silt, and shale). When drilling through sand and gravel, a drilling fluid needs to serve two important functions—stabilization of the borehole and suspension and transportation of cuttings. When drilling through clay, the same functions need to be performed; however, an additional requirement of the fluid is to retard swelling and reduce sticking of the soil to the downhole tooling and product line being installed. Geological conditions may vary between fine and coarse soils; consequently, different combinations of drilling fluid additives will be needed to perform the required functions under actual conditions. In general, for coarse soils bentonite should be used; for fine soils polymers (possibly added to a bentonite base) are recommended. When drilling through sands and gravel, drilling fluids may migrate out of the bore into the native soil formation.*"

Ariaratnam, Lueke, and Anderson (2004) stated that the primary objective of fluid mix design is to achieve and maintain borehole stability. At the same time, the drilling fluid shall maintain pumpable during the drilling process by a proper viscosity. *"Historically, contractors have approached gravel and cobble bores from the standpoint of using drilling fluids with excessively high viscosities (i.e., the thicker the better). Viscosity is defined as the resistance to flow. As the viscosity of a drilling fluid increases, the force required to push the fluid through the annular space increases. Annular space, which is comprised of drilling fluid mixed with native soil, is defined as the region between the outside diameter of the installed product pipe and the wall of the borehole. Therefore, the pressure exerted on the surrounding formation is amplified. This factor results in greater losses of drilling fluid into the formation and a higher potential for inadvertent returns (i.e., fluid migration to the surface). Considering the high permeability and porosity of the gravel/cobble formation, reducing the loss of fluid to the formation, and maintaining manageable fluid properties are of paramount importance.*

Unfortunately, many contractors choose to formulate the base drilling fluid with high-yield bentonite. This practice results in an initial fluid with excessive viscosity prior to the addition of supplementary products. The use of extended yield bentonite materials provides lower filtration rates and allows for higher concentrations of bentonite to be added to the base system without resulting in the development of excessive viscosities" (166).

Additionally, Ariaratnam, Lueke, and Anderson (2004) mentioned that the development of baseline gel strengths is necessary for suspension properties of drilling fluid mix design:

> *The baseline gel strength properties developed by extended yield bentonites such as Bore-Gel are effective, but require enhancement from xanthan-based polymers to suspend coarse materials. These polymeric additives, such as No-Sag, enhance suspension properties of the drilling fluid with only a moderate increase in viscosity. Unfortunately, the nature of gravel/cobble environments is such that additional suspension is necessary to address the obvious requirements. The drilling fluid formulation is now at a point where increasing the concentration of bentonite or polymers will render the fluid impossible to pump. It should be noted that a certain degree of viscosity is unavoidable in order to obtain the properties necessary for success. However, it should be the objective to limit viscosity as much as possible so as not to create conditions that are detrimental to the outcome of the bore. The development of fibrous additives, such as Barolift, enhances suspension properties through mechanical means without an increase in viscosity. Barolift [*Figure 18*] is a treated polyfiber, which with adequate shear during mixing develops a matrix to enhance suspension properties and improve hole-cleaning efficiency. BoreGel, No-Sag, and Barolift have proved to be very effective, but they still do not address the subsequent loss of large volumes of whole drilling fluid to the formation. A product that was easily mixed, and compatible with rig pumps and mixing equipment was chosen to address this problem. The product would not adversely affect viscosity and would reduce the loss of drilling fluid to the formation. The product chosen was N-Seal [*Figure 19*] a fibrous loss of circulation material. The addition of N-Seal reduces the loss of fluid to the formation and enhances hole-cleaning efficiency. It should be noted that all of the drilling fluid components have respective Material Safety Data Sheets indicating that these components contain no hazardous substances.* (166)

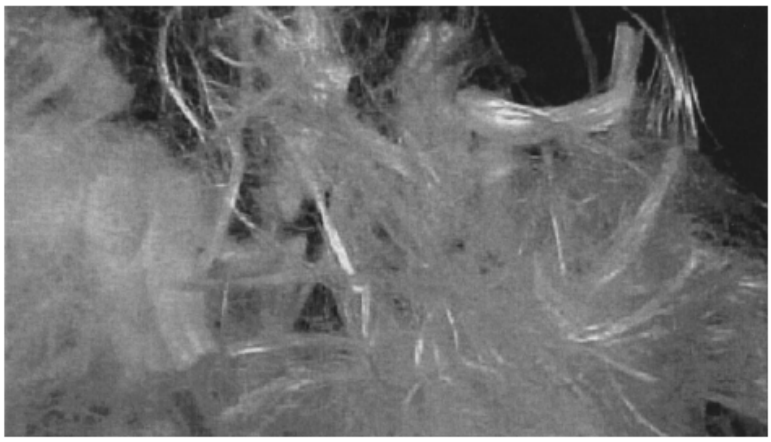


Figure 18. Photo. Barolift fiber additive (Ariaratnam, Lueke, and Anderson 2004).

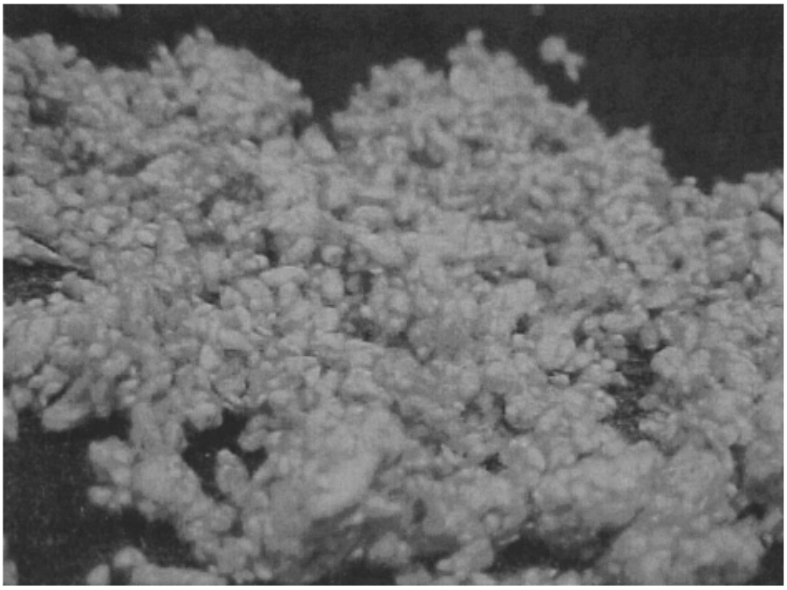


Figure 19. Photo. N-Seal fiber additive (Ariaratnam, Lueke, and Anderson 2004).

Furthermore, Cai, Wu, and Gu (2011, 2088-2089) pointed out that *"As one kind of drilling fluid additive, LG vegetable gum has excellent performances in terms of thickening, fluid loss control and lubrication, a certain extent of salinity tolerance and strong inhibitive capability. Its performances had been confirmed by several coal drilling and scientific drilling projects. LG vegetable gum can be acquired from the leaves of natural Lauraceous plants. It has good filtration control ability, excellent lubricating capability and obvious anti-sloughing effectiveness. Basing on the lots of lab tests, its optimal amount in drilling fluid was determined as 2.0 weight percent."*

F.4.6 Construction Equipment

F.4.6.1 Steering and Tracking

Steering

Ariaratnam and Allouche (2000b, 143) describe the two common types of downhole steering tools used in the industry, compaction heads and mud motors: "*Compaction heads are used in unconsolidated soils and soft to medium consolidated soil conditions (i.e., silt, clay, sand, and soft sandstone). To bore a straight hole, the drill string is rotated and pushed simultaneously. When a correction in direction is required, rotation stops and the drill head is preferentially oriented in the borehole. The entire drill string is then pushed forward by the drill rig. As the slant on the face of the drill head is pushed against the soil, the entire assembly is deflected in the desired direction. After the steering correction occurs, rotation is resumed until another correction is required. Mud motors, are used in ground conditions ranging from hard soil to medium rock. This system uses a positive displacement motor, which generates torque and rotation at the drill bit from the flow output of the mud pump. Direction control is attained by a small bend in the drill string, just behind the cutting head, which serves the same function as the slant on the face of a compaction head.*"

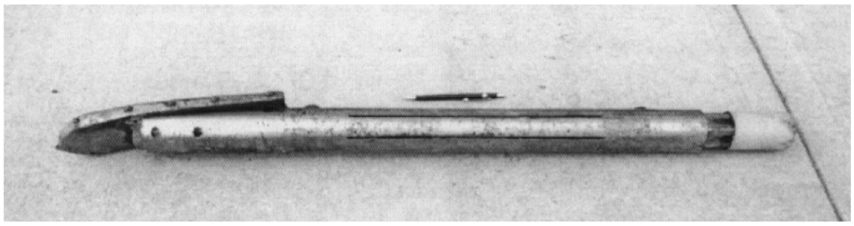


Figure 20. Photo. Compaction drill head (Ariaratnam and Allouche 2000).

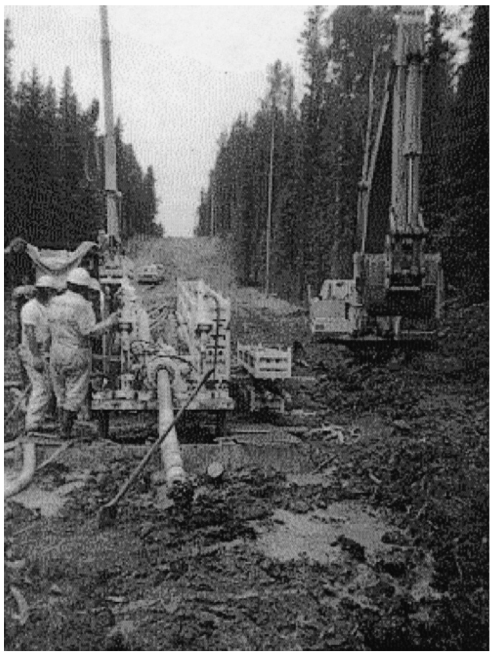


Figure 21. Photo. Mud motor assembly on HDD rig (Ariaratnam and Allouche 2000).

Tracking

The drilling head's position, depth, and orientation are tracked during drilling, and this information is communicated to the rig operator who uses this information to steer the bit. Ariaratnam and Allouche (2000b) describe the two common methods used for tracking, the walkover and the wire-line systems:

> *A walk-over system consists of three components: a transmitter (or sonde), a receiver, and a remote monitor. The transmitter is located in the borehole assembly near the front of the drill string and emits a continuous signal which is received by the receiver, a portable hand-held unit then displayed on the remote monitor. Accuracy of this system may be assumed to be within 65% in terms of the drilling head's true depth (Allouche and Como 1997). Transmitters are available for operational depths of 10, 15, or 30 m (33, 50, or 100 ft).*
>
> *When access to a location directly above the borehole alignment is not possible, or when borehole depths exceed 30 m, wire-line systems (magnetic or gyroscopic) are used. Magnetic systems uses three magnetometers to measure the position (or azimuth) of the tool in the*

earth's magnetic field and three accelerometers to measure the position (or inclination) of the tool in the earth's gravitational field. The steering tool sends the information by wire line to a computer at the surface, where the tool's azimuth and inclination are calculated. The information provided by a wire-line system is considered to be accurate within 62% in both plan and profile, regardless of the borehole's depth (Allouche and Como 1997). Those systems may suffer from magnetic interference when magnetic anomalies (like near metallic objects or cables) are present. Disadvantages of these systems include the high capital costs and need for expert operators. Gyroscopic systems rely on gyroscopes and are not affected by magnetic anomalies. Those systems suffer from drift, but this drift maybe reduced by using north-seeking gyros. (Ariaratnam and Allouche 2000b, 143)

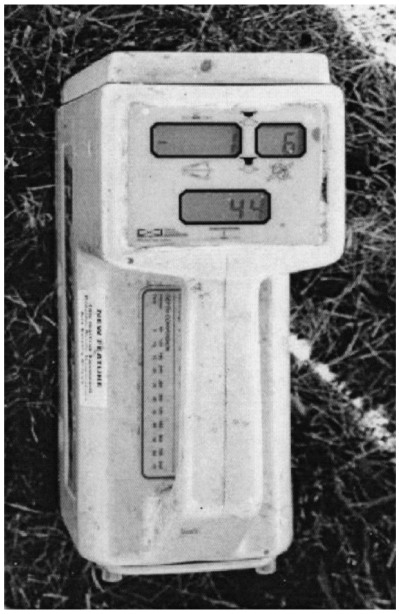


Figure 22. Photo. Walk-over tracking device (Ariaratnam and Allouche, 2000).

An alternative or supplementary monitoring option is surface monitoring which locates the downhole probe by inducing a magnetic field in a surface coil of a known location. The probe senses its location relative to this magnetic field and communicates this information to the surface (Watson 1995).

Accuracy and Tolerance

According to Skonberg and Muindi (2014, 17), *"The actual drilled path cannot be constructed exactly on the specified drilled path. Differences between the specified drilled path and the actual drilled path are caused by the downhole tooling and the driller's ability to control changes in direction plus the inaccuracies in downhole surveying methods and variations in subsurface conditions. Allowable deviations from the specified drilled path must be provided taking into account constraints at a particular location. This is particularly critical where HDD is being used to install a gravity sewer. The required line and grade tolerances may not be achievable or may be achievable only after multiple pilot holes have been attempted."*

F.4.6.2 Reaming

According to Allouche, Ponnam, and Shu (2012, 1343-1344), "*the key function of a reamer is to enlarge the borehole to a size sufficient to accommodate the installation of the required pipe product. In addition, the reamer, which houses the jets that discharge the drilling fluids, mixes the soil and/or rock cutting with the drilling fluid to create slurry that can be displaced to the side of, or discharged out of, the borehole to allow room for the pipe product. The resulting cavity should be stable to accommodate the pipe product. Reamers vary in their performance metrics including cutting and mixing capacities, fluid discharge, borehole stability, torque, slurry formation and suspension and transport of the cuttings. They vary in design by in shape and optimal orientation of the cutters, length and weight of the reamer, total contact area with the borehole wall, number, area and location of nozzles, and, number and placement of the teeth.*"

Allouche, Ponnam, and Shu (2012) describe the different parts of a reamer:

- *Compaction Cone: Compaction cone in a reamer serves to enlarge and stabilize the borehole. Size of compaction cone determines the size of the borehole that is formed during the reaming operation. Stability of the borehole can be improved by increasing the length of the compaction cone.*

- *Cutters or cutting teeth: Cutting capacity of a reamer is governed by the capacity of the cutting teeth. The orientation of the cutting teeth varies with the soil type. For soft soils, like clayey and loam soils, the orientation is not as aggressive when compared to medium to rough soil conditions (i.e. gravel cobble). Cutters are usually replaced so that they can be removed when worn out. The number of cutting teeth depends on the soil conditions, torque requirement and cutting capacity.*

- *Nozzles: Nozzles supplies the drilling fluid that assists in cutting and keeping the cutting face clean. The placement of the nozzles on the reamer is usually behind the cutting teeth and spread from the shaft to the compaction cone. Rearward facing nozzles are provided to assist in better formation of slurry and to keep the rear part of the reamer clean. The pressure drop across the nozzles is a function of the flow rate, nozzle diameter and number of nozzles. In reaming operations flow rate is considered to be more important than fluid pressure. Thus, orifice diameters are sufficiently large to accommodate a high flow rate at optimum pressure and velocity.* (Allouche, Ponnam, and Shu 2012, 1344-1345)

Allouche, Ponnam, and Shu (2012) also describe the properties of the reamers for different soil conditions:

- *Reamers of clayey soils [Figure 23]: The primary concern in clayey soils is breaking up the clay into small chunks that can be mixed with the drilling fluid to create flowable slurry. If too large, cuttings can ball up on the reamer and increase the amount of pullback force required to install the product pipe. Borehole stability is typically not an issue in clayey soil so principal features to be used in clayey soils includes a minimal surface area in the case of a cutting reamer to avoid balling up of clay and adequate number of high-pressure jets to promote*

cutting, mixing and cleaning of the cutting faces. The reamers used in clayey soils are either compaction (or barrel type) or fly cutter types.

- *Reamers for sandy soils [Figure 24]: Problems encountered when drilling in sandy soils include high resistance to pulling back the product pipe and borehole instability. The reamer must have good mixing capacity to form flowable slurry, pump sufficient volumes of drilling fluid to account for losses of drilling fluid due to percolation into the sandy soil and allow the drilling fluid to flow along the incoming pipe product towards the exit end of the hole. Hence, it is important to consider the size, number and location of nozzles as well as passage of slurry from the front end of the reamer to the rear end, while designing the reamer.*
- *Reamers for rocky formations [Figure 25]: In rocky formation the reamer experiences high lateral loads in addition to torque and drag forces due to the applied tensile load, load distribution among the cutters, rock failure mechanics, torsional loading, and normal force loading due to reamer bending. Reamers for rock formations works like a hole opener, grinding the hard rock. Drilling fluid discharge rate should be adequate to form slurry and avoid the problem of unstable borehole.*
- *Reamers for cobble/gravel formation: Cobble/gravel formations present the most unfavorable condition for carrying out HDD installations. Cobble/gravel is loose hard rock where borehole stability is a significant challenging. Reamers for this formation type should incorporate aggressive cutting features together with an outstanding mixing capability to form a stable borehole*. (Allouche, Ponnam, and Shu 2012, 1346-1347)



Figure 23. Photo. Reamer used in clayey soils (E. Allouche, Ponnam, and Shu 2012).

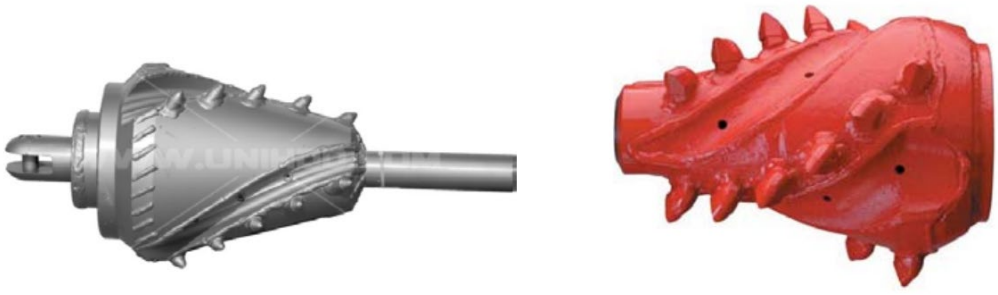


Figure 24. Photo. Reamer used in sandy soils (E. Allouche, Ponnam, and Shu 2012).



Figure 25. Photo. Typical reamer used in rock formation (Allouche, Ponnam, and Shu 2012).

Albert (2013) describes the different types of reamers used, and the problems associated with each of them:

> *Reamers come in various styles and shapes, they can be categorized in three main categories being conical reamers, a combination of fly cutters and barrel reamers and a combination of hole openers and stabilizers. A conical reamer is as per the description a conical style reamer that relies on the first conical part of the reamer to centralize itself in the hole, it is basically a cutter reamer with a conical base which will help in pushing large particles aside so the product can pass. The fly cutter has a small contact surface packed with cutting teeth for smooth cutting of the formation, the blades in the reamer and position of the nozzles help in the proper mixing of the cuttings with the drilling fluid. A hole opener is a reamer for rock and can functionally be compared with a fly cutter, conclusions for this reamer style is similar with the conclusions for the fly cutter, instead of a barrel a so-called stabilizer is used which can be a part of the hole opener body or separate and mounted in front of the hole opener.*
>
> *Conical reamers are traditionally used with smaller rigs while larger rigs are mostly using a combination of a fly cutter and a barrel reamer. At first a fly cutter is used to open the pilot bore up, the potential error is similar with the error described with the first reaming stage when using a conical reamer. For any additional reaming stages a barrel reamer will be installed in front of the fly cutter. The barrel reamer is equipped with cutting teeth, however no cutting outside the outside diameter of the reamer, the barrel will act as a stabilizer keeping the centerline from the new hole as close as possible to the centerline of the previous reamed hole.*
>
> *While the target is to have the reamer follow the exact profile/path that the drill head has made, a reamer is just like the drill head, a tool that is mechanically cutting soil or crushing rock following the path of least resistance regardless the position of the pilot hole. The potential deflection from the pilot bore depends on the reamer type, the reaming operation metrics, the soil conditions and the smoothness of the pilot bore. Pulling fast on a reamer*

might pull the reamer upwards in the hole because of the high pulling force, high pulling forces on the rods in combination with rotation results in the tendency of the rods to move upwards in the hole which is commonly known as the cheese wiring effect. Pulling very slowly on a reamer might result in a downward movement of the reamer because of its heavy weight and continuous cutting on the formation. Cheese wiring can be minimized by limiting the pullback force at the back of the reamer, pre-reaming does help in limiting the potential deflection of a reamer down hole. (Albert 2013, 1096-1097)

After the hole is reamed to its final diameter, one or multiple swab passes are sometimes performed before pulling the pipe. This swabbing helps in removing cuttings, hence enhancing the drilling fluid flow, and in making sure that the hole has no problematic areas.

Front and rear centralizers are sometimes used in limiting the subsidence of heavy reamers during the reaming process, as presented in Figure 26 from Zhu and Yi (2018).

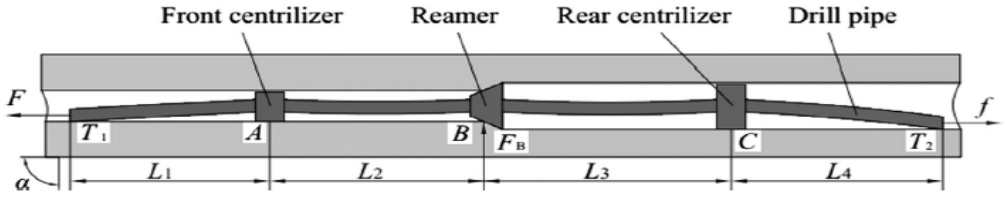


Figure 26. Figure. Centralizers used to limit the subsidence of heavy reamers (Zhu and Yi 2018).

F.4.6.3 Drill Rods

Drill bits and reamers are attached to drill rods that convey the push load and torque of the rig to enable boring operations. Those drill rods may fail because of excess loading or because of fatigue. Failure of drill rods while drilling can cause huge economic losses due to loss of equipment, time loss because of the need of boring a new hole and might lead to complications and litigations. Drill rods are subject to axial loads, torsion loads, and flexural loads.

According to Ma, Sterling, and Allouche (2005, 2), "*All three kinds of loads when applied in a cyclical fashion can cause fatigue failure. Drill rods experience axial forces from the compressive thrust during drilling and the tensile load during pullback, flexure when it is forced into a curved path below ground and torsion from the torque applied to rotate the drill bit during pilot hole drilling or the reamer during pullback.*"

Ma, Sterling, and Allouche (2005) found that the type of material of drill rod, flaws within the drill rod, and corrosion are important parameters that determine fatigue failure susceptibility. From a series of lab tests and FEM analyses, the study developed a fatigue failure prediction equation that concluded the following:

- *The fatigue failure of mini-HDD drill pipe can preferentially occur either at the joint or at the body of mini-HDD drill pipes depending on the drill pipe type.*

- *The fatigue failure prediction equation developed for the oil industry by Grondin at University of Alberta matches reasonably closely to the fatigue curve developed in the current research but provides a more conservative estimate for the mini-HDD pipe tested.*
- *The stress concentration factor at the drill joint has an important influence on the fatigue failure of mini-HDD drill pipes. The FEA analyses show that the stress concentration factor for bending in the drill joint is about 3.0 compared to a simple bending stress estimate in the drill rod body.*
- *Bending fatigue is the key factor in deciding the fatigue life of mini-HDD drill pipes.*
- *The cost of fatigue damage to mini-HDD drill pipe during curved drilling becomes significant as drilling radii drop below 100 ft (30 m).* (Ma, Sterling, and Allouche 2005, 14)

F.4.7 Alternative Construction Methods

Many alternative construction methods were developed to overcome limitations in typical HDD construction. Skonberg and Muindi (2014) describes three of those methods:

- *Drill and Intersect Method: consists of drilling pilot holes from each side of the installation and intersecting the pilot holes. Intersecting pilot holes require a great deal of drilling precision. The benefits of implementing this method should be carefully weighed against the level of experience of the drilling contractor. This method significantly increased the achievable length of HDD installations in the past few years.*
- *Multiple Line Installations: where a bundle of lines are placed in one drilled hole. Different ways of doing this are described in Skonberg and Muindi (2014)*
- *Casings: used to provide strength to resist installation loads as in the case of an HDPE within a steel casing. HDPE may have been selected because of its resistance to corrosion during operation, but it may not have the tensile capacity to resist installation loads over a long drilled segment. The steel casing provides the structural strength needed for HDD installation. Casings are rarely used in HDD installations because they require an additional step in the construction process and thus increase cost*. (Skonberg and Muindi 2014, 17-18)

Some examples of HDD installations that employed the intersect method were presented in Tu, Ma, and Zhao (2011) and Zhang, Zhou, and Ma (2011).

Maidani, Fergerson, and Carpenter (2006) describe another method, the Cartridge Method:

> *In contrast to the assembled-line method used with HDPE pipe, flexible restrained joint ductile iron pipe can be installed using the cartridge method. This method allows for the installation of one joint at a time. A single joint is assembled on to the bell joint of the previous pipe then the assembled unit is pulled into the bore path the equivalent of one joint length, stopped, and a new single joint is added* (Figure 27)*. This process is repeated until the line is installed complete. The cartridge method is ideally suited for HDD projects in congested urban areas because it requires only a very small staging area.* (Maidani, Fergerson, and Carpenter 2006, 5-6)

Orton (2008) describes three more methods:

- *Bore Salvage Method: which is used to free stuck pipes by attaching a pipe rammer to the end of the partially installed product pipe a fabricated sleeve for example. A winch is used to assist the rammer during operation. In many cases, the percussive power of the pipe rammer is enough to free the stuck pipe and allow it to be removed from the ground* [Figure 28].

- *Pullback Assist Method: The pullback assist technique works directly on getting the product pipe installed. When drilling underwater or in loose flowing soil conditions a condition known as hydrolock, in which the external pressure being put on the product pipe from ground water pressure, drilling fluid pressure and/or soil conditions exceeds the drill rig's pullback capability or the product pipe's tensile strength, can occur. The percussive action of a pipe rammer in this situation is used to help free the immobilized pipe* [Figure 29].

- *Conductor Barrel Method: in which casings are rammed into the ground, at a predetermined angle, until desirable soil conditions are met. The spoil is removed from the casing with an auger or core barrel. Drilling proceeds within the casing in the desirable soil conditions. In addition to assisting drilling operations at the start, the conductor can also serve as a friction-free section during pullback. The Conductor Barrel is claimed to prevent situations in unstable soils, where drilling fluids under pressure force their way into waterways or wetlands, by acting in a similar fashion to containment cells* [Figure 30]. (Orton 2008, 1-3)



Figure 27. Photo. An HDD project employing the cartridge method (Maidani, Fergerson, and Carpenter 2006).

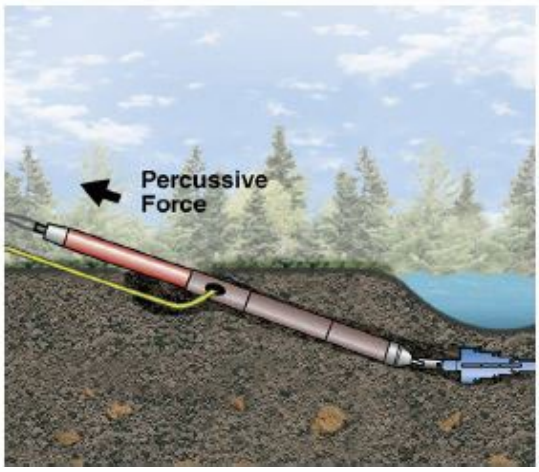


Figure 28. Schematic. Bore salvage method (Orton 2008).

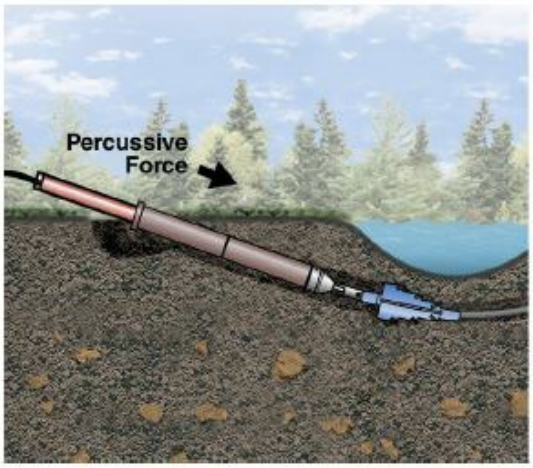


Figure 29. Schematic. Pullback assist method (Orton 2008).

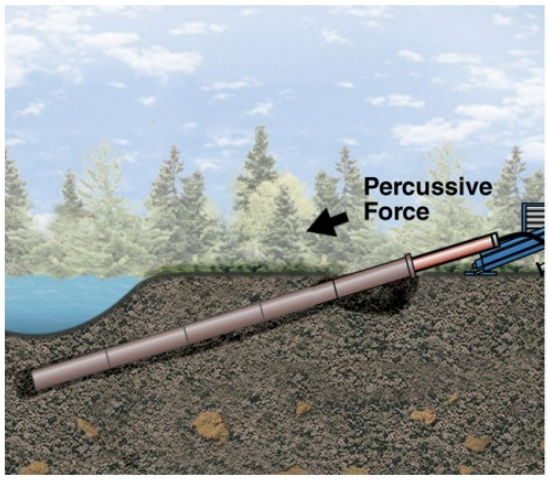


Figure 30. Schematic. Conductor barrel method (Orton 2008).

Kong et al. (2013) describe two buoyancy control methods:

- *Buoyancy control using PE pipe filling with water [Figure 31]: is the generally method being used, which is to insert one or several PE pipes into the product pipe, filling all the PE pipes with water while pullback, output volume should be suitable to the pulling back speed. Diameter of PE pipe is estimated based on the specifications of the product pipe and density of drilling mud in the borehole, and the ideal state is that the net unit weight of product pipe be dropped to 0, but it's difficult to achieve in field. This method has some limitations:*
  - *there must be water source in the job site, and it needs lots of water*
  - *suitable generator, water pump and other equipments are needed during pulling back, and the cost is high*
  - *it does little help to the borehole condition such as large cuttings and increasing of annular pressure*
  - *it does no help when pull force getting bigger because of dirty borehole condition or slightly*
- *Open Type Pullback Method: in which the drilling fluid is used instead of water for buoyancy control. A special pullhead with openings and connection subs for the PE pipe and product pipeline is used. Prior to pullback, the PE pipe is connected to the pullhead with long bolts to the inner connection sub at first, then the product pipeline is welded to the outer sub of the pullhead. When pipeline be pulled in, drilling mud in the borehole flows into the PE pipe continuously through the openings. When pullback is completed, drilling mud in the PE pipe can be discharged with sand pump or compressed air, and then pull out the PE pipe for reuse.* (Kong et al. 2013, 1695-1696)

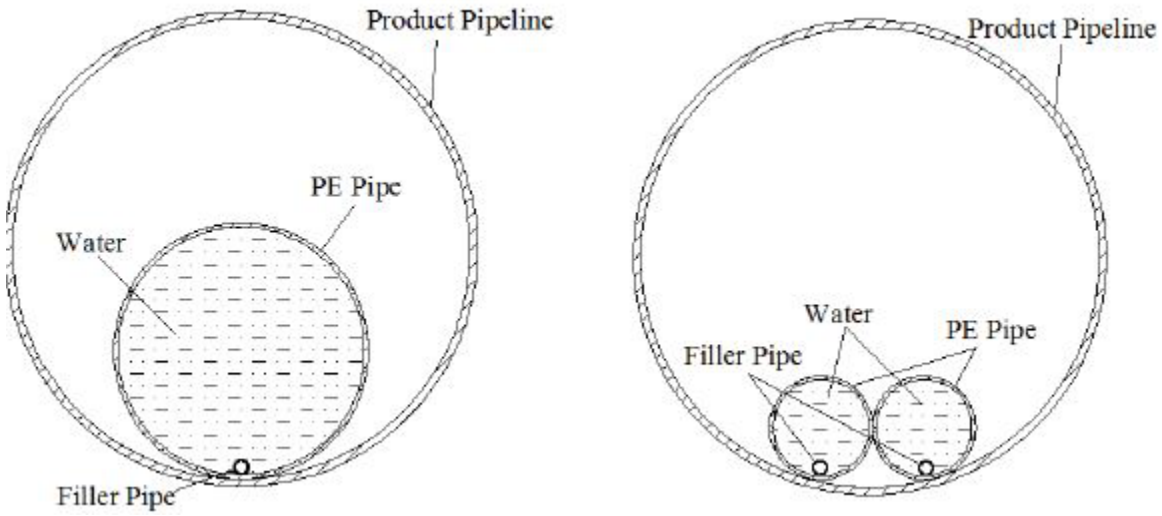


Figure 31. Schematic. Buoyancy control using PE pipe filling with water (Kong et al. 2013).

In some circumstances, operating or continuing the HDD construction activities during nighttime is needed or can provide a solution to some daytime construction limitations; examples include many river crossings where the continuous circulation of fluid in the boring is required (Ariaratnam 2001).

Ariaratnam (2001) presents considerations and recommendations for nighttime HDD, primarily emphasizing the need for additional lighting around the work area and well-lit signs along with standard traffic control measures to maintain public safety despite the typically-reduced public presence and to ensure quality performance.

Shu and Zhang (2018) describe a technique that employs front reaming and one-way drilling mud return in order to force the return of the drilling fluid to the entry point, enabling its recycling:

> *Front reaming with one way drilling mud return: There are normally two scenarios of non-level drill holes: A. the exit point is higher than the entry point; B. the entry point is higher than the exit point. In scenario A, the drilling mud tends to flow back to the entry point (lower side), where the drill rig is located, and therefore the drilling mud can be recycled.*
>
> *In scenario B, the drilling mud tends to flow to the exit point. If the elevation difference is very big, there may be even no drilling mud return to the entry point. Recycling drilling mud, which is essential in large HDD projects were tons of drilling fluid is pumped every minute, then pumping it back to the entry point where it can be reused, requires extra pumps and solid control facilities and is typically hard to implement. Besides, without the support of drilling mud pressure at the empty borehole section, the borehole wall may become unstable. In reality, due to the limitation of drilling techniques and/or the site topography, scenario B sometimes is inevitable in mountain areas. For example, due to the limitation of mud pump capacity, it is difficult and sometimes even impossible, for the mud pump to send the drilling mud to a high elevation if it was drilling up.*
>
> *If the exit point was not drilled through, or it was sealed after drilled through, all the drilling mud may only return to the entry point which is the so-called one-way drilling mud return. This can be achieved naturally by not drilling through the exit point in the pilot drilling phase, or manually be sealing it with cement for example.*
>
> *After the pilot hole was completed, the drill rods and the drill bit are pulled back to the entry point side. Then, each cycle of front reaming process starts from the entry point and stops at the same location as the pilot hole stops. After all the front reaming cycles are completed and the borehole diameter has reached the designed size, the end portion may be drilled through.*
>
> *Front reaming has limitations including the risk on drill rods because they are vulnerable to buckling due to operating in compression. One way drilling mud return has limitations including the risk of hydrofracture due to the elevated pressure especially in long installations.* (Shu and Zhang 2018, 2)

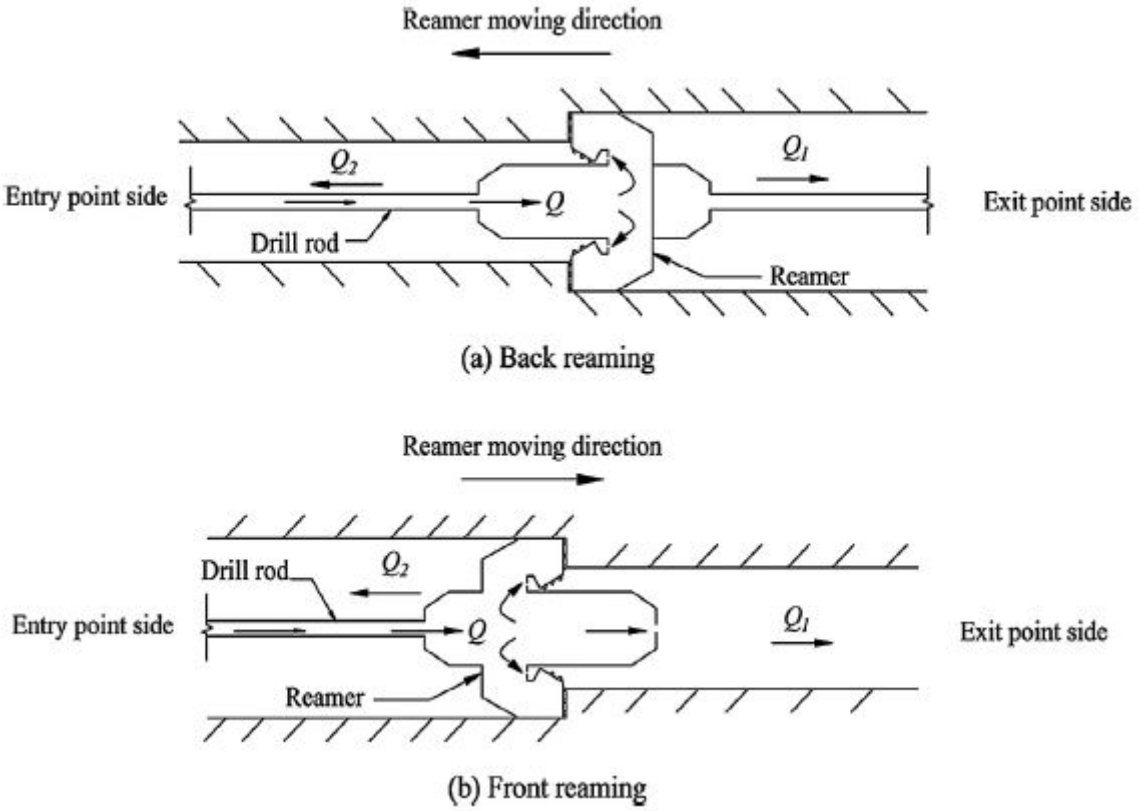


Figure 32. Schematic. Difference between (a) back reaming, (b) front reaming (Shu and Zhang 2018).

Burman et al. (2009) describe a system, called OnGrade, for installing gravity sewers which is capable of controlling the grade to the tight limits imposed by this application:

> *OnGrade Method: During pilot drilling, to be able to maintain the grade of the pipe, the OnGrade™ HDD method uses grade-capable beacons (sondes) with a pitch resolution of 0.1% grade. A laser plane with a dial in grade capability is established at or near the start of the bore. The grade of the laser plane is set to match the desired grade for the sewer installation. This system includes a special grade poll on which the tracker system is mounted, which is in communication with the tracker system. Laser receiving sensors incorporated into the grade pole allow it to measure the height of the laser plane above the tracker unit. The electronics described had a functional depth limit of 30 ft (9 m).*
>
> *The pipe should be inspected after installation. A few methods which may be used for inspection are a water test, pouring a known quantity of water into the installed pipe from one end and collecting the water at another end. If a large quantity of water is lost in transition, it is an indication of the presence of a dip in the installed pipe. Commercial camera systems are also available which include pitch sensing elements for plotting the profile of the installed pipe. Additionally, the camera systems provide a visual indication of any dips along the pipe if water is introduced prior to the inspection.* (Burman et al. 2009, 846-847)

The factors that affect the applicability and economic feasibility of using this method according to the paper are 1) soil conditions, 2) depth of the installed pipe, 3) number of connections, and 4) length of the laterals.

Cherrington (2002) describes a setup where HDD rigs are equipped with a forward-thrusting system, which has similarities with the micro-tunneling systems, and pipes extended inside the product pipe, which are used to provide buoyancy control and to transport drilling fluid back to the entry point while controlling the pressure behind the cutting head. The paper claims that this method is becoming economically feasible because of the need to extend utility crossing distances beyond 6562 ft (2000 m) and because of its ability to control the pressure behind the cutting head, which is very valuable for avoiding hydraulic soil fracture.

Stauber, Frame, and Kedzierski (2003) describe a case where grout was injected during pipe pullback to fill the overcut annular space between the pipe and the boring:

> *The grout was designed to meet specific performance criteria. In order for the grout to displace the bentonite drilling slurry in the borehole, it needed to be heavier than the slurry. The maximum expected drilling slurry weight for this project was 11 pounds per gallon. The permit required the grout to achieve a maximum unconfined compressive strength of 50 psi (345 kPa) within 48 hours. The grout needed to stay flowable for at least 24 hours in the event pullback was interrupted due to mechanical failure or other problems.*
>
> *Since the pullback would take several hours to complete it was necessary for the grout to remain flowable and pumpable for an extended period of time including periods of pumping and periods when the pump would be stopped to allow a drill rod to be removed. Probably the most important characteristic of the grout was its resistance to flash setting. Flash setting occurs when grout loses water to the surrounding soil formation. The water is squeezed from the grout due to the higher pressures within the grout column. The associated rapid decrease in the water to cement ratio triggers an acceleration of the hydration process causing the grout to set up rapidly. Several failed pullbacks have been attributed to this phenomenon.* (Stauber, Frame, and Kedzierski 2003, 998)

Stauber, Frame, and Kedzierski (2003, 1001) conclude that "*three HDD installations were successfully completed while injecting cement grout through the reamer during pullback. The cement grout was designed to meet specific performance criteria including density, unconfined compressive strength, consistency, cyclic pumpability, and resistance to flash setting. While injecting cement grout during HDD pullback is considered a risky operation, using a grout that is specifically designed for HDD applications can enhance the probability of a successful outcome. The need for grout in the annulus should be carefully evaluated before attempting to grout during HDD pullback. Other options such as the use of tremie tubes should be considered.*"

Steitle, Hooten, and Issa (2013) describe the challenges and solutions in an HDD project with grouting. During construction, the pipe floating is possible due to the low-density grout. It was determined that the grouting operations would need to take place in multiple lifts in order not to

float the pipe. The pipe segments would be filled with water in order to add weight and prevent floatation.

F.5 PERFORMANCE AND QUALITY CONTROL

Researchers have studied the performance of HDD, specifically its impact on the ground above and its effect on the pipe being installed.

F.5.1 Impact on Ground and Structures

Ground movements due to HDD installations might result in damage to structures and embedded utilities. Those movements may happen over the short or the long term.

According to J. D. Hair Associates and PRCI (2008, 27), "*Short-term, immediate settlement and sinkholes can occur when the reamed hole is empty during periods of drilling fluid circulation loss or with significant elevation differentials between end points. Sinkholes are more common in loose non-cohesive soil, especially near the entry and exit points where cover is shallow. Large diameter reaming tools moving in and out of the hole can accelerate the process. Rapid sinkhole formation on an HDD installation can be a threat to public health and safety. When they occur next to friction piles, sinkholes might result in a reduction of their load carrying capacity and possibly to settlement of structures. Long-term settlements along the drilled alignment can occur as the annulus of the drilled hole fills in with soil after installation.*"

Ariaratnam and Beljan (2005) studied the development of the properties of the annular space around the pipe after the completion of the HDD. The study consisted of installing three HDPE pipes, of diameters between 4 and 12 in. (100 and 300 mm), in two different soil mediums, clay and sand, in Canada. Subsequently, the pipes were excavated, and visual and strength measures of each of the installations were taken at different periods ranging between 1 day and 1 year after installation. Reamers used were 1.5 times bigger in diameter compared to the product pipe.

The authors made the following observations:

- *Small voids may initially be present in cohesionless soils, but more solids are present in the annular space region, thereby providing support to the installed product pipe. No voids were detected in any of the installations in the cohesive soil.*
- *The shear strength of the annular space is dependent on the characteristics of the native soil and its reaction with water. As was evident when comparing the clay and sand installations, the state of the clay annular space was far more solidified than the sand installation. It also exhibited strength and cohesive characteristics while the annular space in sand was fluid-like. In addition, the sand installations did exhibit initial voids. Measures of the unconfined shear strengths of the annular space in the clay soil medium indicate that it reaches about 70–80% of the native soil after 1 year.*
- *The annular space was discovered to change in shape, texture, composition, shear strength, and moisture content from cross section to cross section. In all cases, the diameter of the annular space region decreased over time to the point that it equalized or consolidated with the native soil.*

- *Surface monitoring points showed that no ground settlement occurred on the short and long terms.* (Ariaratnam and Beljan 2005, 124-125)

Based on those observations, Ariaratnam and Beljan (2005, 125) concluded that "*the six pipes installed and the 28 cross sections that were excavated and analyzed support the opinion that the annular space does provide the necessary attributes for the short-term and long-term success of a pipe installation using horizontal directional drilling.*"

Lueke and Ariaratnam (2003) studied the impact of the major horizontal drilling parameters on surface deformations which are, according to the study, borehole pressure, depth of cover, soil density, backream rate, soil composition, annular space, and reamer type and diameter. The study focused on four of those parameters: the borehole pressure, depth of cover, backream rate, and reamer type. The depth of cover used was either 41 or 53 in. (105 or 135 cm); the reamers used were 7.9 in. (20 cm) in diameter and were either fluted or spiral; the borehole pressure resulted from two drilling fluid rates of 19 and 38 gal/min (72 and 144 L/min), when adjusted for altitude are closer to 13.2 and 26.4 gal/min (50 and 100 L/min), and the backream rate was either 2 min/rod or 6 min/rod. Consequently, 16 different combinations were tested. Those 16 combinations were employed in 4 HDD installations, i.e., changing the combinations four times over the length of each installation.

Ground movements were recorded after the drilling and backream phase of each installation utilizing a rod and level. Surface heave was observed after both the drilling and reaming phases. During the drilling phase of the installation, ground movements ranged from 0 to approximately 1 mm; for the reaming phase, vertical ground displacement ranged from 0.08 to 0.24 in. (2 to 6 mm).

From comparing the results, the paper concluded (as summarized in Lueke and Ariaratnam [2005]):

- *Low drilling fluid application rates, or mud flow, produced greater surface displacement with almost all combinations of factor levels, and had larger displacements than those installations conducted with the higher flow rate. There is an inverse relationship between mud flow and surface heave.*
- *Installations conducted at the 900 mm (35 in) depth with the slower backream rate had greater surface displacements than those conducted at the faster backream rate. With increasing depth, the difference between the magnitudes of displacements exhibited between the slow and faster backream rate diminished. An exception to this pattern was the 1,200 mm (47 in) deep installation utilizing the fluted reamer, as it produced greater surface heave at the faster backream rate.*
- *Regardless of depth and mud flow rate, the spiral compactor type reamer generally induced greater surface displacements than the fluted reamer.*
- *In general, shallow installations produce greater surface heave than deeper installations. For installations conducted with a slow backream rate, the difference between the magnitude of the installations at 900 and 1,200 mm (35.4 and 47.2 in.) depths were smaller than those installed with the faster backream rate. There is an inverse relationship between surface heave and depth of cover.*

- *Reamers may behave differently depending on drilling practices utilized*. (Lueke and Ariaratnam 2005, 647)

J.S. Lueke and Ariaratnam (2003, 839) state that "*based on the framework presented in this paper, future research could be conducted to expand the explored factor space by the inclusion of the original four factors not selected. Factors such as soil composition and density, reamer diameter, and annular space would enhance the applicability of the model and provide greater insight into factor interaction. Additional factors such as the effect of the water table and drilling fluid composition could also be added to this framework. Through this model, guidelines may be developed based on construction methodology, or drilling practice, to minimize ground movements.*"

Adedapo (2007) presents a field investigation that consisted of installing two 7.9 in. (200 mm) HDPE pipes 4.9 ft (1.5 m) beneath flexible pavement using HDD and open-cut construction methods while instrumenting the pipe and monitoring the pavement during and after the installations. According to the paper,

> *The condition of the pavement in the vicinity of the installed pipe was observed prior to and after pipe installations to identify any changes in pavement condition that may have resulted from the pipe installations. The pavement was also examined throughout the long-term monitoring period to determine the influence of pipe installations on the pavement structure performance. Surface elevation survey data, ground penetration radar (GPR) surveys, Falling Weight Deflectometer (FWD) and distress surveys were conducted to evaluate pavement performance. There was no observable change in the condition of the pavement structure performance in the vicinity of the HDD installed pipe following pipe installation. The elevation survey and pavement surface distress data indicated that there has been no change in elevation, no crack or other visible pavement distress at the HDD installed pipe location. FWD and GPR survey data also showed that the pavement structure integrity was not altered by the HDD pipe installation. The effect of frost at the HDD installed pipe location was similar to the rest of the pavement. Therefore, no discontinuity was created in the pavement as the result of the HDD installation.*
>
> *Despite the use of best construction practices, the traditional buried pipe installation technique resulted in a noticeable hump more than 25mm (1 in) in the pavement section in the vicinity of the buried pipe. The patch pavement section started to show signs of surface distress after the first year following pipe installation. The construction joint between the repair section and the existing pavement has widened considerable allowing infiltration of water into the pavement. Infiltration if not addressed could subsequently leads to alligator cracking and may cause structural damage. GPR survey revealed that the pavement section was significantly altered by open-cut installation. The deflection data from the FWD test also showed that the repair section is not as structurally sound as the undisturbed pavement sections.* (Adedapo 2007, 336)

F.5.2 Ground Surface Movement Monitoring

Monitoring ground surface movements is traditionally done using surveying triangulation, geometric leveling, and global positioning system (GPS) surveying (Lueke et al. 2012). Lueke and Ariaratnam (2010) studied the use of photogrammetry to monitor ground movements during HDD and claimed that it appears to be suitable for a large diameter HDD. Photogrammetry is the science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant imagery and other phenomena. Lueke et al. (2012) compile and list the following benefits for photogrammetry:

- *Simultaneous measurement of all targets/surface points in the area monitored (all targets in the camera's field of view can be measured)*
- *Fast measurements (each measurement set requires a minimum of two pictures, more are preferable, and the measurement of all targets is complete in the time required to take the pictures)*
- *Minimal equipment required (camera and tripod, with a computer to process the photos)*
- *No specialized equipment required (typically, the equipment required to monitor ground movements, a camera, is generally standard issue for a foreman or superintendent)*
- *Minimal training required for operator (operator must be familiar with operation of camera and how to stage pictures for optimal area coverage)*
- *Quick turnaround for results (after downloading pictures to the computer, software can analyze photos in a matter of minutes and provide Cartesian coordinates for all targets included in the photos)*
- *Measurement without access to targets (measurements can be made without having to access the area where the targets are located).* (Lueke et al. 2012, 25)

Lueke, Pinghe, and Ariaratnam (2011) compare the results of photogrammetry to conventional rod and leveling techniques through a full-scale field trial and found that it is effective and accurate. J.S. Lueke et al. (2012) report that measurements taken using photogrammetry were on average within 1 mm (0.04 in.) from measurements taken using traditional leveling techniques.

Lan et al. (2018) present and compare the three methods used to monitor ground movements in experiments designed to investigate horizontal borehole instability due to excessive mud pressures: particle image velocimetry, structure for motion, and multi-view stereo, and LiDAR (light detection and ranging). The experiments were conducted in a 2 x 2 x 2 m (6.6 x 6.6 x 6.6 ft) pit filled with sand monitored by three cameras placed in different positions. Three factors that impact the stability of bores were studied: ratio of the depth of cover to bore diameter, pumping rate, and multi-layering of soil (dense sand overlain by different thicknesses of loose sand or dense sandy gravel). The study focused on how these factors influence maximum allowable mud pressure and showed that the three monitoring methods yielded relatively similar results. Lan et al. (2018) commented on the high financial and time cost of LiDAR and the challenges in establishing clear reference points for the particle image velocimetry and structure for motion and multi-view stereo methods.

F.5.3 Pipe Performance

F.5.3.1 HDPE Pipes

Adedapo (2007) presents a field investigation that consisted of installing two 200 mm (7.9 in.) HDPE pipes 1.5 m (4.9 ft) beneath flexible pavement using HDD and open-cut construction methods while instrumenting the pipe and monitoring the pavement during and after the installations. According to the paper,

> *Field test results show that the HDD installed pipe have significantly lower construction induced strains and ring deflections when compared to the open cut-and-cover installation. The two pipes performed satisfactory over the long-term monitoring period as deflections and strain levels were below acceptable limits and there was no apparent deterioration of the pipe. Pipe deflections resulting from environmental effects (freeze and thaw) were found to be more significant than those due to material creep.* (Adedapo, 2007, iii)

> *The mechanism that produced deformation in open cut is different from that of HDD. There is no axial load imposed on open-cut installed pipe and the pipe does not negotiate any bore trajectories. Open cut installed pipe construction induced deformation and bending strain that progressively increased during the installation and compaction of backfill lifts. The maximum change in pipe diameter measured at the end of installation in the HDD and open-cut installed HDPE pipe was 0.4 and 1.2 mm (0.02 and 0.05 in) respectively. The change in diameter of the HDD installed HDPE pipe immediately after installation using Plastic Pipe Institute design equations was about 100 percent higher than the field measured deflections.* (Adedapo 2007, 333)

> *The performance of the HDPE pipes was continuously monitored for a period of about three years following installation. At the end of the monitoring period, the measured field deflection data indicate the HDD installed pipe had experience gradual cumulative decrease, approximately -0.75mm (0.03in), in the horizontal diameter and approximately +0.2mm (0.008in) change in vertical diameter at the end of the monitoring period which indicating that the pipe deflected outwardly in the vertical direction. The maximum change in pipe diameter of the HDD and open-cut installed pipe measured during the long-term monitoring period were approximately 1.2 and 0.75 mm (0.05 and 0.03 in), respectively.* (Adedapo 2007, 334-335)

Gelinas, Polak, and McKim (2000) present the results of two 200 mm (7.9 in.) diameter HDD installations 55 and 90 m (180 and 295 ft) in length bored in dense fine sand overlaid by 1 m (3.3 ft) of silty clay. In each case, a pressure transducer was attached to the drill rig hydraulic system and strain gauges were installed close to the pull-head. Measurements were taken during the pullback operations and for several hours after the installations were completed.

The study concluded the following:

- *The amount of axial force required from the drill rig for pull back increases as the length of pipe within the borehole increases. Much larger axial strains were recorded for the 90m (295ft)*

than for the 55m (180ft) pull. However, it should be noted that the 55m (180ft) pull was pre-reamed to 343 mm (13.5 in.), as opposed to 305 mm (12 in.) for pull.

- *The curvatures of the borehole impose bending deformations on the pipe. These deformations can produce large tensile and compressive stresses in the pipe. Larger borehole diameters decrease the bending deformations. Larger bore path angles also decrease bending deformation.*

- *For any specific point within the bore path, the strains produced in the installed pipe during pull-back operation are approximately the same.*

- *Following installation, some strains are released immediately due to the elastic rebound. However, a significant amount of the measured strains remains in the installed pipe.*

- *The pulled pipe experiences torsional deformations during installation. These deformations can have influence of the material and structural behaviors of the pipe during both pulling and further utilization. More research and detailed measurements are needed to establish the magnitude and significance of the rotation of the pipe. The presented conclusions are based on only two tests of HDD installed pipes. These tests were performed at the same location and under almost ideal installation conditions. More field testing and research is needed to validate the described findings and to gain more information about the behavior of HDD installed pipes.* (Gelinas, Polak, and McKim 2000, 136-137)

Ariaratnam and Colwell (2002) present the results of three 60 m (197 ft) long field installations of HDPE using HDD ranging in diameter between 100 and 300 mm (4 and 11.8 in.) installed in cohesionless soil. Pressure transducers recording the drilling rig pressures used in generating thrust/pullback, torque, and drilling fluid pressure were installed. Linear potentiometers were installed inside the pipes to measure their axial strain and an external load cell was used to measure the loading on the pipe during pullback (separate from the load on the reamer). The study concluded the following:

- *The machine pullback pressures increase as more of the product pipe enters the borehole during the pullback process. In relation to the installed pipe diameter the pullback pressures are greater for a larger diameter pipe.*

- *The rotational pressures experienced by the drilling rig during the pullback process remain relatively constant throughout the length of the installation. Fluctuations occur in these pressures, and the drilling rig experienced larger fluctuations in rotational pressure for larger diameter installations.*

- *Loading on the pipe during the pullback phase increases as more of the product pipe enters the borehole. The magnitude of the loading was responsive to the installed pipe diameter as the load was greater for a larger diameter pipe. The loading on the pipe displayed the same trends as exhibited by the pullback pressures experienced by the drilling rig during the pullback operation.*

- *Strain on all of the installed diameters did not exceed 0.2%. This magnitude of strain is well below the 5% point where permanent structural damage may occur. For the two smaller diameter pipes the strain increased gradually over the installation length, suggesting that longer installations may approach a response of 5% strain.* (Ariaratnam and Colwell 2002, 9-10)

Polak, Duyvestyn, and Knight (2004) present the results of five 200 mm (7.9 in) diameter field tests 90 to 177 m (300 to 580 ft) in length of instrumented polyethylene (PE) pipes installed using HDD. The instrumentation used included pressure transducers installed on the feed and return of hydraulic pull back lines, strain gauges, pressure transducers to measure slurry pressure in the borehole, thermocouples for temperature monitoring, and a load cell placed in a pulling head. The HDD parameters studied were the quality of the drilling fluids, the ratio of borehole to pipe diameters, pipe material, and construction sequence. Those parameters were varied during the testing program to evaluate their influence on pipe behavior. The study concluded the following:

- *Pulling loads and axial straining of the pipe result from a combination of mechanisms contributing to the friction between the pipe, the soil and the drilling fluid.*

- *Borepath geometries, both vertical and in plan-view, impact pulling loads and strains.*

- *The decrease of the overcut ratio between the pipe and the borehole results in an increase in the pulling force*

- *Proper assessment of friction, both pipe–soil and pipe–fluid, is essential in rational modeling of pipe behavior in HDD.* (Polak, Duyvestyn, and Knight 2004, 216)

Once the pulling head of the pipe is released at the end of pullback, the pipe recovers part of its extension; the immediate drop in the pipe extension is related to elastic recovery, whereas the gradual decrease is related to the time-dependent viscoelastic recovery (Chehab and Moore 2011). Chehab and Moore (2011) developed a one-dimensional model, implemented in FORTRAN Program HDDPIPE, to calculate the short- and long-term response of pipes installed using HDD. It considers gravity forces and pipe-soil interaction forces, as well as viscous drag force due to mudflow past the pipe. The pipe-soil interaction model accounts for adhesion, friction, and the stiffness of the soil medium. The program estimations were verified by comparing them for a theoretical problem with those of widely used methods that estimate pulling force. An example was used to demonstrate that the new model can also predict the cyclic nature of the axial stress histories, not just the maximum stresses estimated by other algorithms.

Chehab and Moore (2010) present a theoretical parametric study, using the computer code "HDDPIPE," to examine the effect of the following parameters on the short and long term stresses in HDPE pipes: pull-back procedure, duration of the pull-back, pipe diameter, friction with borehole, effect of overstressing the pipe, and effect of filling the pipe with water or mud. The study concludes the following:

- *Slower installation rates usually lead to higher pipe strains during installation. Long-term stresses are also higher when installation is slower. Therefore, pipes used in slower installations should be designed using higher axial strength (low term allowable tension). ASTM (1999) recommends different safe pull stresses for different installation durations. For example, safe pull stresses of 9.0 and 7.6 MPa (1305 and 1102 psi) are recommended for HDPE pipes for installation durations of 30 min and 24 h, respectively. However, rapid installations may lead to construction complications if not performed properly and carefully. For example, blockage of the borehole will lead to additional pulling load and possible failure of the operation.*

- *The friction coefficient between the pipe and the ground surface outside the borehole has a smaller effect on the short- and long-term response of the pipe than the pipe–borehole friction coefficient. This is especially true for empty polymeric pipes where net buoyancy forces inside the borehole are substantially higher than the normal forces due to pipe weight when it is outside the borehole. Wet installation where the pipe is filled with water or mud is an effective method of reducing friction in the borehole, though the friction between the pipe and the ground surface then becomes more significant.*

- *Even though larger pipe size leads to significantly higher installation loads, the resulting short term and long-term stresses and strains are not significantly affected as long as the standard dimension ratio (SDR) is kept unchanged. Based on the results of the parametric investigation, the axial load close to the center of the pipe immediately after installation is approximately equal to half the peak installation load applied at the end attached to the drill string. Given that tensile stresses usually decrease with time, conservative calculations of service life could use half the maximum axial stress during installation as the long-term stress for comparison with long-term stress limits to prevent tensile fracture. More sophisticated and less conservative estimates can be obtained using program HDDPIPE.*

- *High installation loads cause higher axial stresses over the entire service life of the pipe. This can increase the likelihood of crack propagation and increase the potential for ring fracture in the barrel or at the welded joints. Most of the examples considered in this study have long-term stresses that remain below long-term stress limits typical of those for HDPE pressure pipes, though the calculations for thinner pipe demonstrate that the control of installation loads is necessary to ensure that long term axial stresses stay within acceptable levels*. (Chehab and Moore 2010, 793-794)

In Cholewa, Brachman, and Moore (2010), 26 HDPE pipes were tested in the lab to investigate the response of an HDPE pipe to cyclic loading, similar to that experienced during HDD, in the short- and long-term. The outside diameter of the pipe is around 167 mm (6.6 in.); the wall thickness is around 10 mm (0.4 in.); the length of the test pipe is around 500 mm (20 in.). The applied load is in the axial direction. The soil-pipe interaction was excluded from the study. Tensile axial stresses and strains in the pipe were quantified during cyclic loading, strain recovery, and stress redevelopment after the pipe is restrained, leading to the following conclusions:

- *During a typical HDD installation, the HDPE pipe being installed experiences a complex stress and strain history including periods of rapid loading, creep, rapid unloading and strain recovery as the pipe is pulled then released to remove each subsequent drill rod. During installation, axial strains progressively accumulate as the pipe is installed. This may be followed by a period of axial strain recovery. Subsequently, the pipe can be axially restrained which may lead to a build-up of axial tensions.*

- *It was shown that the maximum strain of the HDPE pipe samples depends on the magnitude of the pulling force, length of pipe installed, and drilling rod length. Longer lengths of pipe installed and increased pulling forces led to higher maximum strains. When the allowable pulling stress was exceeded by a factor of 1.5 the axial strain accumulated was 8.3%, surpassing the generally accepted strain limit of 5% for HDPE.*

- *When subjected to identical pulling force histories, HDPE pipe samples manufactured on different production lines responded differently highlighting the influence of crystallinity and density on the stress–strain response of HDPE.*

- *The redevelopment of tensile axial stress is caused by the resistance required to prevent further recovery of the visco-elastic strain component. For the particular pipes tested, very little axial stresses were redeveloped in the pipe (i.e. less then 0.1 MPa) after a recovery period of 24 h that is typical of what occurs during field operations.*

- *Tensile axial stress levels that redeveloped in the pipes did not exceed possible long-term performance limits for high-density polyethylene. Even when the short-term performance limits were exceeded, the long-term axial tensions that redeveloped did not exceed the hydrostatic design stress of 5.5 MPa applicable to the particular pipes that were tested. For the specific conditions examined, none of the measured data suggests that the HDPE pipes subjected to the simulated installation sequence would experience long-term tensile stresses that would lead to stress conditions conducive to slow crack growth over time frames generally accepted for circumferential tensile stresses in pressure pipes (ASTM D2837). The available data suggests that limiting the installation force to values stipulated by ASTM F1804 and allowing a minimum of 24 h of recovery time is sufficient to ensure adequate long-term pipe performance from installation induced tensile axial stresses, provided that proper installation practices are employed.* (Cholewa, Brachman, and Moore 2010, 780-781)

F.5.3.2 Ductile Iron Pipes (DIP)

Ariaratnam, Bonds, and Crabtree (2008) studied the corrosion of a 60 m (200 ft) DIP installation, which is claimed to be the primary concern for DIP pipes:

> *The installation was successfully pressure tested to 200 psi (1.7 MPa) over two hours and exhibited the suitability of specific restrained joint ductile iron pipe for these types of installations. Separate sections of the two hundred linear feet of ductile iron pipe were polyethylene encased using the linear low-density polyethylene or the high-density cross-*

laminated polyethylene. At various times over a three-year period, six excavations were conducted to inspect the pipe section and its enhancements.

The inspections were focused to evaluate the condition of each of the polyethylene encasements and the condition of the joint bonds. Additionally, after removal of the polyethylene encasement at each of the excavations, a close inspection of the pipe's surface was performed. At all six of the areas where the HDD installed pipe was uncovered, the polyethylene encasement was intact with no indications of significant damage from the pull. At two of the excavation sites the joint bond connections were inspected with no damage to them either. This was expected because the continuity testing had already confirmed that the pipe section was electrically continuous. Inspections of the pipe surfaces exhibited no corrosion related problems or any evidence of soil/drilling fluid under the wrap.

Although research indicates that HDD drilling fluids are not significantly aggressive to ductile iron pipe (Horton, 2007), the inspections from this research confirm that the polyethylene encasement corrosion control system would not be compromised from the HDD installation procedure. It was, however, revealed that the 0.02mm (8mils) linear low-density polyethylene encasement provided slightly better protection during installation, as slight tears were observed in the high-density material. (Ariaratnam, Bonds, and Crabtree 2008, 7-8)

F.5.4 Tunnel-induced Deformations

The HDD construction could potentially introduce settlements trough, which is similar to tunnel-induced deformation. The settlement trough can be estimated by the Peck Method (Peck 1969) or finite element analysis.

F.6 Case Histories

F.6.1 Overview

The literature review of case histories checked more than 100 documents. Information from 68 case histories was summarized in a master table comparing project conditions, parameters, and highlighting lessons learned, which is located in Appendix F.6.3. Some case histories and their lessons are summarized in this chapter.

Section F.6.2 lists some selected case histories that are represented in different aspects, such as extreme length, grouting application, and problematic soil interface. Section F.6.3 presents a table that summarizes details about all 68 case histories.

F.6.2 Selected Case Histories

Long maxi installation: O'Rourke and O'Donnell (1995) document the installation of a dual 1000 mm (39.4 in.) HDPE force main beneath the Kapalama Basin in Honolulu Harbor, which replaced a 50-year-old reinforced concrete pipe. The dual HDPE lines were installed in dual 1,150 mm (46 in.) O.D. steel casings each around 973 m (3,200 ft) long, placed 6 m (20 ft) center-to-center by horizontal directional drilling (HDD).

Geotechnical Baseline Report (GBR), grouting, and multiple lines: Irani et al. (2007) document the installation of a 2000 ft (610 m), 30 in. (76.2 cm) diameter HDPE force mains crossing beneath Lake Austin in Texas by HDD. The paper presents some interesting design, permitting, and construction considerations and challenges: "*A pipe lay-down area that is equal in length to the total installation is most desirable. Stopping during pullback to connect additional pipe greatly increases the risk of pipe becoming stuck in the hole. The City elected to prepare a geotechnical baseline report to provide bidders a set of baseline conditions that would serve as a common basis for bid development. The GBR was intended to facilitate more accurate bidding without inflating the risks that may not eventuate. A combination of factors pushed this project to the edge of HDD's technical limits: the project's length, large diameter, but most importantly, the need for multiple conduits to accommodate the dual-purpose electric service and wastewater conveyance contained inside of a single casing pipe. To address the dispersion of heat generated from the electrical lines, the annular space within the steel casing had to be filled using a grout with a very low thermal resistivity. The grout also had to be designed to travel long distances within limited intestinal spaces. The key element of the grout mix that made this application a success was to use silica flour instead of sand along with other more traditional components of cement, fly ash and polymers to meet all requirements*" (6-7).

Problematic soil interface: Robison et al. (1997) document two HDD installations. In one of the installations, "*the first ream was attempted using a 0.44-m (1.4-ft) barrel reamer, back-reaming from the West Canyon towards the drill. However, the barrel reamer advanced approximately 427-m (1400-ft) until it reached the harder quartz-diorite. The barrel reamer was unable to advance through the quartz-diorite. Consequently, the barrel reamer was removed, and a 0.44-m (1.4 ft) diameter hole-opener was installed. The hole-opener was successful in reaming through the quartz-diorite. The second ream was made using a 0.71-m (2.3-ft) diameter hole-opener pushed from the drilling pit. The next two reams were performed as back-reams, using 0.91-m (3-ft) and 1.07-m (3.3-ft) hole-openers pulled by the drill. The method worked well in both the soft sedimentary rock and in the harder igneous rock. HDD was also successful in drilling across the transition from the soft sedimentary rock to the hard quartz diorite*" (132).

Conductor casing, centralizers and magnetic coils used in a shore application: McCaffrey, Mulligan, and Kendall (2010, 81-85) document the Hueneme ocean outfall, which was installed using HDD: "*The outfall consists of 2,300-ft (701-m) of horizontal directionally drilled (HDD) 36-in (91-cm) outside diameter (OD) high density polyethylene (HDPE) pipe connecting to 2,700-ft (823-m) of 30-in (76.2-cm) inside diameter (ID) steel pipe laid on the seafloor and terminating in a 30-in (76-cm) I.D. steel pipe multi-port diffuser with duckbill valves. The HDD segment exits in about 30-ft (9.1-m) of water and involved reaming, pipe layout, and pipe pullback using the assistance of divers, barges and marine support vessels. The seafloor segment, including the diffuser, will be laid on the ocean floor using marine vessels and divers. After installation and clean out of the 54-in (134-cm) conductor casing, an 18-in (45.7-cm) steel casing with centralizer pads welded on was inserted the entire length of the 54-in (134-cm) casing plus an additional 17 ft (5.2-ft) in preparation for the pilot bore. TruTracker coil, to track the location of the drilling head and maintain the appropriate alignment, was laid out along the onshore portion of the alignment in a shallow hand dug trench above the centerline of the bore. A second TruTracker coil was placed on the ocean floor from the exit point extending 500-ft (152.4-m) toward the shore, held in place by concrete ecology blocks set 50-ft (152.4-m) apart."*

Buoyancy line, conductor casings, and intersect method in a long large diameter crossing: Ellenberger et al. (2014) document the installation of one of the longest large-diameter crossings in the US. The HDD installation crossing the St. Johns River aimed at installing 6,500 ft (1918 m) of 36 in. (91.4 cm) steel pipe:

> *Prior to drilling operations, 60-in (152.4-cm) diameter conductor casing was installed by pneumatic hammer on each side of the River, including 80-ft (20.4-m) on the west side and 190-ft (58-m) on the east side. The conductor casings stabilized the surface near the entry/exit points, the area of highest potential for ground disturbance and drilling fluid to return to the surface. The pilot hole was drilled using the intersect method with a drill rig on each side of the river to reduce the distance spoils need to travel back to the entry/exit point, which reduced the potential for inadvertent returns to occur. The 36-in (91.4-cm) steel pipe was welded into six intermediate segments along a congested, limited access right-of-way. Just prior to pullback the segments were maneuvered and welded into one complete pipe string, requiring a heavily coordinated closure of a travel lane and seven ramps. When the pipe assembly and drilling/reaming operations were complete, the pipe pullback was performed utilizing a technique of pulling the pipe with the west side drill rig in conjunction with a hydraulic thruster pushing the pipe from the east side of the river. A 6-in (15.24-cm) HDPE buoyancy line was placed inside the pipe string during pullback to provide water ballast to prevent the pipe from floating in the hole. The first two pullback attempts encountered an obstruction that caused a drill rod to break. The pipe was pulled out of the hole utilizing the hydraulic thruster and the broken rod was recovered in both attempts. After the second attempt, a down hole survey revealed a low spot in the bore hole between the end of the conductor casing and the rock layer. For the third pullback attempt, the buoyancy line was temporarily drained until the pipe was advanced into the rock layer using the hydraulic thruster. The buoyancy line was filled and the combination of pulling with the drill rig and pushing with the thruster resumed until the pipe installation was completed.* (Ellenberger et al. 2014, 421-422)

One of the longest HDD installations: Li et al. (2016) describe the installation of a 3,300 m (10,800 ft), 711 mm (28 in.) diameter gas pipeline beneath the Yangtze River in China. The crossing was performed in silty clay and sand and extended to a 142 ft (43 m) depth below the entry point to ensure a minimum depth of 62 ft (19 m) below the river bottom.

Grouting in a multiple line installation: Murray, Dickes, and Botteicher (2015) describe an HDD project that included six sections adding up to a total length of 11,000 ft (3350 m). In those installations, FPVC pipes were used for the 30 in. (76.2 cm) casing that housed the four 8 in. (20 cm) FPVC conduits which in turn housed transmission cables, two 2 in. (5 cm) HDPE conduits for ground and fiber optic lines, and two 3 in. (7.5 cm) HDPE grout delivery tubes. A pneumatic hammer was used to drive 150 ft (45 m) of 54 in. (137 cm) casing into the ground to prevent the soft ground near the surface from collapse during the HDD operations. The paper describes the purpose of the thermal grout and the method of grouting used: "*The purpose of thermally grouting underground installed electrical conduits is to remove heat generated by the transmission of electric power. Heat generated during electrical transmission increases the resistance and thus increases power loss. Additionally, removing heat effectively increases the lifespan of the cable insulation and the cable itself. Overhead*

wires have constant air cooling. Underground, there is no air circulation, thus another method of heat removal is required. Thermal grouts permit the transfer of heat from the cables into the surrounding soil. During grouting, all conduits were filled with water and pressurized to act as a safety factor against unforeseen grouting pressure spikes and to act against any heat buildup on the conduits from cement heat of hydration" (Murray, Dickes, and Botteicher 2015, 62-63).

River crossing HDD installations: Carlin (2014) documented many very long river crossing HDD installations, including a 2,090 m (6857 ft) long crossing of the Yangtze river for installing a 24 in. (61 cm) steel pipeline for crude oil transmission. This installation took over a year to complete and used conductor casing. The study also presented two installations in Texas exceeding 10,000 ft (3,048 m) in length. Carlin (2014) and Carlin and Ariaratnam (2018) compared the HDD industries in the US and China. The studies highlighted the following major differences:

- Design considerations are similar for Chinese and US contractors; however, theoretical calculations of potential pipe stresses are more thoroughly analyzed by Chinese engineers. Design calculations for pipeline projects in both countries are generally performed in accordance with known design standards including the Pipeline Research Council International (PRCI) standards.

- One area that the US appears to be more advanced in is in detailed hydraulic fracturing calculation reports. These reports have become more commonly required, especially for critical crossings and crossings located in environmentally sensitive areas.

- Ultimate installation approval in both countries is almost always based on successful hydrostatic tests, internal pipeline inspection reports, drill profile surveys, and material inspections.

F.6.3 Case History Summary Table

Table 8. Summary of Case Histories

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
1	Installation of Dual 1000mm HDPE Pipe force Mains Under Honolulu Harbor by HDD (O'Donnell et al. 2001)	2000	Kapalama Basin in Honolulu Harbor, Oahu, Hawaii	3,200 ft (975 m)	50 to 130 ft (15 to 40 m) below ground surface, and 120 to 150 ft (36.6 to 45.7 m) below sea level	14 Soil borings including land borings and over-water borings	Fill soils, lagoon deposit, estuarine/ alluvial sediments, and coralline deposit	Wastewater mains	Assembled-line Method	HDPE	40 in. (101.6 cm)		Tensor magnetic guidance system (MGS) and TruTracker surface tracking system		62 in. (157.5 cm)	Pullback of 46 in. (117 cm) steel casing		When installing dual force mains, a drilling rig with adequate pull capacity should be selected.
2	Evaluation and Design of HDD for water transmission main installation (Stinson 2002)	2002	The Town of Stoughton, Massachusetts	550 ft (168 m)	13 ft (4 m) at lowest point	Soil borings with split spoon soil samples and sieve analyses. Borings were advanced utilizing hollow stem augers	Poorly graded sand with gravel	Water transmission main	Assembled-line Method	Flex-Ring Ductile Iron pipe and HDPE pipe.	16 in. (40.6 cm)							Utility survey, geotechnical survey, and other evaluations are needed to reduce potential construction impact when installing long-distance and segmented pipes.
3	Installation of a 24-inch (61-cm) pipeline beneath highway (Stauber 2004)	2002	Interstate I5 in California	1200 ft (365.8 m)		Two exploratory soil boring with mud rotary drilling methods	Semi-consolidated and unconsolidated gravel, sand, silt, and clay	Natural gas pipeline	Assembled-line Method	Steel	24 in. (61 cm)	Bentonite-based Pargel220 system combined with DrillplexHDD and Rod Ease.		10 in. (25.4 cm)	18, 30, 42 in. (45.7, 76.2, 106.7 cm)	3768 ft^3 (107 m^3) of slurry were displaced		If fluid segregation occurs, the slurry flowing out of the hole does not represent the slurry remaining in the hole after pullback.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
4	Reducing Risks in Unfavorable Ground Conditions during Horizontal Directional Drilling (Ariaratnam, Lueke, and Anderson 2004)	2004	Edmonto, Canada	200 ft (61 m)	Depth of 5 ft (1.5 m)		gravel and cobble	Experimental Drilling		HDPE	4 in. (10.2 cm)	soda ash, Bore-Gel, No-Sag, Barolift/ N-Seal		4 in. (10.2 cm)	5.5 in. (14 cm)			Fiber additives could increase installation efficiency up to 67% compared to untreated drilling fluid.
5	HDD using the Flex-Ring joint ductile iron pipe (Ralph Carpenter, Schwarzlose, and Whitaker 2005)	2004	New Braunfels, Texas	1,020 ft (311 m)			Stiff clay, cobble, and gravel	Water transmission main	Cartridge Method	Ductile Iron Pipe	30 in. (76.2 cm)		American Augers DD140 drill	5 in. (12.7 cm)	24, 34, 44 in. (61, 86.4, 111.8 cm)	Pullback of 30 in. (76.2 cm) pipe	Leakage of drilling fluid from bore path to surface as the result of mixed stiff clay and cobble strata.	Ductile iron pipe can be used in cobble and gravel. Cartridge installation option is effective in the case of limited easement or right-of-way.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
6	HDD Utilizing 36-Inch Flexible Restrained Joint Ductile Iron Pipe (Ehrin and Carpenter 2006)	2006	Amherst, New York	785 ft (239 m)		Soil borings	Upper 10 ft (3 m) consisted of stiff, silty-clay, sandy clay. From 10 ft (3 m) to 35 ft (10.7 m) the soils were soft to very soft clay.	Water transmission main	Assembled-line Method	Ductile Iron Pipe	36 in. (91.4 cm)		American Auger DD330	5.5 in. (13.9 cm)	24, 37, 48, 54 in. (61, 94, 122, 137 cm)	Pipes were pre-assembled with copper bonding jumpers.		For the Cartridge Method, a single pipe section is assembled and pulled into bore path sequentially. It is less efficient than the assembled-line method when the bore path is straight. On the other hand, the assembled-line method, allowing the pipe to be pulled in one unit, would require larger construction area, and be more challenging to workers.
7	Crossing Lake Austin Using Horizontal Directional Drilling (Irani et al. 2007)	2007	Davenport Ranch, Austin, Texas	Two 2,000 ft (610 m) segment	100 ft (30.5 m) below the Lake Bottom	Two rounds of soil borings	Poorly compacted silt, clayey silt, clayey sandy silt, and clayey silty sand with small to large limestone gravel, cobbles, and boulders.	Wastewater mains	Assembled-line Method	HDPE	2 segments of 12 in. (30.5 cm) and 6 segments of 3 in. (7.6 cm)	freshwater, bentonite, and polymers.	DD500 (CMS Rig) and DD140 (American Auger Rig). MCS-750 mud mixing/cleaning systems, ParaTrack2 MGS Guidance System			Pullback of 30 in. (76.2 cm) steel pipe	Frac-out of drill mud occurred within 50 to 150 ft (15.2 to 45.7 m) of entry location	Frac-out happened because the existing ground surface sloped at the approximate angle of the drill path resulting in a thin soil layer insufficient to hold down the mud pressures. Can be solved by a steeper entry angle drill along with a casing pipe. The steeper angle facilitated the entry of the drill bit into the rock, while the casing pipe maintained the recirculation of the drilling fluid at the entry point and eliminated frac-outs.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
8	The Bellevue Pump Station Force Main Project in an Urban Environment (Chae, Namini, and Schey 2007)	2007	Bellevue, Washington	3,800 ft (1,158 m) and 1000 ft (305 m)	200 ft (61 m) and 70 ft (21 m) deep, respectively	Three geotechnical soil borings	Glacial soils consisting of glacial till and till-like deposits over a thick sequence of glacial outwash sands.	Sanitary sewer force main		HDPE	28 in. (71 cm)		DrillPath™					There are multiple ways to protect the steel casing pipe, including galvanic anode system, impressed current cathodic protection system, galvanizing the casing pipe, and coating the casing pipe with fusion-bonded epoxy.
9	Twin 30-inch Ductile Iron Pipe HDD Crossings of the San Marcos River (Pontesso and Carpenter 2007)	2007	San Marcos, Texas	1200 ft (366 m)	Maximum depth of 60 ft (18.3 m)		Mainly silt and clay	Water transmission main	Cartridge Method	HDPE and Ductile Iron Pipe	30 in. (76.2 cm)		American Augers DD330	9 in. (23 cm)	24, 36, 48 in. (61, 91, 122 cm)	Pullback proceeded with assembling one joint at a time		For Ductile Iron pipe, its sectional joints allow an option of either assembled line or cartridge assembly. For HDPE pipe, it must use the assembled-line method of assembly where all joints are fused together prior to pullback.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
10	HDD Using Ductile Iron Pipe -A Successful Paradigm Shift (Ralph Carpenter, Schwarzlose, and Whitaker 2005)	2005	Antonio, Texas	1020 ft (311 m)			stiff clay, cobbles, and gravel.	Water transmission main	Cartridge Method	Ductile Iron Pipe	30 in. (76.2 cm)		American Augers DD140, MP 500 mud system	5 in. (12.7 cm)	24, 34, 44 in. (61, 86, 112 cm)	Pullback of 30 in. (76.2 cm) pipe	Numerous hydro-fractures that saw drilling mud oozing through cracks in the ground along the centerline of the pipe's alignment	As the Flex-Ring helps distribute the stress through the joint and into the pipe barrel uniformly, it will dramatically reduce any concentration of stress around the joint and barrel during pullback.
11	Directional Drilling at the World's Third Largest Airport (Hutson, Faughtenberry, and Fissel 2009)	2009	Fort Worth, TX	Six sections range from 2,400 to 3,100 ft (732 to 945 m)	Maximum depth of 35 ft (10.7 m)		rock, sand, clay, silt, cobble, and gravel.	Water and gas pipeline	Assembled-line Method	HDPE	Range from 16 to 24 in. (40.6 to 61 cm)	bentonite.	Wireline guidance system, Walk-over guidance system				There were a few frac-outs during the project, one of which was under a concrete drainage channel and affected utilities.	The pipe tensile strength is extremely important in HDD. This is because the pipe is pulled back through the hole and yield strength of the pipe can be a controlling factor. Typically, the tensile strength of the used pipe is 90% of the yield strength.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
12	Horizontal Directional Drilling on the Snoqualmie River (Staheli and Ramos 2009)	2007	Snoqualmie, Washington	1000 ft (304.8 m)					Assembled-line Method	HDPE	16 in. (40.6 cm)		American Augers HDD rig, Wire-line tracking system		13, 20, 26 in. (33, 50.8, 66 cm)	Pipe pullback commenced with an 18 in. (45.7 cm) reamer leading the pulling head and assembly		The above-average pullback loading recorded could be caused by the frictional loading on the pipe, the weight of fluid displacement, and potential wedging of the pipe in rougher cobbly ground. Also, the additional force required as the pipe ascended to the surface was likely the result of increased friction through the two curved sections of the borehole and the additional gravitational resistance to pulling the pipe up the straight section.
13	Demanding HDD Installation of Fusible 24-inch PVC Pipe (Shae, King, and Botteicher 2010)	2009	The Grand River, Oahe Lake. Bismarck, ND	4,800 ft (1,463 m)	20 ft (6.1 m) below lake bottom			Raw and treated water transmission pipeline delivery system	Cartridge Method	PVC	24 in. (61 cm)		Centerline Directional Guidance Systems, Vermeer 200x300 drill rig, American Augers AA625	9.8 in. (25 cm)	38 in. 997 cm)	The pullback process continued until a contaminated joint was discovered at the 622 m (2,040 ft) mark of the insertion.		The tensile capacity of the Fusible PVC Pipe allows a higher-pressure class to be attained with a thinner wall compared to other fusible thermoplastic systems. In addition, the new material could minimize friction loss. But the fusion process will need careful layout and unique fusion setup.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
14	Hueneme Outfall confronts unique Challenges in Horizontal Directional Drilling (McCaffrey, Mulligan, and Kendall 2010)	2010	Port Hueneme, California	2300 ft (701 m)	91 ft (27.7 m) below sea level			Salinity Management Pipeline	Assembled-line Method	HDPE	36 in. (91.4 cm)		TruTracker coil system		27, 45, 48, 50 in. (69, 114, 122, 127 cm)	Pullback proceeded smoothly up until the pulling head was nearing the end of the 54 in. (137 cm) conductor casing, approximately 90 ft (27.4 m) short of the intended exit point.		During marine horizontal directional drilling, mud in the bore hole will be mixed with sea water, clay, and drilling fluids. Therefore, the torque of the reamer will be easily maxed out for long-distance drilling. In this case, mud needed to be pumped in the bore hole to increase the friction.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
15	The Alameda County Water District project (M. Gelinas et al. 2010)	2010	Fremont and Newark, California	770 and 378 ft (235 and 115 m)	15 ft (4.6 m) below ground surface		soft to stiff lean clay with varying amounts of sand and silt, and very loose to medium dense silty and clayey sands.	Water transmission main	Cartridge Method	HDPE	16 and 22 in. (40.64 and 55.9 cm), respectively						During construction, hydraulic fracturing was noted at the seam between the asphalt concrete and concrete gutter pan of the overlying roadway. When re-drilling the pilot bore, hydraulic fracturing occurred at approximately the same location.	When drilling through very loose soil like sand, silt, or clayey sand, it is highly possible to have hydraulic fracturing, as the soil is very permeable. Therefore, appropriate methods such as adjustment of drilling fluid could be applied to avoid hydraulic fracturing.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
16	Application of Horizontal Directional Drilling in Crossing Gan River Project (Y. Zhang, Zhou, and Ma 2011)	2011	Gan River, China	6890 ft (2,100 m)	9.8 ft (3 m) below ground level		fill, clay, fine sand, mucky sandy loam and muddy loam, medium coarse sand, circular gravel, weathered argillaceous siltstone.	Gas pipeline	Intersect Method	Submerged arc welded pipe	20 in. (50.8 cm)			9.625 in. (24 cm)	22, 30 in. (56, 76 cm)	In order to avoid the rig moving caused by the oversize pulling force, the rig is anchored firmly by ground anchor baffle and cement ground anchor.		For pipe ramming technology, the ramming pipes could not only isolate the loose formation and gravel layer but also benefit the normal mud circulation in the annulus and the accuracy of bore path. The application of software, "Calculation Software Which Aims to Mud Spillover Control in HDD," plays a significant role in preventing and controlling the mud spillover.
17	Design and Construction Challenge for a high-Risk, 24 inch, 5,400 ft HDD Project (Tanzi and Andreasen 2011)	2011	Perth Amboy, NJ	5,800 ft (1,768 m)	60 ft (18.3 m) below ground surface	11 Soil borings with 3 triaxial tests. Silty clay was tested by total stress analysis and effective stress analysis based on Mohr's circle construction method.	soft silty clay, stiff silty clay, sand, shell deposit, and weathered rock.	Water transmission main	Assembled-line Method	FPVC	24 in. (61 cm)		Drill-guide GST (gyro) System, Para-Track II wireline system	10 in. (25.4 cm)	26, 36 in. (66, 91 cm)	In order to reduce pullback loads and to ensure that adequate internal pressure was maintained at all points to counter balance external pressures, the carrier pipe was filled with water as it entered the bore.		To reduce pullback loads and to ensure that adequate internal pressure was maintained at all points to counterbalance external pressures, the carrier pipe could be filled with water as it entered the bore. To provide the most effective pull force for installation of the host pipe, the pipe, that has entered the bore and is below ground level, is required to be full of water during the entire pullback process.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
18	Multiple HDD Applications for Portland Airport Deicing Enhancement Project (Ostlund and Sarin 2011)	2011	Portland, Oregon	1,100 and 3,800 ft (335.3 and 1,158 m)	75 ft (23 m)	Historical information	fine-grained dredge sands, silt, and clay.	Deicing Collection and Treatment System	Assembled-line Method	PE and FPVC	30 in. (76.2 cm) for the first segment and 24 and 6 in. (61 and 15 cm) for the second segment			6 in. (15.2 cm)	42 in. (107 cm)	The pull was completed in 13 hours, exerting a maximum pull force of 117,000 lbs (520, 442 N).		HDPE pipe and FPVC pipe are two very different thermoplastic materials. HDPE pipe was used in this project for its flexibility for water entry. And a water ballast could reduce frictional force in the bore during pullback. Fusible PVC was used, due to its high tensile strength to weight ratio, for an extremely long bundled pull under an operating airfield.
19	HDD Matches Installation Method to Long and Difficult Pipe Crossing (Shell et al. 2012)	2012	Macon, GA	4200 ft (1,280 m)	58 ft (17.7 m)			Water force main	Assembled-line Method	FPVC	24 in. (61 cm)		The ParatrackII steering system, Downhole annular pressure monitoring system, American Augers 70 drill rig	5.5 in. (14 cm)	26 and 38 in. (66 and 97 cm)	During the insertion of the pipe into the borehole, these five lengths of pipe would have four intermediate fusion joints performed to assemble them into the final 4,250 LF that was required.		If the pipe is internally ballasted, the maximum pull load of the pipe could go up 3 to 4 times of the estimated maximum pull load when pulled empty. In addition, pull load differences have a major impact on the buoyancy of the pipeline and resultant friction between the borehole and the product pipe. This is the largest contributor to pull force during pullback.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
20	Crossing the St Johns River with one of the Southeast's Largest HDD Projects (Ellenberger et al. 2014)	2014	Jacksonville, Florida	6500 ft (1,981 m)				Water pipeline	Intersect Method	HDPE	36 in. (91.4 cm)			14 in. (36 cm)	27, 36, 50 in. (69, 91, 127 cm)		A drill rod was broken, and the buoyancy line was temporarily drained.	A HDPE buoyancy line could be placed inside the pipe string to prevent the pipe from floating in the hole, when providing water ballast.
21	Installing the Cheung Chau submarine pipeline in Hong Kong (D. Li, Lo, and Shou 2016)	2013	Hong Kong, China	4593 ft (1400 m)	328 ft (100 m) below sea bottom		rock, hard clay, granite	Water main	Cartridge Method	PE	20 in. (50 cm)	bentonite	Magnetic tools used to collect metallic debris.	12.2 in. (311 mm)	19.3, 27.2, 28 in. (490, 690, 711 mm)			When encountering a large underground cavity, there is a high possibility that the bentonite drilling fluid cannot be contained in the bored hole, leading to the possibility of leakage to the environment and an inability to build up the required driving pressure during drilling. To enhance the thinner pipe, a good way is to apply an advanced abrasion resistant coating over the fusion-bonded epoxy pipe coating and to adopt an aluminum-alloy cathodic protection system to ensure competency of the alternative design.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
22	HDD River Crossing Improves Reliability of Water System (Schuler, Gregor, and Miller 2015)	2015	Indianapolis, IN	1,100 ft (335 m)		Ground penetrating radar (GPR), seismic data collection, and conventional soil borings.	clay, sand, cherty limestone, boulders, and silty soil.	Water main	Assembled-line Method	HDPE	30 in. (76.2 cm)	bentonite	Vermeer 330x500 and Vermeer SA400, The ParaTrack® 2 guidance system and Steering Tool system, Mud Technology MPCT 1000		24, 38, 42, 48 in. (61, 97, 107, 122 cm)	Finally, the boring machine was moved to the other side of the project to pull the pipe in. As indicated earlier, the reamers were pushed from the west side using the boring machine to turn the reamers while 2 excavators on the east side of the river pulled them toward the East.		HDPE pipe's flexibility and exceptional bending radius allows it to adapt to the challenging site conditions. For this project, the minimum bending radius was 25 times the outside diameter.

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23	HDD Utilized to Complete Key Crossings for Transmission Lines (S. Murray, Dickes, and Botteicher 2015)	2014	Central New Jersey	5,280 ft (1,609 m)			silt, clay, and clayey sand.	Electrical power transmission	Assembled-line Method	FPVCP	30 in. (76.2 cm)		American Augers, models DD140, DD440 and DD1100	12 in. (30.5 cm)	24, 36, 48 in. (61, 91, 122 cm)	Using a mechanical pulling head attached to the 30 in. FPVCP, installation of the entire string took less than 200,000 lbs (8,896 N) of force		The tensile capacity of FPVCP provides, for a thinner pipe wall, the same buckling and deflection resistance as other thermoplastic pipe options currently available. This means that the overall borehole size could be reduced by using FPVCP, but still provide the required casing and conduit inner diameter for the cable and thermal grout design. The purpose of thermally grouting underground installed electrical conduits is to remove heat generated by the transmission of electric power. Removing heat effectively increases the lifespan of the cable insulation and the cable itself.

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24	Permitting Requirements Drive Trenchless Design and Project Risk (Price, Olson, and Staheli 2015)	2015	Denver, CO	700 ft (213 m)	50 ft below ground surface (15.2 m)		medium stiff to sandy clay, silty and gravelly sand, and scattered cobbles.	Water pipeline	Assembled-line Method	FPVCP	10 in. (25.4 cm)			8 in. (20.32 cm)	24 in. (61 cm)	The contractor elected to deviate from the initial plan to pull the entire steel casing with FPVC carrier pipe string in one continuous pullback operation.	Drilling fluid had been continuously escaping to the ground surface from the optic line pothole.	The use of a plastic casing pipe allowed the flexibility necessary to adjust the borehole geometry parameters in response to the anticipated geotechnical conditions. In certain pressure ranges, plastic casings can provide the facility owner with assurance that if in operation the carrier pipe were breached, a plastic casing would effectively contain the fluid and prevent damage to the crossing facility.

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25	Waterline Replacement in Kansas City Crossing the Blue River (Reuter and Finn 2015)	2015	Kansas City, MO	500 ft (152.4 m)		The original PCCP installation drawings	rock and fractured limestone.	Water transmission main	Assembled-line Method	FPVCP	30 in. (76.2 cm)			8.75 in. (22.2 cm)	20, 30, 36, 42 in. (50.8, 76.2, 91.4, 106.7 cm)			In order to fulfill the requirement of higher flexibility or bending curvature, FPVCP was chosen over iron and steel. Additionally, when considering bending radius, the curvature of the pipe layout should always be taken into account. Also, vertical and horizontal bending should be taken into consideration. Usually, when reaming the bore path, the hole is enlarged to approximately 1.5 the outside diameter of the pipe. In cases where the pipe is larger than 24 in. (61 cm), it is a common practice to enlarge the bore hole to 12 in. (30.5 cm) greater than the outside diameter of the pipe to be installed.

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26	Record setting 3,300 m of a 711 mm Pipeline Crossing the Yangtze River (G. Li et al. 2016)	2013	Yangtze River, China	10, 827 ft (3300 m)	82 ft (25 m) below ground surface	River Scour Depth Analysis with Zhang Ruijin formula	silty clay, sand, and medium sand.	Gas pipeline	Intersect Method	PE	28 in. (711 mm)	water + 5% bentonite clay + 0.5% Mixed-metal hydroxide (MMH)	Magnetic-signal submarine cable, Flat-barrel combination-type reamer, PIPEFLO 9.3 software, American Augers DD-1100 and DW/TSX DDW-4000, The ParatrackII direction control system	28 in. (270 mm)	26, 36, 42 in. (660, 914, 1067 mm)	Most of the aboveground portion of the pipe string was floated in an existing trench to reduce pulling resistance during the pullback.		PIPEFLO is a steady-state simulator for flow assurance. In sensitivity studies, it facilitates consideration of a wide variety of options to arrive at the best solutions for design issues and operational problems. For river scour depth analysis, Professor Zhang Ruijin assumed a rolling model of sediment transport, deriving the Zhang Ruijin initiation velocity formula from the force equilibrium equations. The Zhang Ruijin formula was suitable not only for cohesive fine sediment but also for cohesionless coarse sediment.
27	Utilizing HDD to install Twin 36” Casings for Sanitary Sewer Siphons (Merten, Holst, and Reuter 2016)	2016	Sioux City, Iowa	1500 ft (457.2 m)	60 ft (18.3 m) below ground surface			Sanitary sewer force main	Assembled-line Method	FPVCP	36 in. (91 cm)		American Auger DD330, Mud Technology MCT1000 recycling system, Tulsa TT 660 mud pump, Wireline locating system	10.6 in. (27 cm)	30, 42, 54 in. (76.2, 107, 137 cm)			The capstan effect around drill-path bends is attuned to a load multiplier. For a given axial force, the load increases at a significant rate as the curve radius decreases. This was particularly apparent in the calculations for this project given the length and depth of the profile.

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28	Soil Improvement Thanks to an Extra-Long Application of Directional Drilling Di Salvo et al. (2017)	2017	Warsaw, Poland	853 ft (260 m)			medium and coarse sand, high plasticity clays, and silty clays	Manchette tubes for ground improvement		Manchette tubes	5.5 in. (140 mm)	bentonite	Magnetic Guidance System, Downhole mud motor					To carry out directional drilling, special bits are utilized. They owe their steerability to the characteristic axial asymmetry. This asymmetry may be of two different types: transversal and longitudinal. The transversal asymmetry is characteristic of the drilling bit that presents at its tip a chamfered surface. The longitudinal asymmetry comprises an angular offset between rod string and drilling bit, created by a bent sub or bent motor housing.

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29	Avoiding Rush Hour with Utilizing Horizontal Directional Drilling (Barnard et al. 2018)	2018	Frisco, TX	2500 ft (762 m)		Three geotechnical soil borings	clay, clayey sand, weathered shale, limestone, soft shale, and stiff clay.	Water transmission main	Assembled-line Method	FPVCP	12 in. (30.48 cm)		Vermeer 220 x 300 drill rig, Wire line locating system, Polycrystalline diamond compact (PDC) drill bit		20 in. (50.8 cm)	During the pull-in, the maximum pull force that was utilized was less than 50,000 lbs. (222,411 N), which is considerably lower than the safe allowable pull force of the pipe and only a fraction of the overall capabilities of the drill rig.		The project specified fusible polyvinyl chloride pipe (FPVCP) for the HDD section of the reuse line to match the characteristics in the rest of the system, which was made up of PVC pipe. FPVCP is compatible with all PVC piping systems, and it has the additional benefit of a low profile fused joint system. The fused joint system allows the pipes to be fused into a single monolithic length.

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30	Muskingum River Sanitary Sewer Force Main Project (Tucker and Scanlan 2018)	2018	Marietta, Ohio	1960 ft (597 m)	90 ft (27.4 m)	Drawings, soil borings, and geotechnical reports from ODOT	sand and shale	Sanitary Sewer Force Main	Assembled-line Method	FPVCP	16 in. (40.6 cm)		American Augers DD-440		24 in. (61 cm)		No impact despite a blockage during the drilling and the overshot exit	It was found that PVC pipe materials consistently have the lowest overall failure rates amongst commonly used piping materials (cast iron, ductile iron, PVC concrete, steel, and asbestos cement). This allows for a lower cost of ownership and greater longevity in the life of the pipe. Due to the PVC pipe's semi-crystalline structure, the width of the pipe is not required to be as thick as HDPE, which has a more randomized molecular structure, to maintain a suitably high strength rating. The crystalline structure of PVC also allows for a higher tensile strength, providing a significantly decreased head loss in comparison to HDPE.

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31	Application of HDD to Limited Right-of-Way Gas Pipeline Design (Godwin and Valenzano 2001)	2000	Antioch and Pittsburg, California	4865, 4776 and 1845 ft (1483, 1456 and 562 m)	Maximum of 140 ft (43 m)	Standard Penetration Test, Cone Penetrometer. The geophysical methods included electromagnetic line location (EMLL), total conductivity (TC) and ground penetrating radar (GPR).	fine and medium grained sand, sandy silt, coarse sand, and gravel.	Gas pipeline			42 and 36 in. (107 and 91 cm)		HD-650 rig	8.75 in. (22 cm)	36 and 42 in. (91 and 107 cm)		There were numerous frac-outs, one particularly at the south end of a public parking lot, about 200 ft (61 m) from the drill path.	Conventional cut and cover trenching construction techniques would have required significant amounts of trench dewatering, spoil removal and disposal, and would not have been possible based on space allocation and restrictions along the BNSF railroad. HDD was successfully used to surmount these obstacles.
32	Combined Directional Drilling to Reduce Design and Construction Costs (Stinson 2006)	2006	Weweantic River, MA	2 segments of 1601 ft (488 m)		The geotechnical boring logs and sieve analysis	sand, silt, and peat.	Water main	Assembled-line Method	HDPE	11.8 in. (300 mm) and 9.8 in. (250 mm)	bentonite				Shortly after the rock core heads were on-site; the driller pulled back the water and sewer casing pipelines.		Installation of a HDPE force main inside a HDPE casing sleeve could provide flexibility for future maintenance. The borings of geotechnical investigation should be taken by proposed crossing alignment to reduce potential frac-out routes. Borings should be taken on the shore and in the waterway.

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33	HDD Shore Approaches in the Biscayne Bay Marine Sanctuary (Halderman and Smith 2006)	2005	Biscayne Bay, Miami	2200 ft (671 m) and 2300 ft (701 m)	75 ft below ground surface		sedimentary rocks, carbonates, marine limestone, and quartz sands.	Powerline	Assembled-line Method	Steel pipe	24 in. (61 cm)			12 in. (30.48 cm)	26, 36 in. (66, 91 cm)	A relatively low weight drilling fluid, with low flow rate, was designed to deal with the intermittent zones of soft and hard geological units and to reduce the potential for frac outs.		In order to minimize potential drilling fluid discharge at the two exit points, a “forward-reaming” process could be used, whereby the various hole enlarging tools would be “pushed” from the land toward the sea exit rather than be “pulled” back according to conventional methodology. A relatively low weight drilling fluid, with low flow rate, could be used to deal with the intermittent zones of soft and hard geological units and to reduce the potential for frac outs.

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34	HDD Utility Tunnel to Peddocks island, Fort Andrews (McHugh and Gabriel 2007)	2007	Peddocks Island, MA	2000 ft (610 m)	125 ft (38.1 m) below sea level	A jack-up barge for five deep borings	glacial till soils	Utilities tunnel	Assembled -line Method	HDPE	20 in. (50.8 cm)		Tru-Tracker system.	12 in. (30.5 cm)	30 in. (76.2 cm)			The steel casing was not intended to provide any structural strength to the conduit bundle but served as a smooth sleeve for pulling the complete bundle through the potentially jagged bedrock walls of the borehole. Because of the significant currents through Hull Gut, the typical floating barge used to locate the drill bit could not be used, and a spud barge was deployed to the site to provide a stable base for the survey equipment.

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35	Installation of segmented PVC watermain pipe in Richmond, Canada (Young and Creelman 2007)	2007	Richmond, Canada	9842 ft (3000 m)			soft soils, silt, and clay.	Water pipeline		Cobra Lock™ PVC Pipe	6 in. (150 mm)		DD30 drilling rig		14 in. (35.6 cm)	This was followed by a compaction reamer ahead on a swivel, which was attached to the pipe to pull in the new Cobra Lock™ Segmented PVC C900 DR18 Water Pipe.		The PVC pipe proposed required a smaller distance between the entry and receiving pits because of tensile strength limitations as compared to high density polyethylene pipe. The use of PVC pipe would require more excavations throughout the project. The recommended maximum deflection for PVC pipe is generally considered to be 7.5%. Calculations completed on the construction basis condition (empty pipe with live load conditions) using the Modified Iowa Formula, which is a primary formula used for predicting horizontal deflection for flexible pipe.

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36	A directional drilled river crossing water main (Lary 2007)	2007	Topsham, Maine	700 ft (213 m)	Maximum of 60 ft (18.3 m)	Test borings	glacial deposits and well-graded coarse gravels.	Water transmission main	Assembled-line Method	Ductile Iron Pipe	12 in. (30.4 cm)							Thermal butt-fused pipe could eliminate pipe joints under the river that could potentially create future leaks. To maximize the flow and minimize hydraulic restrictions, the pipe most closely matched the inside diameter of the 12 in. (30.5 cm) ductile iron water main is selected. Thick-walled pipe was specified to withstand the high static pressures in excess.
37	Horizontal Directional Drilling-Sharing an Inaugural Experience (Stewart, Cohen, and Carpenter 2008)	2007	Washington Grove, MD	560 ft (171 m) and 200 ft (61 m)		Three geotechnical soil borings		Water pipeline	Cartridge Method	Ductile Iron Pipe	3 and 8 in. (7.6 and 20.3 cm), respectively	bentonite	The Ditch Witch JT2720 HDD drilling equipment	6 in. (15.2 cm)	12 in. (30.5 cm)			The strength of ductile iron pipe is not impacted by temperature, and a moderate and dependable coefficient of thermal expansion is generally not a design consideration for buried installations. In comparison, operating temperature has a significant and direct impact on the strength of plastic pipes. The Design Decision Model (DDM™) is a risk-matrix for the evaluation of the likelihood of corrosion occurring on a ductile iron pipeline.

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38	HDD in Severe Environmental Restrictions in 1700-foot River Crossing (Shumaker and Howard 2008)	2008	Santa Margarita River, CA	1650 ft (503 m)	40 ft (12.2 m)	A series of five geotechnical borings	loose to medium dense silty sand with occasional interbedded layers of soft to firm silt, clay, and sand with silt.	Sewer force main	Assembled-line Method	HDPE	18 in. (46 cm)	bentonite	Leak detection system, Wire and guidance system			Utilizing the drilling rig, the end of the pipe was attached to the end drill bit and pulled back into the borehole. A backhoe and crane were utilized to assist the pipe into the bore hole at the exit work area.		To ensure that the HDD progressed through a sufficient depth of well-consolidated sediments that had not been disturbed by flood events of the past several decades, it was important to locate the alignment well below the potential scour zone. Additionally, to prevent frac-outs and collapse of the borehole during the HDD operation, well-consolidated material should extend at least five diameters above the top of the borehole.
39	Challenges of Large Diameter Horizontal Directional Drills (Applegate, Cronberg, and White 2011)	2011	Fort Worth, TX	1005 and 1015 ft (306 and 309 m)	18 ft (5.5 m)	A dry augur bore		Water pipeline	Assembled-line Method	PVC	30 and 20 in. (76.2 and 50.8 cm) respectively				20 and 30 in. (50.8 and 76.2 cm)			During the directional drilling process pressurized drilling mud is continuously being pumped through the excavation. This pressurized mud can migrate through loose or low-density material with relative ease creating blowouts and loss of material. The length of the HDD is dependent upon the depth of conflict obstructions, the drilling equipment, and the pipe material properties.

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40	Design and Construction of HDD for the Natural Gas Pipeline Project (C. Gao, Nie, et al. 2011)	2011	Zhantian Lake, China	708 ft (216 m)	Maximum of 42.7 ft (13 m)		artificial fill, silt, silty clay, mucky silty clay, and round gravel.	Gas pipeline	Assembled-line Method	PE	7.87 in. (200 mm)	water, high-quality bentonite and the mud additives	Drilling rig KSD-25, RD386 radio detector		19.7 in. (500 mm)	After stress testing, the pipe was laid by anti-pulling. While laying traversing pipeline by anti-pulling, the high-quality lubricating mud must be grouted into the hole in order to minimize the friction force between the pipe and hole wall.		In general, the pilot hole trajectory design must consider the following factors: the site environmental conditions, the equipment capacity, the drilling characteristics of stratum, the physical properties of the planned pipeline, the guided boring technology, and the technical and economic evaluation of adopted technical measures.
41	High-Risk, 610 mm (24-Inch) Diameter, 1,645 m (5,400-Foot) HDD Project – A Case Study (Tanzi et al. 2011)	2011	Southern Middlesex County, New Jersey	5397 ft (1,645 m)	Maximum of 59 ft (18 m)		construction debris, diabase bedrock and organic soils, including peat and medium dense, silty sands containing organics, or soft organic silty clays.	Water pipeline	Cartridge Method	FPVCP DR-18	24 in. (610 mm)				26 and 36 in. (66 and 91 cm)	An inflatable plug was inserted immediately upstream of the pull head to seal the pipe from the pull head and any possible drilling fluid infiltration into the pipe during pullback.		The route is partly under river, so the complexity of subsurface condition and extremely soft material throughout the entire length added difficulty to the project.

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42	High-Risk, 610mm Diameter, 2,090m HDD Project – A Case Study (G. Li et al. 2013)	2012	Wuhan, Hubei, China	6857 ft (2,090 m)	Maximum of 39.4 ft (12 m)	Geotechnical survey and 11 geotechnical soil borings	conglomerate and glutenite	Oil pipeline		API 5L X65	24 in. (610 mm)	bentonite	RP-5 - head rig; HK450 - auxiliary rig					For long-distance pipeline with large moment of torsion, the pushing force cannot be applied to drill pipe, otherwise, it will make the drill pipe break under combined stress. For long-distance pipeline, each side should be equipped with one rig (intersection method). Reaming and withdrawal of reamer should be done separately. Lubrication result of graphitic lubricant that was added into mud was ideal during the stage of pull-back with the force always less than 100t.

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43	Comparison of Trenchless vs. Open-Cut Construction Methods for the Replacement of a Leaking Water Distribution System (Kramer and Gary 2000)	2000	Fort Worth, TX	5200 ft (1585 m)	3.9 to 5.9 ft (1.2 m to 1.8 m)	Several soil borings were taken within the subdivision to confirm the expected underground conditions and determine the suitability of the ground conditions for directional drilling.	sandy clays and clays with moderate to high plasticity. Small amounts of gravel were also noted in several of the borings.	Water pipeline	Assembled-line Method	HDPE	8 in. (203 mm)		The DrillPathTM software	2 to 2.5 in. (51 to 63.5 mm)	12 in. (305 mm)	Install the water main by pulling the pipe through the exit pit into the drilled hole.		Typical overcut for the hole is 30 to 50% of the product pipe. The primary difference between directional drilling and open-cut methods is the amount of surface restoration required.

44	HDD Bonus for Early Completion (Deering, Bardin, and Pollak 2001)	2001	San Diego, CA	1100 ft (335 m)	40 ft (40 m)	While design work continued, additional soil work was recommended with borings to a depth of 55 ft (17 m) Below Ground Surface (BGS).	soft alluvial soils	Water force main	Assembled-line Method	HDPE	28 in. (71.1 cm)	bentonite	DDR 300 drilling rig	6 in. (15.2 cm)		The ends of the HDPE pipe were fitted with specified flanged fittings fabricated by Independent Pipe Products, and the pipeline was hydrostatically tested before installation. This operation only took several hours with a pulling force never exceeding 60,000 lbs. (264,779 N, 27,000 kg).	When the pilot bore progressed across the busy intersection, the project experienced some “frac out.” The heaviest frac out occurred dead center in the busy intersection. The contractor added a cedar wood amendment to the drilling mud and pumped this material into the frac out. This sequence occurred several times both during the pilot bore and during the back reaming.	The exit angle should be maintained at a certain degree from horizontal in order to maintain depth as long as possible to the pipe side target. Determining entry angle of the drill path was important because the pilot boring and back reaming were both accomplished with hydraulic jetting. The residual pressure from the jetting had to be sufficient to transport drilling mud and spoils back to the entry pit.

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45	Installation of Horizontal Wells in Landfilled Waste Using HDD (Cox et al. 2006)	2006	Rainham, UK	328 ft (100 m)	25.6 ft (7.8 m)	The drilling trials detailed in this paper were restricted to Phase 2, a 21-hectare (251,158-square yard) area previously used as an open silt lagoon. Hydraulically placed silts deposited prior to the deposition of landfilled waste make up a 6.6 ft (2 m) deep layer above the alluvial clays that form the site base.	alluvial clays and municipal waste	Horizontal wells	Assembled-line Method	Low carbon steel pipe	5.9 in. (150 mm)				5.9 in., 9.8 in. (150 mm, 250 mm)	Despite these potential difficulties, it was decided to attempt to install the 5.9 in. (150 mm) diameter well screen, which was constructed from sections of heavy gauge perforated steel pipe welded together on site to create a continuous length. This was undertaken on the day following the 9.8 in. (250 mm) back ream.		The simple analysis following Milligan and Norris (1996) confirms that partial closure of the bore would be sufficient to prevent installation of the well screen using the 26,977 pounds (120 kN) pullback rig. A pipe of weight per unit length while sliding in a stable, open borehole will generate a frictional resistance in proportion to its length.

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46	Application of Both Pipe-ramming and Intersection in HDD Crossing (Tu, Ma, and Zhao 2011)	2011	Heilongjiang River, China	1804 ft (550 m)			gravel and fine-grained or coarse-grained feldspathic sandstone.	Oil pipeline	Intersect Method		63 in. (1600 mm)							For steering systems with wire, Bottom Hole Assembly (BHA) mainly consists of bit, motor with bend shell, mud pressure sensor, steering probe, and non-magnetic drill collar, of which probe is installed in non-magnetic drill collar. In this project, the technician designed a set of hole-amend reamer to mill the intersection point in order to reduce dig angle.

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47	Successful Practices of Environmental LG Vegetable Gum in HDD (J. Cai, Wu, and Gu 2011)	2011	Wuhan, China	3 sections of 141 ft (33 m), 4 sections of 3937 ft (1200 m) and one section of 6299 ft (1920 m)			man-made fill stratum, new lacustrine formation, clayey formation, mucky soil, sand soil, and fine sand formation.	Communication, gas and iron pipeline		Iron pipe	15 in. (380 mm), 9.8 in (250 mm), and 28 in. (711 mm)	7% bentonite, 4% Na2CO3 (compared to the weight of bentonite), 0.4% CMC, 0.4% LG and 0.03% XC. In the process of making boring fluid, 44.1 lbs. (20 kg) of LG vegetable gum were added into 35.3 ft^3 (1 m^3) of water with the mixer mixing for 30 minutes.	ZT-18 HDD rig					As one kind of drilling fluid additive, LG vegetable gum has excellent performances in terms of thickening, fluid loss control, lubrication, a certain extent of salinity tolerance, and strong inhibitive capability. Its performances had been confirmed by several coal drilling and scientific drilling projects. LG vegetable gum can be acquired from the leaves of natural Lauraceous plants. It has good filtration control ability, excellent lubricating capability, and obvious anti-sloughing effectiveness. Basing on the lots of lab tests, its optimal amount in drilling fluid was determined as 2.0 weight percent.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
48	Reconstruction in an Urban Environment 8" Water Line HDD (C.H. Kirby and Leclair 2012)	2012	Houston, TX	1500 ft (457 m)	8 ft to 10 ft (2.4 m to 3 m)			Water pipeline	Assembled-line Method		8 in. (20.3 cm)							HDD had a lower impact to the site conditions over the augering and open-cut methods. The overall impact from HDD was less disruptive to the local businesses and the environment, which was directly related to the number of pits needed. This reduction in pits provided cost savings to both the contractor and the client since the additional excavation would have required more time and labor. Although HDD was more difficult to complete, and the contractor takes a larger risk with this method, it adds value to the project by enhancing the economic impact of the work completed.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
49	Using Trenchless Technologies to Minimize Public Impacts (Steitle, Hooten, and Issa 2013)	2007	Dallas, TX	1200 ft (366 m)				Water main	Assembled-line Method		48 in. (122 cm)							During construction, the pipe floating is possible due to the low-density grout. It was determined that the grouting operations would need to take place in multiple lifts in order not to float the pipe. In this project, the new pipe segment would be filled with water in order to add weight and prevent floatation.
50	Directional Drilling Applications in Adverse Geological Conditions (X. Zhang et al. 2014)	2014	Qinghe River, China	3287 ft (1002 m)			cultivated soil, silt, gravel sand, gravel round, pebbles, mudstone.	Petroleum pipeline	Assembled-line Method	Steel pipe	55 in. (1400 mm)							Gravel and sand layer formation are easy to collapse and unable to form a stable channel, which makes HDD difficult to implement.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
51	Fast-tracked HDD in Biscayne Bay for Emergency Bridge Replacement (Alonso et al. 2014)	2014	Key Biscayne, Miami	1300 ft (396 m)	82 ft to 110 ft (25 m to 33.5 m)	Test borings conducted near the entry and exit areas revealed sand layers from the ground surface to depths of 40 ft (12 m), cemented sand to depths of 46-54 ft (14-16 m), sand layers to depths of 81-90 ft (25-27 m), and cemented sand and/or limestone to 100 ft (30 m).	cemented sand, limestone and sand.	Water main	Assembled-line Method	Ductile Iron Pipe and HDPE	12 and 16 in. (30.5 and 40.6 cm)		Magnetic and gyroscopic guidance systems.	12 in. (30.5 cm)	24, 30 in. (61, 76.2 cm)			A magnetic guidance system requires two wires to be laid on the surface along the bore path. The wires are then surveyed. To locate the drill bit during the pilot drill, the wires are electrified with a direct conduit (DC), and the location of the steering head is triangulated within the magnetic field caused by the two wires. A gyroscopic guidance system measures the azimuth and inclination of the drill bit and uses that information to calculate its location.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
52	HDD Installation Practices for Buried Pipeline Infrastructure in China (M. Carlin et al. 2014)	2013	Jiangyin, China and Weinan, China	10,827 ft and 9,672 ft (3300 m and 2948 m)	142 ft and 105 ft (43.2 m and 32 m)		fine sand and clay.	Crude oil pipeline and coal slurry pipeline	Intersect Method	Steel pipe	24 in. and 10.7 in. (610 mm and 273 mm)		The Paratrack2 control system, The magnetic signal system, Mud recycling system, DD-1100RS, DW/TSX DDW-4000, GD5000-LL Drill Rig, and GD3500D-L Drill Rig	9.9 in. (251 mm)	24, 30, 36, 44, and 18 in. (610, 762, 924, 1118 and 457 mm)			Some projects that use the intersect method choose a “docking” location that is equal distance from each rig. For the Jiangyin project, however, the intersect location was selected to be 6562 ft (2,000 m) away from the main rig along a potential docking area of 328 ft (100 m) long. Once the drill paths are connected, the main drill rig is pulled backed while the other drill rig is propelled along the established drill path.
53	The City of Lafayette, Louisiana: Another Positive First Experience with HDD Installation Using Ductile Iron Pipe (RR Carpenter et al. 2016)	2016	Lafayette, Louisiana	740, 1140 and 940 ft (226, 347.5 and 287 m)			sandy clay	sewer force main	Cartridge Method and Assembled-line Method	Ductile Iron Pipe	24 in. (61 cm)		American Auger DD-140		42 in. (107 cm)			The installation of ductile iron pipe using HDD is possible because of the flexible restrained joint. To realize the advantages, it is necessary to understand the mechanics and the unique functionality of the flexible restrained joint.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
54	Horizontal Directional Drilling for Bypass Tunnel (Robison et al. 1997)	1994	Santa Cruz, CA	1342 ft and 2057 ft (409 m and 627 m)	115 ft (35 m)		weak sedimentary rock and hard crystalline rock	Bypass Tunnel	Assembled-line Method	HDPE pipe	3 ft (0.91 m)			0.82 ft (0.25 m)	1.44, 2.49, 3.84 ft (0.44, 0.76, 1.17 m)			Blast vibration could fracture host rock and create flow paths for groundwater, which could possibly contaminate leachate from landfill, so drilling and blasting would not be permitted in this case. If there are potential damage to protective coating or concerns of corrosion, steel pipe lining should be avoided. To stabilize the opening around the pipe and prevent groundwater from reaching the outside wall of the pipe and traveling to the outlet structure, contact grouting can be used around final pipe lining.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
55	Experience of horizontal directional coring in Hong Kong (Boden et al. 2018)	2013 - 2018	Hong Kong, China	from 295 to 4209 ft (90 to 1283 m)	230 ft (70 m)		granite	Sewage tunnels	Assembled-line Method									It should be noted that horizontal directional coring does not give information on rock head or rock cover to the tunnel, so vertical and inclined boreholes targeted suspected weakness zones and areas of shallower cover. The smaller coring diameter and larger ratio of cutting head to coring barrel on the curved sections reduced the core recovery ratio. If the curve radii are small and are at the start of the borehole, the drill rods will be subjected to repeated strain and there will be increased risk of breaking. Curve radii should be as large as possible to avoid this.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
56	Planning for the Future: 30-Inch HDD FM Crossing of Halifax River (Peters, Lloyd, and Tatum 2018)	2018	Volusia County, Florida	2385 ft (727 m)			soft silt with organics within the first 14 ft (4.27 m) of depth, followed by 30 ft (9.1 m) of loose to medium dense fine sand, 30 ft (9.1 m) of soft to medium sandy clay and finally soft to hard weathered limestone at depths below 75 ft (23 m).	Subaqueous force main	Assembled-line Method	FPVCP	30 inches (76.2 cm)		Vermeer D500x500 and Vermeer R9x12T reclaimer		24, 36, 48 in. (61, 91, 122 cm)	The pipe pullback commenced using two strings of pipe (1,395 ft and 990 ft) (425 m to 302 m) to be fused together after one string was pulled into the borehole due to the limited available distance to layout a single string through the Bethune Point Sports Complex. The total duration of pullback operations was approximately 14 hours.	During construction, noise abatement was conducted to minimize disturbance to the nearby residents. The design incorporated the installation of a sound barrier around the HDD entry staging area.	Perform geotechnical borings much deeper than the anticipated HDD design depth. The extra available geotechnical data is invaluable to all stakeholders when unforeseen challenges require the HDD to be installed deeper. Maximize the room behind the drill rig during design so the drill rig can be shifted back to avoid unknown obstructions. There is always the potential for unforeseen obstructions, so allowing more room will give the contractor more flexibility.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
57	Lessons Learned from Rock Crossings Using Directional Drilling (Kramer, Meinhart, and Bettger 2001)	2001	St. Louis, Missouri	3474 and 1050 ft (1059 and 320 m)	131 and 57 ft (40 and 17.4 m)		Ordovician-aged dolomite of the Shakopee Formation and the overlying St. Peter sandstone.	Transmission main	Assembled-line Method	Steel pipe	42 and 20 in. (1066.8 and 508 mm)							Boring locations are selected to determine existing conditions at or near the proposed entry and exit pits; near the edge of the river, highway, or other areas that will be crossed; near significant changes in the topography, which may affect the selection of the final crossing profile, and at selected locations to provide coverage at intervals ranging from 300 to 1000ft (91.4 to 304.8m) along the proposed alignment. Test borings can include both land and water borings, with minimum depths extending at least 20 to 40 ft (6.1 to 12.2m) below the proposed crossing profile.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
58	Utilization of Trenchless Construction Methods in Mainland China to Sustain Urban Infrastructure (Ariaratnam, Chan, and Choi 2006)	2003, 2004, 2005	Multiple locations in mainland China	197 to 262 ft (60 to 80 m)				Gas pipeline		Steel pipe and HDPE	3.94 to 280 in. (100 to 720 mm)		Vermeer D200-300, Vermeer D3344, Vermeer D100-120					Case studies of projects in several Chinese cities are presented. HDD of gas, electrical conduits, and potable water lines in Shanghai and Fuzhou demonstrate the benefits of the technology.
59	Special Practices of Horizontal Directional Drilling in China (H. Gao, Li, et al. 2011)	2006, 2007	Multiple locations in mainland China	3773 to 8038 ft (1150 to 2450 m)	62 to 180 ft (19 to 55 m)		silty sand with silt, silt clay, silt sand with mucky soil, mucky silty clay with silt, clay.	Gas pipeline			18 to 48 in. (457 to 1219 mm)						Several fractures were observed in multiple projects.	When crossing in hard soil, a larger entrance angle and curvature radius should be chosen, and, when crossing in dense sand, both teeth bit and mud motor for rock crossing should be used; a drill pipe with nozzle should spray mud to weaken the earth. Locating casing pipe should be used in soft soil and long-distance crossings. When the entrance or exit point is in soft soil, gravel, or cobble, a larger diameter casing pipe should be installed to prevent borehole collapse.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
60	Emergency relocation of 20-inch sewer force main (Alfonso and Sibila 2012)	2012	the Miami International Airport	800 ft (244 m)			gravel with sand and silt, hard and weathered limestone, and very dense brown sand with variable percentages of limestone fragments.	Sewer force main	Assembled-line Method	HDPE	20 in. (50.8 cm)			5 in. (12.7 cm)	18, 24, 36 in. (45.7, 61, 91 cm)	Pull 24 in. (61 cm) O.D. DR-11 HDPE Pipe		HDPE Pipe is similar in many ways to PVC in that they are both lightweight, flexible, and corrosion-resistant. However, HDPE differs from PVC in that it comes in four pressure classes, and these pressure ratings include an allowance for surge pressures. In addition, this pipe does not require special joint restraints at changes in direction.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream-ing	Pullback	Impact	Lesson Learned
61	Non-excavating Horizontal Directional Drilling Applied in the 2nd Phrase Project of Feed Pipelines Expansion in Xi'an City, China (Shi and Yang 2014)	2011	Xi'an City, China	7448 ft (2270 m)				Feed pipeline	Assembled-line Method	Steel pipe	48 in. (1220 mm)		GD-280T, MGS steering system	8.5 in. (21.6 cm)	19.7, 27.6, 35.4, 43.3, 49.2, 53.1, 57.1, 61, 63 in. (500, 700, 900, 1100, 1250, 1350, 1450, 1550, 1600 mm)	Reamer with diameter 59 in. (1,500 mm), 500T cardan and cross pipeline with diameter 48 in. (1220 mm) were adopted for the back-dragging major pipeline. Continuous operation was applied for back-dragging in order to prevent increased resistance caused by shut down. And connectors are checked for fastness before the back-dragging.		One-step dragging (the to-be-dragged pipes are welded before dragging) is applicable for the directional drilling of large diameter pipes in long distances. Because of the limited site, one-step welding could not be adopted.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
62	A Comparative Analysis of Horizontal Directional Drilling Construction Methods in Mainland China Introduction (M.C. Carlin 2014)	2008 to 2013	Multiple locations in mainland China	5900 to 12000 ft (1798 to 3657.6 m)				Gas pipeline and water mains	Intersect Method	Steel pipe	24 to 59 in. (61 to 150 cm)						There are minor hydraulic fractures in several projects, with no severe issues.	In general, design considerations between Chinese contractors and North American Contractors are similar; however, theoretical testing of potential stresses is more thoroughly analyzed by Chinese engineers. It was found that both Chinese and North American project designs are carried out in accordance with national standards of each country as well as the Pipeline Research Council International (PRCI) standards.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
63	Under the River and through the Woods Design and Construction of Two Large Diameter Horizontal Directional Drills for the City of Corpus Christi (Carrel and Cecil 2015)	2015	Corpus Christi, TX	2000 ft (609.6 m)		For typical open trench design, 25 ft (7.62 m) deep geotechnical bores were drilled every half mile for all 42 miles (67.6 km) of the project. To gather further soil information required for the HDD, additional 100 ft (30.48 m) deep geotechnical borings were drilled on both sides of each crossing, as close as possible to the rivers and the proposed alignment.	sand and clay	Water force main	Assembled -line Method	Steel pipe	54 in. (137.6 cm)		3M Scotchkote system for coating and lining, Magnetic Guidance System (MGS), Para-Track System					With HDD installation, the pipe is typically not installed within a casing pipe but pulled into a reamed hole that is drilled first using a guided pilot drill. Bore pits are not required for HDDs. A critical component of the HDD pipe design was the coating system. Once the steel pipe was selected, multiple options of both coatings and linings were analyzed to select a resilient coating that would require limited maintenance in the future.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
64	A Contractor's Perspective on Constructability for Trenchless Project (Veidmark III 2008)	2008	Multiple locations in the US	445 to 712 ft (135.6 to 217 m)				Water force main	Assembled-line Method		42 to 60 in. (107 to 152.4 cm)							Once the site is studied and decisions are made on how long the bore will be and also the depth the path will be at, the methodology can be further honed. Some trenchless methods are better suited for short installations while other technology is available for longer lengths. The depth of the bore impacts the bore pit—how deep it will be will determine shoring requirements and drives equipment access considerations.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
65	Design of Mid-Path Intercept HDD Crossing of the Santa Maria River (Hanlon et al. 2017)	2017	Santa Maria, CA	2,000 ft (609.6 m)			alluvium derived from the Paso Robles Formation and dune sand.	Water force main	Intersect Method		30 in. (76.2 cm)				48 in. (114. 3 cm)			The mid-path intercept utilizes two HDD drill paths intersecting at a predetermined point along the design drill path. The two drill rigs establish the pilot hole towards a common point along the predetermined drill path. The mid-path intercept was proposed to reduce the opportunity for a frac-out at the toe of the slope and to reduce potential issues associated with drilling uphill in a dry hole of running sand. Frac-outs at any location were unacceptable and could actually stop the project.
66	Abandoned Coal Mines Make for Challenging HDD Design and Installation (J. Lueke et al. 1998)	1998	Whitemud Creek, CA	2297 ft (700 m)			topsoil over clay and sand over sandstone and clay shale bedrock. Coal and evidence of mining activity were also encountered.	High-pressure pipeline	Assembled-line Method	Steel pipe	20 in. (508 mm)							In this project, the stress calculations were completed based on the Pipeline Research Council Institute model. The calculation sheets could also be expanded to allow for the addition of the finite element analysis stresses provided by the geotechnical modelling.

No.	Project	Year	Location	Length	Depth	Site investigation	Soil type	Usage	Installation Method	Pipe Material	Pipe Diameter	Drilling Fluid	Notable Equipment	Pilot hole	Ream -ing	Pullback	Impact	Lesson Learned
67	Water and Sewer Construction with Horizontal Drilling Equipment (Lawson 2003)	2003	Plainview, TX; Beaumont, TX; Colombia, Missouri; and in Carmel, Indiana	320 to 900 ft (98 to 274 m)	14 to 26 ft (4.3 to 7.9 m)			Sewer force main		PVC	8 in. (20 cm)							Directional drills are perfectly suited for installing the types of pipe used in water and sewer systems. HDD crews are experienced in the installation of fused lengths of HDPE pipe. Restrained-joint PVC pipe products are ideally suited for installation by HDD equipment; couplings quickly lock sections of pipe together, holding them firmly together while pipe is pulled into place by a directional drilling unit.
68	Planning the Use of Horizontal Directional Drill to Minimize Site Impacts (Bailey and Drylie 2018)	2018	Norfolk, Virginia	2067 and 2953 ft (630 and 900 m)			dense to very dense dark grey fine sand with clay.		Assembled-line Method		42 and 48 in. (1067 and 1219 mm)							When the construction area is located in places with potential historical value, the construction team should eliminate potential impacts to historical site wherever possible and minimize those impacts that cannot be eliminated. Similarly, when constructing in wetland area, potential impacts should be avoided with alternative alignments or methods of installation.

F.7 CODES, GUIDELINES AND SPECIFICATIONS SUMMARY

Sixteen codes, guidelines, and specifications documents were reviewed in detail for this project. The collected information is categorized and summarized by different phases and elements in HDD construction, as presented in Table 9. The following are included in this summary:

- Illinois Department of Transportation (IDOT), "68D74-IL 26 Culvert Replacement: Proposed Specifications for Horizontal Direction Drilling (HDD)."
- Illinois Department of Transportation (IDOT), "HDD Guidance Specifications." (Draft, Appendix C:).
- Australasian Society for Trenchless Technology (ASTT), 2009, "Specification for Horizontal Directional Drilling."
- Washington Suburban Sanitary Commission (WSSC), 2011, "Standard Specifications, Section 02446, Horizontal Directional Drilling."
- Florida Department of Transportation (FDOT), 2013, "Standard Specifications for Road and Bridge Construction, Section 555 Directional Bore."
- New York State Department of Transportation (NYSDOT), 2013, "Geotechnical Design Manual."
- Atalah and Brown (2013) for Ohio Department of Transportation (ODOT), "Development of a Standard Specification for Horizontal Directional Drilling."
- Unified Facilities Guide Specifications (UFGS), 2013, "Utility Horizontal Directional Drilling."
- City of Overland Park, Kansas, 2014, "Right-of-Way Permit: Horizontal Directional Drilling Guidelines Handbook."
- City of Baton Rouge, Louisiana, 2015, "Horizontal Directional Drilling for Sewers."
- The Highways Agency, UK, 2018, "Guidance on the trenchless installation of services beneath motorways and trunk roads."
- New York State Department of Transportation (NYSDOT), 2008, "Standard Specifications: Revised Section 650-Trenchless Installation of Casing."
- The Plastic Pipe Institute, 2009, "Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe."
- American Society of Civil Engineering (ASCE), 2014, "Pipeline Design for Installation by Horizontal Directional Drilling."
- American Society of Civil Engineering (ASCE), 2005, "Pipeline Design for Installation by Horizontal Directional Drilling."
- Latorre et al. (2002) for US Army Corps of Engineers, "Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling."

Table 9. Summary Table for Codes, Guidelines, and Specifications

Phase	Element	Illinois Department of Transportation (IDOT) 68D74-IL 26 Culvert Replacement: Proposed Specifications for Horizontal Direction Drilling (HDD)
Before Construction	Site Investigation	
	Plan	(a) When required by the engineer, provide a detailed plan to show how damage to any roadway facility will be remedied. The details will become part of the As-Built plans. When remediation plans are necessary, they must be approved by the Engineer before work proceeds.
	Design	(a) Drilling fluid design: Use a mixture of bentonite clay or other approved stabilizing agent mixed with potable water with a minimum pH of 6.0 to create the drilling fluid for lubrication and soil stabilization. Do not use any other chemicals or polymer surfactants in the drilling fluid without written consent from the Engineer. Certify to the Engineer in writing that any chemicals to be added are environmentally safe and not harmful or corrosive to the facility. Identify the sources of water for mixing the drilling fluid. Any water source used other than a potable water source may require a pH test. (b) Bore hole diameter: Minimize potential damage from soil displacement and or settlement by limiting the ratio of borehole to the pipe size. The size of the back reamer bit or pilot bit, if no back reaming is required, will be limited to the pipe diameter to be installed as detailed in the Work Plan.
During Construction	Materials	(a) The pipe will be tested and shall be according to ASTM F714. (b) The fusion of the pipe shall be according to ASTM F2620.
	Equipment and Machinery	
	Locating and Tracking	(a) Use of a locating and tracking system capable of ensuring the proposed pipe is installed to proposed line and grade as intended. The tracking system shall provide information on clock and pitch, depth, transmitter temperature, battery status, X Y position, and azimuth. (b) Proper calibration of all equipment will be performed before the direction drilling begins.
	Installation	(a) Carry out excavation for entry, exit, recovery pit, slurry sump pits, and any other excavation as specified according to applicable portions of Article 202 of the Standard Specifications. Sump pits are required to contain drilling fluids if vacuum devices are not operated throughout the drilling operation unless approved by the Engineer. (b) Ensure adequate removal of soil cuttings and stability of the bore hole by monitoring the drilling fluids such as the pumping rate, pressures, viscosity, and density during the pilot bore, back reaming, and pipe installation. Relief holes can be used as necessary to relieve excess pressure down hole. Obtain the Engineer's approval of the location and all conditions necessary to construct relief holes to ensure the proper disposition of drilling fluids is maintained and unnecessary inconvenience is minimized to other facility users. (c) To minimize heaving during pull back, the pullback rate is determined to maximize the removal of soil cuttings without building excess down hole pressure. Contain excess drilling fluids at entry and exit points until they are recycled or removed from the site or vacuumed during drilling operations. Ensure that entry and exit pits are of sufficient size to contain the expected return of drilling fluids and soil cuttings. (d) Ensure that all drilling fluids are disposed of or recycled in a manner acceptable to the appropriate local, state, or federal regulatory agencies. When drilling in suspected contaminated ground, test the drilling fluid for contamination and appropriately dispose of it. Remove any excess material upon completion of the bore. If in the drilling process it becomes evident that the soil is contaminated, contact the Engineer immediately. Do not continue drilling without the Engineer's approval. (e) When conditions warrant, as determined by the Engineer, back reaming for enlarging the bore diameter shall be accomplished by connecting the reamer to trailing drill stems at the exit pit of the pilot bore. The drill pipe shall remain in the bore hole until the final product is pulled into place. After the pilot bore is established, do not push anything from the entry pit to the exit pit. (f) The timing of all boring processes is critical. Install a product into a bore hole within the same day that the pre-bore is completed to ensure necessary support exists.
	Site Restoration	(a) Within 48 hours of completing the installation of the pipe, clean the work site of all excess spoils. (b) Take responsibility for the removal and final disposition of excess slurry and spoils. (c) Ensure the work site is restored to pre-construction conditions or as detailed on the plans. (d) Take responsibility for any restoration for any damage caused by heaving, settlement, separation of pavement, escaping drilling fluid (frac-out), or the directional drilling operation at no expense to the Department.

Phase	Element	Illinois Department of Transportation (IDOT) 68D74-IL 26 Culvert Replacement: Proposed Specifications for Horizontal Direction Drilling (HDD)
	Remediation	(a) If an obstruction is encountered during boring that prevents completion of the installation in accordance with the design location and specification, the pipe may be taken out of service and left in place at the discretion of the Engineer. Immediately fill the product left in place with excavatable CLSM. Submit a new installation procedure and revised plans to the Engineer for approval before resuming work at another location. If, during construction, damage is observed to the IDOT facility, cease all work until resolution to minimize further damage and a plan of action for restoration is obtained and approved by the Engineer.
	Inspection	
After Construction	Quality Control	(a) Always take control of the operation. The contractor will have a representative who is thoroughly knowledgeable of the equipment, boring, and Departmental procedures present at the job site during the entire installation and available to address immediate concerns and emergency operations. No work will be performed until the Resident Engineer is present at the jobsite and agrees that the proper preparations have been made. (b) Product testing: When there is any indication that the installed pipe has sustained damage and may leak, work will stop, the Resident Engineer will be notified, and damage will be investigated. The Engineer will determine what type of testing is to be performed dependent upon the damage assessment. Testing methods include but are not limited to pressure testing and or watertight joint methods. (c) Failed bore path: If conditions warrant removal of any materials installed in a failed bore path, as determined by the Engineer, it will be at no cost to the Department. All voids created by any failure will be promptly filled with CLSM.
	Final Delivery	(a) Submit a Bore Path Report to the Engineer within seven days of the completion of each bore path. Include the following in the report: 1. Location of project 2. Name of person collection data, including title, position, and company name 3. Investigation of site location (Contract plans station number or reference to a permanent structure within the project right-of-way) 4. Identification of the detection method used 5. Elevation and offset dimensions as required. (b) As-Built Plans: Provide the Engineer a complete set of as-built plans showing all bores (successful and failed) within 30 calendar days of completing the work.

Phase	Element	Illinois Department of Transportation (IDOT) HDD Guidance Specifications (Draft, Appendix C:)
Before Construction	Site Investigation	(a) Notify owners of subsurface utilities along and on either side of the proposed drill path of the impending work. All utilities along and on either side of the proposed drill path are to be located. Most utilities can be located by calling JULIE for downstate projects (outside the limit of the City of Chicago) or DIGGER in the Chicagoland area. (b) Obtain all necessary permits or authorizations to carry out construction activities near or across all such buried obstructions. (c) Expose all utility crossings using a hydro excavation, hand excavation, or other approved method (potholing) to confirm depth. (d) Arrange construction schedule to minimize disruption (e.g., drilling under major highways and/or river crossings). (e) Determine and document the proposed drill path, including horizontal and vertical alignments and location of buried utilities and substructures along the path. It is recommended to use State Plane Coordinate system or Universal Transverse Mercator coordinate system, measured by GPS, as a reference for the entry and exit point. (f) Utility survey, geotechnical survey, and other evaluations are needed to reduce potential construction impact when installing long-distance and segmented pipes. The geotechnical survey shall follow the procedures in IDOT Geotechnical Manual.
	Plan	(a) Prior to beginning work, a Work Plan should be prepared to detail the procedure and schedule to execute the project. The work plan will be detailed, realistic, and based on actual working conditions for this project. The work plan documents the planning required to successfully complete the project. The work plan includes complete descriptions of proposed plans, procedures, equipment, personnel, and if applicable, supporting material, for the following: 1) Project design plots including a profile of the crossing plotted at the proper scale, site layout including entry and exit points and surface survey plots, pipe stress and pullback calculations. 2) Drilling operation plan illustrating the plan of the pilot hole drilling procedure, the reaming operation, and the pullback procedure. 3) Equipment list and setup plan including drilling rig, drill bit, back-reamer(s), mud mixing and pumping systems, guidance system with calibration records and rig safety system. 4) Drilling fluid management plan, including drilling fluid types and specifications, drilling fluid pressure calculations, procedures of cleaning and recycling equipment, estimation of flow rates, procedures for minimizing drilling fluid escape, and the procedure of final disposal of waste drilling fluids with location provided. 5) Other plans, including pipe storage and handling details and pipeline assembly and installation procedures, Safety Data Sheets (SDS) of any potentially hazardous substances to be used, contingency plans based on risk analysis and personnel qualifications. (b) All potentially affected work areas shall be visually inspected to assess and document conditions prior to any work being conducted. Once occurring during the construction, all incurred damage and repairs should be documented in the Damage and Repairs Plan and submitted to the Department. If there is a boring failure during construction, the failed bore path should be shown in the plan along with the final bore path. The failed bore path should be noted as “Failed Bore Path - Taken Out of Service.” The name of the Utility, location, and length of the drill head, and any drill stems not removed from the bore path should be indicated in the Plan.

Phase	Element	Illinois Department of Transportation (IDOT) HDD Guidance Specifications (Draft, Appendix C:)
	Design	(a) In the design of borehole path, the Engineer needs to consider the existence of the obstacles, site and soil conditions, space for future projects, conflicts with existing utilities to determine the depth of penetration. More importantly, the risks of inadvertent drilling fluid return and surface settlement or heaving should also be included in the considerations. If the risks existed, the depth of penetration should be increased, which typically has a minor effect on construction costs unless more difficult ground conditions are encountered at greater depth. (b) In HDD projects, dry boring is seldomly used and may only be used for short-range applications. Drilling fluid is commonly applied. The main purposes of the drilling fluid are to stabilize the bore hole, carry away cuttings, reduce friction (pullback and torque on drill rods and product pipe), maintain temperatures of bits and transmitter, clean cuttings from the drill bit and reamers, and control groundwater pressure. In fine-grained soils like clays, the fluid could also prevent swelling of the surrounding soil. (c) The mixture of drilling fluids needs to be designed to perform the preceding functions in the expected soil. The viscosity of the drilling fluid shall be varied to best fit the encountered soil conditions. Fluid segregation can cause the slurry flowing out of the bore hole to be unable to represent those remaining in the bore hole. The design of the drilling fluid mixture shall prevent fluid segregation from happening. (d) In suitable ground conditions, water alone should not be used because it may destabilize the hole easily. It is more common to use a mixture of bentonite clay or other approved stabilizing agent, such as polymers, lubricants, and viscosifiers mixed with potable water to create the drilling fluid. Bentonite works best for sandy soils because it has the ability to form a filter cake on the borehole wall which reduces infiltration of the drill fluid into the surrounding soils and aids in stabilizing the bore hole. Polymers can be added as additives in drilling fluid for clayey soil. (e) Use of any other chemicals or polymer surfactants in the drilling fluid without written consent from the Engineer is prohibited. The Engineer should certify that any chemicals to be added are environmentally safe and not harmful or corrosive to the facility. Waste oil or environmentally non-compatible polymers cannot be part of the composition. Fiber additives could increase installation efficiency up to 67% compared to untreated drilling fluid. (f) The source of water for mixing the drilling fluid should be identified before construction. Any water source used other than a potable water source may require a pH test. The water shall be from a clean source. Water of a lower pH or excessive calcium shall be treated with the appropriate amount of sodium carbonate or equal. Approvals and permits are required for obtaining water from such sources as streams, rivers, ponds, or fire hydrants. Hard water may be treated with soda ash to reach the required pH value. In conclusion, water with a pH between 7.5 and 10 and free of chlorine with calcium, sodium chloride, and chlorine should be used. (g) Before HDD construction, the contractor shall provide detailed information about drilling fluid and fluid mix in work plan.
During Construction	Materials	(a) Handling the casing and pipe, especially while pulling, is a stage that should be planned at the design phase. It is highly recommended that the pipe be pulled as one segment (fully welded or fused), which decreases the time of pulling and hence decreasing the chances of bore failure and stuck pipes. It is necessary to check that the right-of-way is sufficient to layout the pipe and pull it as one segment while designing its profile and location. Pipe handling and pulling machinery and equipment, such as excavators, roller-stands, and swivel should also be enough in number to enable the pulling of the casing and pipe without exceeding stress and deformation limits. The pulling scheme should be designed, and the bending angles should be calculated and checked. (b) The pipes for installation need to be homogenous and free of visible cracks, holes, and other faults. The Contractor shall transport, handle, and store the pipes in accordance with the manufacturer's recommendations at all times. Materials that are damaged or lost shall be repaired or replaced by the Contractor at no additional cost to the Engineer. (c) The Contractor should prevent the pipes from being cut, kinked, or damaged. The pipes should be stored on level ground that is free of sharp objects. In construction sites, they can be stored on wooden sleepers with suitable space between supports. Stacking of pipes should be limited to a height that would not cause excessive deformation for those at the bottom layers. Ropes, fabrics, or rubber-protected slings and straps shall be used to handle the pipes, while chains or cables with hooks inserted into the pipe ends shall be prevented. In pipe transporting, dragging pipes over sharp objects and dropping pipes onto rocky or unprepared ground shall be prevented.
	Equipment and Machinery	(a) The directional drilling machine needs to consist of a power system to rotate, push, and pull back hollow drill pipe into the ground at variable angles while delivering a pressurized fluid mixture to a guidable drill head (bit). It should have sufficient strength to drill the pilot hole, ream the hole to adequate diameter, and pull the carrier pipe through the hole for the length and pipe diameter indicated through a leak-free hydraulic system. (b) The drill rig is anchored to the ground to withstand the pulling, and rotating pressure. Depending on the diameter and length of product pipe being installed, the capacity of drill rig and its auxiliary equipment need to be adequate for the installation, especially for installing dual force mains. (c) The employed drill rig shall be capable of exerting a pullback force of at least two times that of the total anticipated pulling force required to complete the installation of the pipe specified.

Phase	Element	Illinois Department of Transportation (IDOT) HDD Guidance Specifications (Draft, Appendix C:)
	Locating and Tracking	(a) Locating and tracking systems are used to ensure the proposed installation is executed as intended. The Department recognizes walkover, wire line, and wire line with surface grid verification, Magnetic Guidance System (MGS) probe, proven (non-experimental) gyroscopic probe, or any other system as approved by the Engineer as the accepted methods of tracking directional bores. (b) If signal interference is encountered that significantly affects the ability to accurately track the drill bit, the Engineer may specify the use of a suitable tracking system. If the Owner informs the Contractor about signal interference, or it is reasonable to expect interference at the site prior to bidding, a suitable tracking system without extra cost to the Owner shall be selected; otherwise, the Owner shall adjust the contract value and time accordingly. The drill path shall be surveyed for any surface geo-magnetic variations or anomalies if the Contractor is using a magnetic guidance system. (c) The locating and tracking system should provide information of the depth of the drill head from the transmitter to the surface at any location along the path of the bore; pitch, roll, and clock face orientation to determine the location of the drill head. (d) All facilities need to be installed such that their location can be readily determined by electronic designation after installation. For non-conductive products, detection wire should be attached.
	Installation	(a) The Contractor shall verify the loading capacity of the HDD machine before the pilot hole drilling. The size of the entrance and exit pits, controlled by the pipe depth, diameter, and material, should be of sufficient size to avoid a sudden radius change of the pipe and consequent excessive deformation at these locations. The entry hole should be angled so that curvature of pilot hole does not exceed allowable bending radius of product pipe. After the pilot bore is established, do not push anything from the entry pit to the exit pit. (b) There are two types of installation options for an HDD project: the Cartridge method and the Assembly-line method. The Assembly-line method allows the pipe to be pulled in one unit. It requires large construction area. The Cartridge method assembles a single pipe section, then pulls one section into bore path sequentially. It is less efficient than the Assembly-line method when the bore path is straight. However, the Cartridge method is effective for limited easement or right-of-way. The Assembly-line method can be used for both ductile iron pipe and HDPE pipe, while the Cartridge method cannot be used for HDPE pipe usually. (c) The Contractor shall ensure the soil cuttings are removed effectively, and the borehole is stable during the process of pilot hole boring, forward/back reaming, and pipe installation. The drilling fluid needs to be monitored, and the pumping rate, pressure, viscosity, and density shall be recorded. When the excess pressure gets very high, relief holes might be constructed at locations approved by Engineers. When the relief holes are to be constructed on IDOT ROW, approval from IDOT would be needed. (d) The Contractor shall minimize heaving during the pullback process by selecting a pullback rate that tends to maximize the removal of soil cuttings without building excess down hole pressure. When drilling in suspected contaminated ground, test the drilling fluid for contamination and appropriately dispose of it. If in the drilling process it becomes evident that the soil is contaminated, the Contractor shall stop the drilling and contact the Engineer immediately. Approval from Engineer is required to continue the drilling. (e) During construction, low-density grout could cause pipe floating. It is recommended to make the grouting operations in multiple lifts to prevent pipe floating. In addition, filling the new pipe segment with water in order to add weight and prevent floatation could also be considered. (f) In the drilling process, the Contractor shall provide methods to control line and grade. Locating and tracking system should be used to accurately locate the pilot hole by the Contractor. The recommended tolerance of both the vertical and horizontal alignment should be within plus or minus 1% of the bore length, and the vertical path of the pilot hole must not establish new high points not shown in the designed path. The Contractor shall include electronic monitoring of horizontal and vertical drilling head location and furnish tabulations of horizontal and vertical alignment to Engineer at the completion of pilot hole drilling. When the pilot bore deviates from the planned bore path, the Contractor shall notify the Engineer. The Contractor may be required to pull back and re-drill from the location along the bore path where the deviation occurred, if deemed necessary by the Engineer. If conditions warrant removal of any materials installed in a failed bore path, as determined by the Engineer, it will be at no cost to the Department. All voids need to be filled promptly with controlled low-strength material, backfill.

Phase	Element	Illinois Department of Transportation (IDOT) HDD Guidance Specifications (Draft, Appendix C:)
	Site Restoration	(a) The Contractor should restore the site to its original conditions or better at no additional cost to the Department. The restoration shall include but not be limited to paved and unpaved surfaces, structures, shrubbery, landscaping, trees, and all else encountered. Any damage caused by heaving, settlement, separation of pavement, escaping drilling fluid due to the drilling operations shall be repaired by the Contractor. If, during construction, damage is observed to the IDOT facility, cease all work until resolution to minimize further damage and a plan of action for restoration is obtained and approved by the Engineer. (b) The Contractor should backfill and compact all excavations, including subsurface exploration borehole, entry and exit pits, relief holes (if applied), etc. The subsurface exploration boreholes shall be sealed in accordance with IDOT Geotechnical Manual Section 4.4.2.1. Before sealing the annulus space, the Contractor shall allow the installed product pipe to cool and relax from the heat generated during the pull-back process due to friction and high-tension stresses. Before backfilling the entry and exit pit, the Contractor shall ensure that the product pipe is properly connected, installed, and supported by suitable material, as approved by the Engineer, in order to avoid sagging after backfilling and compaction. (c) Any excess material shall be removed upon completion of the bore. All drilling fluids need to be disposed of or recycled in a manner acceptable to the appropriate local, state, or federal regulatory agencies. All drilling fluid and fluid additives shall be disclosed. Excess drilling fluid shall be confined in a containment pit at the entry and exit locations until recycled or removed from the site. Precautions shall be taken to ensure that drilling fluid does not enter roadways, streams, municipal storm, or sanitary sewer lines, and/or any other drainage system or body of water. Unintended surfacing of drilling fluid shall be contained at the point of discharge and recycled or removed from the site. Drilling fluids that are not recycled and reused shall be removed from the site and disposed at an approved disposal site.
	Remediation	(a) In HDD construction, boring failure happens when the drilling equipment cannot proceed. In this kind of situation, the Contractor shall firstly cease the operations to allow the ground induced hydro-lock effect to subside. Then, if the drilling equipment remains stuck on re-commencement of the operations, the Contractor shall notify the Engineer immediately. The Engineer and Contractor shall discuss the appropriate equipment recovery plan (e.g., open cut) to allow the drilling to continue. If the encountered obstruction can prevent installation to be as designed, the drilling pipe can either be taken out of service or left in place with approval from the Engineer. The pipe left in place should be filled with excavatable flowable fill immediately. A new installation procedure and revised plans should be submitted to the Engineer for approval before resuming work at another location. In the case of permit work, the Department shall be notified of boring failure and approve the mitigation plan. (b) Hydraulic fracturing could happen when the soil layer is insufficient to hold down the mud pressure. Drilling under the shallow part of a sloping surface could easily cause hydraulic fracturing. Using pressure relief holes and increasing cover depth are effective ways to reduce the risk of hydraulic fracturing. Hydraulic fracturing is also common when drilling through loose and highly permeable soil like sand, silty sand, or clayey sand. In this case, the drilling fluid shall be adjusted properly. (c) Hydro-lock and hydraulic fracturing could be noticed by monitoring the drilling fluid pressure. If the pressure goes abnormally high, the Contractor shall ensure that the contingency plan is implemented. The Engineer and the Contractor will discuss and implement additional options as needed. (d) If the pilot bore deviates from the planned bore path, the Contractor shall notify the Engineer. The Contractor may be required to pull back and re-drill from the location along the bore path where the deviation occurred, if deemed necessary by the Engineer.
	Inspection	(a) The Department reserves the right to request a warranty from the Utility for any or all work performed within the ROW. The warranty shall guarantee the work performed by the Utility/Contractor to be free from failure, shifting, settlement, erosion, roadway damage, facility damage, etc., for a period as defined by the Department. All warranty work shall be at no cost to the Department. All warranty work shall begin within 30 days of written notice by the Department to the Utility. (b) The Department reserves the right to require a Surety Bond from the Utility/Contractor for boring operations and utility installation. A Surety Bond will remain in effect until released by the Department. The amount of the Surety Bond shall be specified by the Department. The amount may be based on experience level and performance record of Utility/Contractor, as well as potential monetary value of damages to Department facilities. The specified amount shall guarantee full compliance with the permit, proper installation, maintenance, repairs, relocation, modification, abandonment, remediation, emergency costs, traffic control, removal items (if required), etc., at no expense to the Department and no potential risk of harm to the public or the environment.
After Construction	Quality Control	(a) The Contractor shall conduct appropriate pipe joint testing methods and ensure the joints follow ASTM C828, ASTM C1103, and ASTM C969. The test records shall be provided to the Engineer as part of the As-Built Plan. (b) If there is any indication that the installed product has sustained damage, work must be stopped, and the Engineer must be notified. The Engineer may require exploratory investigations or testing and reserves the right to be present during this work. In these conditions, a pressure test is typically required by Engineer to be performed after the installation of the product pipe. The Engineer shall review the test results and determine whether the product installation satisfies the specifications. Non-compliant installations may need to be filled with controlled low-strength material backfill. (c) Further testing may be required to ensure the pipeline (including joints) is leakproof. For example, watertight configurations are usually required for the product pipes that are installed beneath any pavement, including sidewalks and shoulders.

Phase	Element	Illinois Department of Transportation (IDOT) HDD Guidance Specifications (Draft, Appendix C:)
	Final Delivery	(a) The Contractor needs to submit a Boring Path Report to the Engineer within seven days of the completion of each bore path. The Boring Path Report shall include (1) location of the project, project number and contract number or permit number; (2) Name of the person who collected the data (title, position, company name); (3) Investigation site location (Contract plans station number or reference to a permanent structure within the project right-of-way); (4) Identification of the detection method used; (5) Elevation and offset dimensions as required. (b) At the completion of the HDD product pipe installation, the Contractor shall provide the Engineer a Marked-up Plan noting all deviations from the plans in the design phase that result in change of location, material, type, or size of work guided by the boring operations and guidance system log. The mark-ups shall include pipe final alignment, entry and exit pit, pipe connection joints, and lateral service connections. (c) Upon completion of HDD installations, the Permittee shall provide IDOT with As-Built plans and any supporting documents within 60 days of project completion. As-Built plans are preferred in common software (like: MicroStation, Geopak, AutoCAD, etc.), but may be submitted in paper form. The plans must show appropriate elevations and be referenced to a Benchmark (mean-sea level) or to a U.S. Geological Survey (USGS) grid system and datum. Plans must be the same scale in black ink on white paper, of the same size and weight as the permitted plans. As-Built plans shall be derived from the tracking data and operator logs. Specific contents may include but not be limited to: (1) Drawings that indicate the center line location of each facility installed and abandoned (if applicable). Notes should be added to indicate the final bore path diameter, product diameter, drilling fluid composition, composition of any other materials used to fill the annular void between the bore path and the product, or facility placed out of service. If the product is a casing, size of casing and product pipe placed within the casing should be noted. (2) Construction plan, including size, capacity, and arrangement of drilling equipment, type of used steering and tracking equipment, location and size of entry and exit pits, method of installing detection wire, method and equipment to fuse pipe, boring procedure (including water source for drilling, method to control slurry, etc.) (3) Detection of surface movement. The pre-construction and post-construction elevations of the Department facilities at maximum 10 ft (3 m) intervals along all roadway shoulders, lane edge lines, and centerlines shall be reported. The limits of the as-built plans shall be a minimum of 100 ft (30.5 m) on each side of the bore line or as directed by the Engineer. (4) Cross-section for each bore path. The ground or pavement surface and crown elevation along each facility installed or installed and placed out of service should be indicated to an accuracy of 1 inch (25.4 mm). On profile plans for bore paths crossing the roadway, show Department roadway centerline stationing at the crossing on the plans. (5) Drawings show top elevation, diameter, and material type of all utilities encountered and physically observed during the subsurface exploration. For all other obstructions encountered during a subsurface exploration or the installation, the type of material, horizontal and vertical location, top and lowest elevation observed should be indicated. It is necessary to note if the obstruction continues below the lowest point observed.

Phase	Element	Australasian Society for Trenchless Technology (ASTT) Specification for Horizontal Directional Drilling (2009)
Before Construction	Site Investigation	(a) The contractor shall ensure that the geotechnical data report (GDR) provided is sufficient to complete the work. Additional geotechnical investigation may be requested by the contractor if it is deemed that the GDR provided is insufficiently detailed to complete the work without undue risk to the project.
	Plan	(a) The Contractor shall prepare a drilling contingency plan specific to the site of operation. The plan should address, but not be limited to, the following: (i) General procedures and labor issues for the duration of the project, (ii) Equipment requirements and the basis of duty and standby, (iii) Boring fluid fracture (borehole) and general spillage, (iv) Time considerations, (v) Clean up, environmental and surface monitoring methods, (vi) Contract details for the client and any local regulatory bodies that may be affected by the project, (vii) Waste disposal plans, (viii) General Public Relations requirements. (b) The Contractor shall undertake works in accordance with an approved Traffic Management Plan (TMP). The TMP shall be in accordance with the provisions of AS 1742 - Manual of Uniform Traffic Control Devices and any additional requirements of the local and state authority. The Contractor shall ensure that access is maintained for public and construction traffic. Public traffic shall be isolated from construction traffic wherever practicable. In areas where access for public traffic cannot be separated from construction traffic, appropriate traffic measures shall be clearly identified in the TMP. The TMP shall clearly identify what traffic control equipment shall be implemented for the duration of the works. All traffic control equipment shall be kept in good order to ensure visibility and reflectivity is maximized for both day and night traffic. Any by-pass roads, detours, and other temporary works proposed shall be clearly identified in the TMP. Details of the proposed temporary works shall be provided to the Client and other relevant traffic authorities for approval prior to the start of the Works. Pursuant to these requirements, traffic management notices shall be provided to parties nominated by the Client for distribution and displayed on all safety notice boards. These notices shall be updated to display the current conditions at all times. Traffic management actions implemented on site shall be inspected at least daily or at such greater frequency as required to ensure they are in accordance with the plans. The contractor shall complete and maintain a register of traffic management actions to reflect inspections and maintenance undertaken. The Contractor shall provide for Client approval a Public relationship management Plan in accordance with the relevant Australian Standards. (c) A drilling fluid design plan, including a recycled fluid handling system shall be established and agreed upon with the Client prior to commencing the Works. This plan shall be revised, when warranted throughout the project to ensure the drilling fluid is performing as per specification. The Contractor's drilling execution plan shall identify the equipment to be retained onsite to check drilling fluid properties. Alternations to the drilling fluid mix shall be made, when warranted, to stay within the specification of the drilling fluid plan.
	Design	
During Construction	Materials	(a) The pipe manufacturer shall be designated at the time of the tender. The Client must approve, in writing, any subsequent change of pipe manufacturer. The Contractor shall provide a record of product-specific experience and product information at the time of tendering. The Contractor shall transport, handle, and store the pipes and fittings in accordance with the manufacturer's recommendations at all times. Materials that are damaged or lost shall be repaired or replaced by the Contractor at no additional cost to the Client.
	Equipment and Machinery	
	Locating and Tracking	(a) Upon successful completion of the pilot hole, the Contractor shall ream the borehole using the appropriate tools. The bore diameter shall be a minimum of 25% greater than the outside diameter of pipe.

Phase	Element	Australasian Society for Trenchless Technology (ASTT) Specification for Horizontal Directional Drilling (2009)
	Installation	(a) The Contractor shall take all necessary action to ensure the safety of the work and shall always ensure compliance with the pre-approved Safety Management Plan requirements. The sizes of all excavations shall conform with the following requirements: (i) All pits shall be of the minimum possible size commensurate with safe working practices. The Contractor shall select the size and provide for client approval the details of all pits. (ii) Every face of any excavation that exceeds a depth of 1.5 m (4.9 ft) shall be supported or contained by appropriately designed shoring. (iii) The shoring of the excavation shall be braced in accordance with the appropriate trench safety standards as the excavation progresses. (iv) All necessary measures must be taken to ensure that excavations are left after each operating hour in a safe condition at the end of each workday. This should include the erection of suitable hard barricades, warning signs, and hazard lights. (v) The Contractor shall inspect the site, and verify all existing levels, survey control points, and set out points shown on the Drawings, before commencing the earthworks. (vi) The earthworks shall be set out in accordance with the design drawings. (vii) All excavations shall be made to the depth and extent as shown on the Drawings with proper allowance for fill, additional cover (where required), and formwork. The excavations shall be kept free and clear of loose materials, water, and rubbish. Should excavation to the nominated depth reveal unstable or unsuitable ground, the Contractor shall immediately notify the Client and take steps to make it safe. This work will be undertaken at additional cost to the Client if the ground conditions are found to be different from the initial ground conditions investigation. After satisfactory completion of all testing and removal of all equipment and excavated materials, the Contractor shall prepare the bottom of all pits to the same specification as required by the rest of the pipelines. The contractor shall remove all loose and disturbed materials below pipe grade to the undisturbed earth level and shall re-compact the materials to an agreed specification. (b) Connections of the pipe ends shall be achieved by means of Central Plastics Electro Fusion couplings if PE pipe were used or other methods approved by the Client. The electro-fusion couplings shall be slipped over the pipe ends at the entry and fused in place. Installation of electro-fusion couplings shall be done in accordance with the manufacturer's recommended procedures. (c) The Contractor shall not attempt to drill, ream, and install a new pipe without verifying the capacity of the HDD machine. (d) The Contractor shall pull the pipe through the borehole during the last step of reaming with the new pipe attached to the back of a swivel connector. Once pullback operations have commenced, the operation must continue without interruption until the pipe is completely pulled through the reamed hole. This is to prevent the slurry hardening in the borehole. During the pullback operation the Contractor will not apply more than the maximum safe pipe pull force as specified by the pipe manufacturer. Due to the heat generated during the pullback process due to friction and high-tension stresses, prior to sealing the annulus space (space between outer pipe installed and the conduits inside), restoring the exit pit, and backfilling the entry pit, the installed pipe shall be allowed for cool and relax for the manufacturer's recommended amount of time, but not less than four hours. Sufficient excess length of new pipe shall be allowed to protrude into the access chamber to allow for cooling and relaxation and the consequential axial contraction that will take place. (e) Prior to backfilling the entry and exit pits, the Contractor shall ensure that the new pipe has been properly connected and installed. Suitable material, approved by the Client, shall be used directly under the new pipe as support, in order to avoid sagging after backfill and compaction.
	Site Restoration	
	Remediation	(a) In the event of a boring fluid fracture or return loss occurring during pilot hole boring operations, the Contractor shall ensure that the contingency plan for frac-out or fluid loss is implemented. The Client and the Contractor will discuss additional options and implement as required. (b) In the event that the pilot bore deviates from the planned bore path, the Contractor shall notify the Client. The Contractor may be required to pull back and re-drill from the location along the bore path where the deviation occurred, if deemed necessary by the Client. (c) In the event that the drilling equipment becomes stuck, the Contractor shall immediately cease operations to allow any ground-induced hydro-lock to subside. Then, if upon re-commencement of the operations, the pipe remains stuck, the Contractor shall immediately notify the Client. The Contractor, in consultation with the Client, will discuss the appropriate equipment recovery plan (e.g., open cut) to be implemented to allow the work to continue. (d) The Contractor shall cease operations when monitoring points indicate surface disruption that falls between the agreed specifications. The Contractor shall propose an action plan for review and approval by the Client to remedy the problem.
	Inspection	

Phase	Element	Australasian Society for Trenchless Technology (ASTT) Specification for Horizontal Directional Drilling (2009)
After Construction	Quality Control	(a) After satisfactory completion of the installation of the new pipe and removal of all equipment and excavated material, the Contractor shall conduct inspection and testing as follows: (i) All appropriate pipe joint testing methods shall be applied. The joints shall follow ASTM C828, ASTM C1103, ASTM C969, and BS 5911. (ii) Hydrostatic pressure testing and CCTV inspection for the entire pipeline. (iii) Further testing may be required to ensure the pipeline is leak-proof, based on manufacturer-provided material properties. If a sewer pipeline is installed, the testing shall be as recommended in the following testing standards (EN160, EPA). (iv) All test records shall be provided to the Client as part of the “As-Built” documentation. (b) The Contractor shall take all care and necessary precautions to protect existing structures, utilities, and services in planning and execution of the Works. All potentially affected work areas shall be visually inspected to assess and document conditions prior to any work being conducted. Any damage to adjacent properties caused by or part of this work shall be repaired and restored to its original condition at the Contractor’s expense. The Contractor shall be responsible for the identification and protection of services where these are crossed by construction activities. (c) Where crossing of roadways and railways are involved, the Contractor shall be required to measure, record, and report any ground settlement to the satisfaction of the respective controlling agencies. Where crossing any utilities and pipelines during the HDD process, minimum of the Contractor shall monitor ground settlement or heave directly above and 3 m (9.8 ft) before and after the utility or pipeline intersection.
	Final Delivery	(a) All construction drawings and design calculations used during the construction shall return to the client marked up and revised to status. The mark-ups shall include pipe final alignment, entry and exit pit, pipe connection joints, and any lateral service connections. (b) The Contractor shall submit an Inspection and Testing Plan (ITP) and Manufacturers Data Report (MDR) for approval. (c) The Contractor shall maintain a record of “As-Built” drawings and other data in accordance with the General Conditions of Contract, this Specification, and the approved Scope of Works. (d) The Client reserves the right to reasonable access to the Contractor's facilities and Quality Assurance records for the purposes of a Quality Assurance Audit and inspection throughout the contract period. (e) The Contractor's Quality Management Plan shall define the method for performing its own internal audits.

Phase	Element	Washington Suburban Sanitary Commission (WSSC) Standard Specifications Section 02446 Horizontal Directional Drilling (2011)
Before Construction	Site Investigation	(a) Do not use HDD in rock stratum or subsoil consisting of boulders and underground obstructions that impede the process.
	Plan	
	Design	(a) Determine drilling length and equipment pull strength for type of soil encountered. (b) Bentonite drilling mud should be compatible with environment. Waste oil or environmentally non-compatible polymers cannot be part of drilling fluid composition. (c) Angle entry hole so that curvature of pilot hole does not exceed allowable bending radius of HDPE pipe. Be able to make a turn of up to 90 degrees and maintain curvature not to exceed allowable bending radius of HDPE pipe.
During Construction	Materials	
	Equipment and Machinery	(a) Equipment must be capable of following boring lengths in a single bore.
	Locating and Tracking	(a) Provide a method to control line and grade. Provide and maintain instrumentation that accurately locates pilot hole. Drill pilot hole along path following Drawings to these tolerances: 1) Vertical alignment plus or minus 0.5 foot (15.24 cm). Vertical path of pilot hole must not establish new high points not shown on Drawings. 2) Horizontal alignment plus or minus 1.0 foot (30.5 cm). Include electronic monitoring of horizontal and vertical drilling head location. Obtain accuracy range within 1 inch (2.54 cm) of the actual position of the pipeline. Record position readings at a maximum of 10 foot (3 m) intervals. At completion of pilot hole drilling, furnish tabulations of horizontal and vertical alignment to Engineer.
	Installation	(a) When water is encountered, provide and maintain a dewatering system of sufficient capacity to remove water. Keep excavation free of water until backfill operation is in progress. Perform dewatering in a manner that removal of soils particles is held to a minimum. Dewater into sediment trap following Section 01570. (b) Provide clean water for drilling, at no cost to the Commission, at Engineer's requirement. (c) Provide a swivel to reaming assembly and pull section of pipe to minimize torsional stress on pull section after drilling pilot hole. (d) Hold reaming diameter to 1.5 times outside diameter of HDPE pipe being installed. (e) Protect pull section as it proceeds during pullback so it moves freely and is not damaged. (f) Pull detection wire along with HDPE pipe. Extend wire into the locator station at each end of HDPE pipe. (g) When connecting to adjacent pulled or non-pulled section of HDPE pipe, allow pull section of pipe to extend past termination point. Make tie-ins the next day after pullback of HDPE pipe. (h) Test pit pipe installation to verify horizontal and vertical alignment at Engineer's direction. One test pit for every 500 feet (152 m) along the length of pipeline. The Engineer may order additional test pit for each test pit that reveals pipeline installation is not in compliance with Contract Documents at no additional cost to the Commission. (i) Replace portions of pipeline not in compliance with Contract Documents at Engineer's direction and at no additional cost to the Commission. (j) Detection Wire: TW, THW, THWN, or HMWPE insulated copper, 10 gage or thicker wire. (k) Detection Wire: Install detection wire without splices as shown on Standard Details. Terminate detection wire inside locator box using proper sized crimp type connectors on wire ends. Connect each wire to terminal maintaining at least 18 inches (45.7 cm) slack in each wire for underground flush-mounted locator stations. Neatly coil slack wire in test station below the terminal board. Locate wires on top and along HDPE pipe. Allow adequate slack and support to protect wires from damage during backfilling operations. Test each detection wire for continuity after backfill is completed. 1) If test for continuity is negative, repair or replace at Engineer's direction. 2) After continuity is verified, connect each detection wire to terminal block in locator station.
	Site Restoration	(a) Dispose of drilling fluid and other spoils at location following laws, ordinances, rules, and regulations of local jurisdiction. Transport excess fluids and other spoils to disposal site, at no additional cost to the Commission. Minimize drilling fluid at locations other than entry and exit points. Immediately clean up any drilling fluids that inadvertently surface.
	Remediation	
	Inspection	

Phase	Element	Washington Suburban Sanitary Commission (WSSC) Standard Specifications Section 02446 Horizontal Directional Drilling (2011)
After Construction	Quality Control	(a) Complete HDD so as not to interfere with, interrupt, or endanger surface and activity thereon. (b) Maintain close observation to detect settlement or displacement of surface and adjacent facilities. Notify Engineer immediately if settlement or displacement is detected. Maintain safe conditions and prevent damage. (c) Perform field testing of HDPE pipe following Section 02533. (d) Follow pipeline alignment on Drawings within tolerances specified herein. Before adjustments, notify Engineer for approval. (e) Notify Engineer when forward motion of operation is stopped by an obstruction. 1) Abandon in place with drilling fluid, unless Engineer directs otherwise. 2) Upon Engineer's approval, attempt the second installation at an approved location or excavate at point of difficulty and install HDPE pipe by trench method following Section 02533. (f) Withdrawals, abandonments, and restarts are at no additional cost to the Commission when HDD is provided as an option of installation of pipe. (g) Exercise caution including, but not limited to, locating utilities following Section 01150, drilling downhole (test pits) to observe drill stems or reamer assembly to clear other existing utilities at locations following Drawings. (h) Keep the number of boring pits to a minimum, no closer than following distances, unless otherwise approved by Engineer. (i) Test each detection wire for continuity after backfill is completed. If the test for continuity is negative, repair or replace at the Engineer's direction. After continuity is verified, connect each detection wire to the terminal block in the locator station.
	Final Delivery	

Phase	Element	Florida Department of Transportation (FDOT) Standard Specifications for Road and Bridge Construction Section 555 Directional Bore (2013)
Before Construction	Site Investigation	
	Plan	(a) When and where installations temporarily disrupt the use of a pedestrian way, provide a safe alternate route in accordance with the Design Standards, Index Nos. 600 and 660.
	Design	(a) Drilling fluid design: Use a mixture of bentonite clay or other approved stabilizing agent mixed with potable water with a minimum pH of 6.0 to create the drilling fluid for lubrication and soil stabilization. Do not use any other chemicals or polymer surfactants in the drilling fluid without written consent from the Engineer. Certify to the Engineer in writing that any chemicals to be added are environmentally safe and not harmful or corrosive to the facility. Identify the source of water for mixing the drilling fluid. Any water source used other than a potable water source may require a pH test. (b) Use materials that are appropriate for the stresses generated by the selected equipment and field conditions. It is not intended to portray that the use of materials with these minimum material standards will retain their required properties if the stress limits are exceeded for which they were designed during installation. Ensure that the appropriate material is used to retain compliance once it is installed. (c) The size of the back reamer bit or pilot bit, if no back reaming is required, will be limited relative to the product diameter to be installed as follows: 1) when the O.D. of pipe is from 8 in. (20 cm) to 24 in. (61 cm), the maximum bit diameter is 1.5 times O.D. of pipe; 2) When the O.D. of pipe is greater than 24 in. (61 cm), the maximum bit diameter is O.D. of pipe plus 12 in. (30 cm). Use manufacturer's recommendation O.D. for pipe with restrained joints. (d) Match equipment to the size of pipe being installed. (e) Ensure that the drill rod can meet the bend radius required for the proposed installation.
During Construction	Materials	(a) Materials are defined as carrier pipe or conduit, casing, or duct that becomes the installed product. Incidental materials that may or may not be used to install the product depending on field requirements are not paid for separately and will be included in the cost of the installed product. Plastic pipe sections are to be butt fused. Metal pipe sections are to be butt welded. Restrained joint connectors (external connectors, bell and spigot, and any joint that overlaps a portion of the product to be installed) are to be installed according to the manufacturer's specifications and instructions.
	Equipment and Machinery	

Phase	Element	Florida Department of Transportation (FDOT) Standard Specifications for Road and Bridge Construction Section 555 Directional Bore (2013)
	Locating and Tracking	(a) The method of locating and tracking the drill head during the pilot bore will be shown in the Plans. The Department recognizes walkover, wire line, and wire line with surface grid verification, or any other system as approved by the Engineer, as the accepted methods of tracking directional bores. Use a locating and tracking system capable of ensuring the proposed installation is installed as intended. If an area of radio signal interference is expected to exceed 5 feet, the Engineer may specify the use of a suitable tracking system. (b) The locating and tracking system must provide information on (1) Clock and pitch information, (2) Depth, (3) Transmitter temperature, (4) Battery status, (5) Position (x, y), and (6) Azimuth, where direct overhead readings (walkover) are not possible (i.e., subaqueous or limited access transportation facility). (c) Ensure proper calibration of all equipment before commencing directional drilling operation. (d) Take and record alignment readings or plot points such that elevations on top of and offset dimensions from the center of the product to a permanent fixed feature are provided. Such permanent fixed features must have prior approval of the Engineer. Provide elevations and dimensions at all bore alignment corrections (vertical and horizontal) with a minimum distance between points of 100 feet (30.5 m). (e) Provide a sufficient number of elevations and offset distances to accurately plot the vertical and horizontal alignment of the installed product. A minimum of three elevation and plot points are required. (f) Install all facilities such that their location can be readily determined by electronic designation after installation. For non-conductive installations, attach a minimum of two separate and continuous conductive tracking (tone wire) materials, either externally, internally, or integral with the product. Use either a continuous green sheathed solid conductor copper wire line (minimum #12 AWG for external placement with the carrier pipes or minimum #14 AWG for internal placement in the conduit, casing, or duct) or a coated conductive tape. (g) Conductors must be located on opposite sides when installed externally. Connect any break in the conductor line before construction with an electrical clamp, or solder, and coat the connection with a rubber or plastic insulator to maintain the integrity of the connection from corrosion. Clamp connections must be made of brass or copper and of the butt end type with wires secured by compression. Soldered connections must be made by tight spiral winding of each wire around the other with a finished length minimum of 3 inches (7.62 cm) overlap. Tracking conductors must extend 2 feet (61 cm) beyond bore termini. Test conductors for continuity. Each conductor that passes must be identified as such by removing the last 6 inches (15.24 cm) of the sheath. No deductions are allowed for failed tracking conductors. Failed conductor ends must be wound into a small coil and left attached for future use.
	Installation	(a) Carry out excavation for entry, exit, recovery pits, slurry sump pits, or any other excavation as specified in Section 120. Sump pits are required to contain drilling fluids if vacuum devices are not operated throughout the drilling operation unless approved by the Engineer. (b) Ensure adequate removal of soil cuttings and stability of the bore hole by monitoring the drilling fluids such as the pumping rate, pressures, viscosity, and density during the pilot bore, back reaming, and pipe installation. (c) Relief holes can be used as necessary to relieve excess pressure down hole. Obtain the Engineer's approval of the location and all conditions necessary to construct relief holes to ensure the proper disposition of drilling fluids is maintained and unnecessary inconvenience is minimized to other facility users. (d) To minimize heaving during pull back, the pullback rate is determined in order to maximize the removal of soil cuttings without building excess down hole pressure. (e) Contain excess drilling fluids at entry and exit points until they are recycled or removed from the site or vacuumed during drilling operations. (f) Ensure that entry and exit pits are of sufficient size to contain the expected return of drilling fluids and soil cuttings. Ensure that all drilling fluids are disposed of or recycled in a manner acceptable to the appropriate local, state, or federal regulatory agencies. (g) When drilling in suspected contaminated ground, test the drilling fluid for contamination and appropriately dispose of it. Remove any excess material upon completion of the bore. If in the drilling process it becomes evident that the soil is contaminated, contact the Engineer immediately. Do not continue drilling without the Engineer's approval. (h) When conditions warrant, as determined by the Engineer, back reaming for enlarging the bore diameter shall be accomplished by connecting the reamer to trailing drill stems at the exit pit of the pilot bore. The drill pipe shall remain in the borehole until the final product is pulled into place. (i) After the pilot bore is established, do not push anything from the entry pit to the exit pit. The timing of all boring processes is critical. Install a product into a borehole within the same day that the pre-bore is completed to ensure necessary support exists.

Phase	Element	Florida Department of Transportation (FDOT) Standard Specifications for Road and Bridge Construction Section 555 Directional Bore (2013)
	Site Restoration	(a) Within 48 hours of completing the installation of the product, clean the work site of all excess slurry or spoils. Take responsibility for the removal and final disposition of excess slurry or spoils. Ensure that the work site is restored to pre-construction conditions or as identified in the Plans. (b) Exposure of product shall be limited to 3 feet (1 m) and 14 consecutive days unless approved by the Engineer. (c) Take responsibility for restoration for any damage caused by heaving, settlement, separation of pavement, escaping drilling fluid (frac-out), or the directional drilling operation, at no cost to the Department. (d) If conditions warrant removal of any materials installed in a failed bore path, as determined by the Engineer, it will be at no cost to the Department. Promptly fill all voids with excavatable flowable fill.
	Remediation	(a) When required by the Engineer, provide detailed plans which show how damage to any roadway facility will be remedied. These details will become part of the As-Built Plans Package. Remediation plans must follow the same guidelines for the development and presentation of the As-Built Plans. When remediation plans are required, they must be approved by the Engineer before any work proceeds. (b) If an obstruction is encountered during boring that prevents completion of the installation in accordance with the design location and specification, the pipe may be taken out of service and left in place at the discretion of the Engineer. Immediately fill the product left in place with excavatable flowable fill. Submit a new installation procedure and revised plans to the Engineer for approval before resuming work at another location. If, during construction, the damage is observed to the FDOT facility, cease all work until resolution and a plan of action for restoration is obtained and approved by the Engineer to minimize further damage.
	Inspection	
After Construction	Quality Control	(a) Take control of the operation at all times. Have a representative who is thoroughly knowledgeable of the equipment, boring, and Department procedures present at the job site during the entire installation and available to address immediate concerns and emergency operations. Notify the Engineer 48 hours in advance of starting work. Do not begin installation until the Engineer is present at the job site and agrees that proper preparations have been made. (b) When there is any indication that the installed product has sustained damage and may leak, stop all work, notify the Engineer, and investigate the damage. The Engineer may require a pressure test and reserves the right to be present during the test. Perform pressure test within 24 hours, unless otherwise approved by the Engineer. Furnish a copy of test results to the Engineer for review and approval. The Engineer is allowed up to 72 hours to approve or determine if the product installation is not in compliance with the specifications. The Engineer may require non-compliant installations to be filled with excavatable flowable fill. (c) Testing may consist of one of the following methods and must always meet or exceed the Department's testing requirements: 1) Follow the product manufacturer's pressure testing recommendations. 2) Ensure carrier pipes installed without a casing meet the pressure requirements set by the owner. If the owner does not require pressure testing, the Engineer may require at least one test. 3) A watertight pipe and joint configuration where the product is installed beneath any pavement (including sidewalk) and front shoulders is required. The Engineer will determine when and where watertight joint requirements will be applied to the ultimate roadway section for future widening. When a product is located elsewhere, the pipe and joint configuration must meet or exceed soil tight joint requirements. Conduct tests for joint integrity for one hour. The test for a soil tight joint allows up to 0.1 gallons (0.4 L) of water leakage at a sustained pressure of 2 PSI (13.8 kPa). The watertight joint criteria allows no leakage at all for a sustained pressure of 5 PSI (34.5 kPa). (d) Minimize potential damage from soil displacement/settlement by limiting the ratio of the bore hole to the product size.
	Final Delivery	(a) Furnish a Bore Path Report to the Engineer within seven days of the completion of each bore path. Include the following in the report: (i) Location of project and financial project number including the Permit Number when assigned (ii) Name of the person collecting data, including title, position, and company name (iii) Investigation site location (Contract Plans station number or reference to a permanent structure within the project right-of-way) (iv) Identification of the detection method used (v) Elevations and offset dimensions as required in 555-4.2. (b) Provide the Engineer a complete set of As-Built Plans showing all bores (successful and failed) within 30 calendar days of completing the work. Ensure that the plans are dimensionally correct copies of the Contract Plans and include roadway plan and profile, cross-section, boring location, and subsurface conditions as directed by the Engineer. The plans must show appropriate elevations and be referenced to a Department Bench Mark when associated with a Department project, otherwise to a U.S. Geological Survey (USGS) grid system and datum, or a specific location on top of an existing Department head wall. Plans must be the same scale in black ink on white paper, of the same size and weight as the Contract Plans. Submittal of electronic plans data in lieu of hard copy plans is preferred and may be approved by the Engineer if compatible with the Department software.

Phase	Element	New York State Department of Transportation (NYSDOT) Geotechnical Design Manual (GDM) (2013)
Before Construction	Site Investigation	(a) Before the site reconnaissance is performed, the Departmental Geotechnical Engineer should have initially performed the preliminary office review as described in NYSDOT GDM Section 2.2.3 Preliminary Office Review of Project Site, as well as given some thought to the field exploration plan. (b) The field reconnaissance should be done with the preliminary plans in hand. Cross-sections provided with the preliminary plans should be field checked. The cross-sections are often generated by Photogrammetry and may not accurately represent the existing ground surface, especially at areas with very steep changes in elevation or with dense vegetation. (c) The proposed locations of the subsurface explorations are physically marked in the field by the use of spray paint. (d) Subsurface explorations may include test pits. These are simply manually or mechanically dug holes, often large enough for persons to work in, used to investigate subsurface strata, determine groundwater conditions, or sample granular material sources. They are particularly useful in examining the characteristics of landfill deposits. Small test pits may be used as percolation test pits or holes. The planning for test pits may include 1. Equipment: Test pits shall be performed using appropriately sized backhoe equipment or other suitable excavation equipment and techniques. 2. Stability: Test pits typically do not extend to significant depths. However, if necessary, the stability of the pit should be addressed to ensure worker safety and support for the surrounding terrain. 3. Documentation: The materials encountered during this process shall be logged in a similar manner as are subsurface explorations. Photographs of test pits can also be very helpful to document findings.
	Plan	(a) Planning these borings needs to address aspects such as water used for wash purposes or other similar operations, which may then cause contamination with sand, silt, cement, oil, or other impurities, should not be allowed to return directly to the stream or water body. If water is to be used from any stream or water body, an intake or temporary dam may need to be constructed. With the exception of any paved areas, temporary strawbale dikes should completely surround the subsurface exploration area (including the operating equipment and excavated materials). Planning should also address aspects such as the use of turbidity curtains, pumping wash water to vegetated upland locations, and utilizing drill wash tubs. (b) Planning should extend beyond the progression of the borings and identify the need to backfill the hole. Upon satisfactory completion of each subsurface exploration, the Drill Crews should completely backfill all voids in the ground with compacted, suitable material. For subsurface explorations in pavements, sidewalks, and driveways, the upper 6 ft (1.83 m) of backfill should be continuously compacted with a rod or pole, and sealed with a suitable patch of bituminous or concrete material. In cases where it is necessary that the full depth of a subsurface exploration be sealed to prevent migration of water or hazardous fluids, the Drill Crew shall seal the hole in accordance with NYSDOT Standard Specifications Section 648 Subsurface Explorations.
	Design	
During Construction	Materials	
	Equipment and Machinery	
	Locating and Tracking	
	Installation	(a) Drilling in or near Streams or other Bodies of Water: Drilling should be progressed in such a manner as to prevent any damage to any stream or water body from pollution by debris, sedimentation, or other foreign material resulting from the manipulation of equipment and/or materials. During equipment removal operations, Drill Crews are not allowed to drop waste grout, rock or soil debris, and other materials into or near the water body. Platforms, nets, screens, or other protective devices may be used to catch the material. Non-petroleum products should be used for lubrication during the drilling operations in or near water bodies.
	Site Restoration	
	Remediation	
	Inspection	
After Construction	Quality Control	(a) The Drill Crews are to perform all drilling operations in a manner so as to minimize soil erosion and ensure sediment control. Erosion protection measures are items that minimize the movement of surface soils, and sediment control measures are items that keep loose soil from leaving the project site.
	Final Delivery	

Phase	Element	Atalah and Brown (2013) for Ohio Department of Transportation (ODOT) Development of a Standard Specification for Horizontal Directional Drilling
Before Construction	Site Investigation	(a) Explore and locate existing underground utilities in the areas of Work. Verify the exact physical location and depth of existing utilities by exposing them as needed. If utilities are to remain in place, provide adequate means of protecting the utility during excavation operations. Should uncharted or incorrectly charted piping or other utilities be encountered during the utility exploration, contact the Owner of the utilities and the ODOT Representative in the field. Contractor is responsible for repairing damaged utilities to the satisfaction of the utility owner in accordance with the Ohio revised code 153.64 Protecting underground utility facilities during construction of public improvement and 3781.25 One-call utility protection service definitions. If the utility was accurately marked by the utility locater or on the drawing, repair it at no additional cost. If the damaged utility was not accurately marked by the utility locater or on the drawing, the Owner adjusts the contract value and/or time accordingly. Follow the additional instructions in section105.07 Cooperation with Utilities of the Ohio Department of Transportation Construction and Material Specifications for cooperation with utilities.
	Plan	(a) Prior to beginning work, submit to the Engineer a Work Plan detailing the procedure and schedule to execute the project. The work plan will be comprehensive, realistic, and based on actual working conditions for this particular project. The work plan documents the planning required to successfully complete the project. The work plan includes complete descriptions of proposed plans, procedures, equipment, personnel, and, if applicable, supporting material, for the following: (1) Drilling operations: describe the pilot hole drilling procedure, the reaming operation, the pullback procedure, and illustrate the plan. (2) Profile of the bore plotted at a scale appropriate for the crossing and acceptable to the Engineer. (3) HDD site layout, including entry and exit points. (4) Directional drilling equipment list includes drilling rig, drill bit, back-reamer, mud mixing and pumping systems, down-hole tools, guidance system, and rig safety system. Provide calibration records for guidance equipment. (5) Drilling fluid management plan: drilling fluid types and specifications, cleaning and recycling equipment, estimated flow rates, procedures for minimizing drilling fluid escape, and the method/location for final disposal of waste drilling fluids. Provide the MSDS for all drilling fluid additives that will be used. (6) Pipe storage and handling details. (7) Pipeline assembly and installation procedures. (8) MSDS of any potentially hazardous substances to be used. (9) Contingency plans for possible problems.
	Design	(a) Drilling fluid mixture design: Use a drilling fluids mixture composed of potable water and stabilizing agent - usually bentonite and/or polymer and/or appropriate additives continuously pumped to the drill bit. Design/select the drilling fluid to transport the spoils; maintain temperatures of bits and transmitter; clean cuttings from the drill bit and reamers; reduce friction, pullback, and torque on drill rods and product pipe; stabilize the borehole; control groundwater pressure, and reduce migration of drilling fluids in soil. Use water with pH between 7.5 and 10 and free of chlorine with calcium < 100ppm, sodium chloride < 500ppm, and chlorine < 50ppm. Hard water may be treated with soda ash to reach the required pH. Design the quantity and the mixture of drilling fluids to perform the preceding functions in the expected soil. Vary the fluid viscosity to best fit the encountered soil conditions. Do not use any other chemicals or polymer surfactants in the drilling fluid without written consent from the Engineer. Certify to the Engineer in writing that any added chemicals are environmentally safe and not harmful or corrosive to the product pipe and the environment. Approvals and permits are required for obtaining water from such sources as streams, rivers, ponds, or fire hydrants. Any water source used other than potable water requires a pH test. (b) Select the back-reamer size so it creates a large enough borehole to allow cuttings to transfer from the face of the excavation to the surface with a minimum soil displacement.
During Construction	Materials	(a) Select the product pipe material according to the type of product indicated on the plans. The product pipe must comply with all applicable ODOT specification sections and ASTM standards depending on the purpose and material of the product pipe. Join the pipe sections so that the joined pipe sections are installable using HDD. Ensure that the joined product pipes have adequate strength and flexibility to withstand the installation stresses, overburden pressures, and operating pressures without compromising the structural stability of the pipe wall. Ensure that the product pipe meets the bend radius required for the proposed installation. Join the pipe sections so that the inner surfaces are flush and even.
	Equipment and Machinery	(a) Match the HDD drill rig and its auxiliary pieces of equipment to the diameter and length of the product pipe being installed and ensure that the drill rod can meet the bend radius required for the proposed installation. (b) The directional drilling machine consists of a power system to rotate, push, and pull back hollow drill pipe into the ground at variable angles while delivering a pressurized fluid mixture to a guidable drill head (bit). Select/design the power system to provide sufficient pressure to power the drilling operations through a leak-free hydraulic system. Anchor the directional drilling machine to the ground to withstand the pulling, pushing, and rotating pressure required to complete the HDD installation. Select a drilling fluid mixing system that is self-contained and closed with sufficient size to mix and deliver drilling fluid to the drill bit. The mixing system will continually agitate the drilling fluid during drilling operations. Select fluids delivery system capable of pumping drilling fluid with sufficient volume and pressure from the mixing tank through the drill rods to the drill head (bit).

Phase	Element	Atalah and Brown (2013) for Ohio Department of Transportation (ODOT) Development of a Standard Specification for Horizontal Directional Drilling
	Locating and Tracking	(a) Unless specified on the plan, select an acceptable guidance system to locate, and track the drill head continuously and accurately during the pilot bore. The guidance system must be capable of tracking the drill bit in the expected underground environment and at the depth shown on the plans. The acceptable methods include walkover, wire line, Magnetic Guidance System (MGS) probe, proven (non-experimental) gyroscopic probe, or any other system as accepted by the Engineer. Select the guidance system and the drill rig to deliver the required horizontal and vertical accuracy required for the product pipe. Use a locating and tracking system capable of ensuring that the proposed installation is executed as intended. If signal interference is encountered that significantly affects the ability to accurately track the drill bit, the Engineer may specify the use of a suitable tracking system. If the owner informs the contractor about signal interference or it is reasonable to expect interference at the site prior to bidding; select a suitable tracking system without extra cost to the owner; otherwise, the owner adjusts the contract value and time accordingly. Select the locating and tracking system to provide information on (1) Clock and pitch information; (2) depth; (3) transmitter temperature; (4) battery status; (5) position (x,y); (6) azimuth, where direct overhead readings (walkover) are not possible (i.e., subaqueous or limited access transportation facility). (b) Ensure proper calibration of all equipment before commencing directional drilling operation. Take necessary measures to ensure accurate record drawing. Install all facilities such that their location can be readily determined by electronic designation after installation.
	Installation	(a) Drill the pilot hole along the path shown on the plans and profile drawings within the allowable tolerance of the type of utility. Provide and maintain instrumentation necessary to accurately locate the pilot hole (both horizontal and vertical placements). Ensure adequate removal of soil cuttings and stability of the bore hole by monitoring the drilling fluids parameters such as the pumping rate, pressures, viscosity, and density during the pilot bore, back reaming, and product pipe installation. Relief holes can be used as necessary to relieve excess pressure down hole. (b) Take all necessary measures to eliminate the discharge of water, drilling mud, and cuttings to nearby waterways during the HDD work. If applicable, provide equipment and procedures to maximize the recirculation or reuse of drilling mud to minimize waste. Follow section 107.19 Environmental Protection of the Ohio Department of Transportation Construction and Material Specifications for environmental protection requirements. (c) To minimize heaving during pull back, determine the pullback rate in order to maximize the removal of soil cuttings without building excess down hole pressure. Contain excess drilling fluids at entry and exit points until the recycle, vacuum, or removal from the site during drilling operations. Ensure that entry and exit containments are of sufficient size to contain the expected return of drilling fluids and soil cuttings. Carry out excavation and backfill for entry, exit, recovery pits, connection pits, slurry sump pits, or any other excavation as specified in Section 611 of Atalah and Brown (2013).
	Site Restoration	(a) The contractor should take responsibility for restoration of any damage caused by heaving, settlement, separation of pavement, escaping drilling fluid, or from the directional drilling operation. If the negligence of the contractor causes damage to any facility, restore the facility to its original conditions or better at no additional cost to the Department.
	Remediation	(a) When remediation plans are required by the Engineer, provide detailed and acceptable-by-the-Engineer plans showing how the damage will be remedied before any work proceeds. (b) Have a representative who is thoroughly knowledgeable of the equipment, boring and the owner procedures, present at the job site during the entire installation and available to address immediate concerns and emergency operations. Notify the Engineer 48 hours in advance of starting work. Do not begin installation until the Engineer is present at the job site and agrees that proper preparations have been made.
	Inspection	
After Construction	Quality Control	(a) Upon completion of the directional bore, test tracer wire continuity for each bore before acceptance. (b) Minimize potential damage from soil displacement/settlement/heave by limiting the borehole diameter compared to the product pipe.
	Final Delivery	(a) At the completion of the HDD product pipe installation, the general contractor will provide the Engineer marked up plans noting all deviations from the plans that result in change of location, material, type or size of work guided by the boring operations and guidance system log. Post, on the drawing, the x, y, and z coordinates of the starting and ending points of the line at minimum. Include in the marked-up plans, the station number or reference to a permanent structure within the project right-of-way, name of person collecting data, including title, position and company name, detection method used, and elevations and offset dimensions. Certify the accuracy of the drawing to the capability of the tracking system. If the HDD contractor is the general contractor, the HDD contractor provides the Engineer with the marked-up plans.

Phase	Element	Unified Facilities Guide Specifications (UFGS) Utility Horizontal Directional Drilling (2013)
Before Construction	Site Investigation	(a) Ensure all utilities are located and clearly marked prior to the start of excavation or drilling.
	Plan	(a) Ensure that the field supervisor and workers assigned to this project are experienced in work of this nature and have successfully completed similar projects of similar length, pipe type, pipe size, and soil type using directional drilling in the last three (3) years. As part of the bid submission, submit a description of such project(s) which include, at a minimum, a listing of the location(s), date of the project(s), owner, pipe type, size installed, length of installation, type, and manufacturer of equipment used, and other information relevant to the successful completion of the project.
	Design	(a) Use a high-quality drilling fluid to ensure hole stability, cuttings transport, bit and electronics cooling, and hole lubrication to reduce drag on the drill pipe and the product pipe. Use only fluid with a composition which complies with all Federal, State, and local environmental regulations. Mix the drilling fluid with potable water (of proper pH) to ensure no contamination is introduced into the soil during the drilling, reaming, or pipe installation process. Make any required pH adjustments.
During Construction	Materials	
	Equipment and Machinery	(a) Select the appropriate drill rod to be used. Submit a certified statement that the drill rod has been inspected and is in satisfactory condition for its intended use.
	Locating and Tracking	(a) When walkover guidance systems are not acceptable, use a magnetic survey tool locator installed behind the pilot string cutting head and an electric grid (tru-tracker) system instead.
	Installation	(a) Drill entrance and exit pits are required. Maintain at a minimum size to allow only the minimum amount of drilling fluid storage prior to transfer to mud recycling or processing system or removal from the site. Do not allow drilling mud to flow freely on the site or around the entrance or exit pits. Remove spilled mud and restore the ground to original condition. (b) Include in directional drilling equipment machine safety requirements a common grounding system to prevent electrical shock in the event of an underground electrical cable strike. Ensure the grounding system connects all pieces of interconnecting machinery; the drill, mud mixing system, drill power unit, drill rod trailer, operators booth, worker grounding mats, and any other interconnected equipment to a common ground. Equip the drill with an "electrical strike" audible and visual warning system that notifies the system operators of an electrical strike. (c) The type and size of the pilot string cutting head and the diameter of the drill pipe is at the Contractor's discretion. Drill the pilot hole along the path shown on the plan and profile drawings. Pilot hole tolerances are as follows: (1) Vertical Tolerance: Provide minimum cover below channel bottom as specified on the plans. Pilot hole may go deeper, if necessary, to prevent breakout. (2) Horizontal Tolerance: Plus/minus - 152.4 cm (60 in.) from the centerline of the product pipe. (3) Curve Radius: No curve is acceptable with a radius less than 304.8 m (1,000 ft). (4) Entry Point Location: Make pilot hole entry point within plus/minus - 152.4 cm (60 in.) of the location shown on the drawings or as directed by the Contracting Officer in the field. (5) Exit Point Location: Make the exit point location within plus/minus - 152.4 cm (60 in.) of the location shown on the drawings or as directed by the Contracting Officer in the field. (6) Mandatory pipeline cover requirements are as shown on the drawings or as specified. (d) Fully assemble the entire pipeline to be installed via direction drill prior to commencement of pull back operations. Support the pipeline during pullback operations in a manner to enable it to move freely and prevent damage. Install the pipeline in one continuous pull. Minimize torsion stress by using a swivel to connect the pull section to the reaming assembly. Maximum allowable tensile force imposed on the pull section is not to exceed 90 percent of the pipe manufacturer's safe pull (or tensile) strength. If the pull section is made up of multiple pipe sizes or materials, the lowest safe pull strength value governs, and the maximum allowable tensile force is not to exceed 90 percent of this value. Minimize external pressure during installation of the pullback section in the reamed hole. Replace damaged pipe resulting from external pressure at no cost to the Government. Buoyancy modification is at the discretion of the Contractor. (e) After the product pipe has been successfully installed, allow the product pipe to recover for 24 hours prior to connection of the pipeline. Ensure that a sufficient length of the product pipe has been pulled through the hole so that the pull-nose is not pulled back into bore hole due to stretch recovery of the product pipe.
	Site Restoration	
	Remediation	
	Inspection	

Phase	Element	Unified Facilities Guide Specifications (UFGS) Utility Horizontal Directional Drilling (2013)
After Construction	Quality Control	(a) Maintain drilling logs that accurately provide drill bit location (both horizontally and vertically) at least every 5.1 cm (2 in.) along the drill path. In addition, keep logs that record, as a minimum the following, every 15 minutes throughout each drill pass, back ream pass, or pipe installation pass: (1) Drilling Fluid Pressure; (2) Drilling Fluid Flow Rate; (3) Drill Thrust Pressure; (4) Drill Pullback Pressure; (5) Drill Head Torque. (b) Make all instrumentation, readings, and logs available to the Contracting Officer at all times during operation.
	Final Delivery	

Phase	Element	City of Overland Park, Kansas Right-of-Way Permit Horizontal Directional Drilling Guidelines Handbook (2014)
Before Construction	Site Investigation	
	Plan	(a) Prior to performing work involving HDD under a Right-of-Way Permit, the Permittee (or its Contractor) shall consider the following safety guidelines: (1) Perform all operations in compliance with Occupational Safety and Health Administration (OSHA) guidelines and insure that all personnel are properly trained and equipped to work in the public right-of-way; (2) Insure that the approved traffic control plan (required with the permit application) is implemented and followed at all times; (3) Insure that all storm water pollution prevention measures (required with the permit application) are implemented and followed at all times; (4) Insure all setbacks, offsets, and clearances are maintained; Insure that utility One-Calls and City or other utility coordination requirements have been met (See page ii); (5) Positively identify (by potholing) all crossed utilities that are expected to be above and within 5' (1.5 m) of the proposed vertical alignment, below and within 3' (0.9-m) of the proposed vertical alignment, and additionally as requested by the City Engineer; (6) Positively identify (by potholing) all parallel utilities at the beginning and ending of all bores and every 200' (61 m) if it is within 5' (1.5 m) of the proposed alignment, every 50' (15.2 m) if it is within 3' (0.9 m) of the proposed alignment, and additionally as requested by the City Engineer. (7) The HDD Contractor shall have a planned response in the event of a utility strike, including utility owner notification and avoiding electrocution in the event of an electric strike, avoiding combustion in the event of a gas line strike, avoiding contamination in the case of a sewer strike. (b) The HDD Contractor shall not expand the borehole by more than six inches (6", 15.2 cm) using only compaction reamer(s).
	Design	
During Construction	Materials	
	Equipment and Machinery	
	Locating and Tracking	
	Installation	(a) The HDD Contractor shall contain, handle, and dispose of drilling fluids in accordance with the following requirements: (1) All drilling fluid and fluid additives shall be disclosed, and Material Safety Data Sheets (MSDS) shall be provided to the City Engineer upon request. (2) Excess drilling fluid shall be confined in a containment pit at the entry and exit locations until recycled or removed from the site. (3) Precautions shall be taken to ensure that drilling fluid does not enter roadways, streams, municipal storm or sanitary sewer lines, and/or any other drainage system or body of water. (4) Unintended surfacing of drilling fluid shall be contained at the point of discharge and recycled or removed from the site. (5) Drilling fluids that are not recycled and reused shall be removed from the site and disposed of at an approved disposal site. (6) Drilling fluids shall be completely removed from the construction site prior to back filling or restoring the site. (7) Collection, transportation, and disposal of drilling fluids shall be environmentally safe and comply with local ordinances and government regulations. (b) The HDD Contractor shall plan its reaming and back pulling operations carefully to ensure that, once started, all reaming and back pulling operations can be completed without stopping and within the permitted work hours.
	Site Restoration	
	Remediation	
	Inspection	
After Construction	Quality Control	

Phase	Element	City of Overland Park, Kansas Right-of-Way Permit Horizontal Directional Drilling Guidelines Handbook (2014)
	Final Delivery	(a) The HDD Contractor shall keep detailed and accurate records of all activities associated with the HDD process. Upon completion of HDD installations, the Permittee shall provide the city of Overland Park with As Built plans and any supporting documents within 60 days of project completion. As Built plans are preferred in AutoCAD format but may be submitted in paper form. HDD construction records and As Built plans shall include the following: HDD tracking data and operator logs shall be maintained daily and shall be made available upon request from the City Engineer. These field records and operator notes shall specify: the type of tracking equipment used, the length and depth of the HDD installation, and additional information that may include steering adjustments and other equipment performance parameters; As Built plans shall be derived from the tracking data and operator logs. At a minimum, the drawings shall indicate: horizontal and vertical HDD alignment, existing utility horizontal locations and depths at all exposed or potholed locations, and existing utility horizontal locations indicated with field locations. As Built plans shall conform to the same Overland Park Plans Submission Requirements for Right-of-Way Permits included previously.

Phase	Element	City of Baton Rouge, Louisiana Horizontal Directional Drilling for Sewers (2015)
Before Construction	Site Investigation	(a) Utility Crossings: 1) The Contractor shall field verify the location and depth of all existing utilities, including service connections, to be paralleled or crossed prior to the start of directional drilling operations in accordance with Louisiana law. The Contractor, with approval of the Engineer, shall modify alignment, depth, or grade as necessary to avoid utilities and minimize the number of peaks and valleys along the alignment. 2) The Contractor shall expose all utilities that they will be crossing with horizontal directional drilling. All major utilities (high-pressure gas, fiber optic, high voltage electric, major pipelines, water and sewer lines, etc.) should be exposed every 100 feet (30.5 m) at minimum, if parallel within 5 feet (1.5 m) horizontally to verify depth and location of the utility. If the location is not accurate, the utility owner shall be contacted immediately.
	Plan	(a)The Contractor shall be responsible for the selection of all drilling and auxiliary equipment which, based on past experience, has proven to be satisfactory for excavation of the soils to be encountered. (b) Identify the source of water for mixing the drilling fluid. Approvals and permits are required for obtaining water from such sources as streams, rivers, ponds, or fire hydrants. Any water source used other than potable water must be pH tested, hardness tested, chlorine tested, and approved by the Engineer prior to use. The Contractor shall promptly remove from the project site and properly dispose of all drilling fluids and associated cuttings in compliance with all environmental regulations, construction right-of-way, and workspace agreements and permit requirements at an appropriate disposal site. Disposal, including hauling of all drilling fluids and associated cuttings, shall be at no additional cost to the Owner. (c) If crossing under railroad embankments, highways, or streets, perform the installation to avoid interference with the operation of the railroads, highways, or streets, except as approved by the owner of the facility.
	Design	(a) Drilling fluid mixture design: Use a mixture of bentonite clay, lubricants, polymers, and viscosifiers mixed with potable water with a minimum pH of 6.0 to create the drilling fluid for lubrication and soil stabilization. Drilling fluid mix design shall be in accordance with component manufacturer instructions and shall be based on the soil conditions. Vary the fluid viscosity to best fit the soil conditions encountered. Do not use any other chemicals or polymer surfactants in the drilling fluid without written consent from the Engineer. Certify to the Engineer in writing by submittal that any chemicals to be added are environmentally safe and not harmful or corrosive to the facility.
During Construction	Materials	(a) The pipe shall be handled in accordance with manufacturer's instructions. Any cracks, gouges, scratches, distorted lengths, or other damage shall be repaired per the manufacturer's instructions. (b) Acceptable materials used for HDD Sanitary Sewers are as follows: 1. Polyethylene (HDPE) and fusible PVC butt-welded and fused joints to be in accordance with Section 1016-1.1.2 and 1016-2.2 for gravity and force main applications, respectively. 2. Pipe material for HDD operations shall be as shown on the construction drawings. 3. Fusible PVC will be allowed for HDD operations in diameters up to and including 16" (40.64 cm) if identified on the construction drawings.
	Equipment and Machinery	(a) Minimum equipment required: 1. Horizontal Directional Drilling Rig–to be specified by the Contractor. 2. Drill pipe and trail stem–to be specified by the Contractor. 3. Drill bits and reamers–Contractor specified–generally based on the soils and drilling conditions to be encountered. 4. Drilling fluid mixing tanks, holding tanks, cleaning systems, recirculation containment, collection, and disposal. 5. Freely operating swivels–size and type appropriate for the expected loading. (b) Pumps and/or vacuum truck(s) of sufficient size shall be in place to convey excess drilling fluid from containment areas to storage facilities. (c) Pipe rollers shall be of sufficient size, spacing, and in good working condition (as determined by the pipe manufacturer) to fully support the weight of the pipe while being hydro-tested and during pull-back operations. Sufficient number of rollers shall be used to prevent sagging of pipe. Pipe roller spacing shall not exceed 20 feet (6.1 m). (d) The Contractor shall provide drilling equipment of the size and power so that the pilot hole can be drilled along the path shown on the plan and profile drawings within specified tolerances.
	Locating and Tracking	(a) The Owner recognizes walkover, wire line, and wire line with surface grid verification, or any other system as approved by the Engineer, as the accepted methods of tracking directional bores. Specific Instrumentation requirements are shown on the Contract Documents. Instrumentation specified shall be accessible at all times to the Engineer. Readings shall be submitted promptly to the Engineer as they are recorded. In any case the Contractor must use a locating and tracking system capable of ensuring that the proposed pipe is monitored and installed as intended. (b) Monitoring Line & Grade: 1. Monitoring of bore, reamer, and pipe may be accomplished by manually plotting reference points based on location and depth readings provided by the locating/tracking system. Alternately, computer generated bore logs, which automatically map the bore path based on information provided by the locating/tracking system, may be used. This information shall be readily available upon request of the Engineer. 2. Before any direction drilling commences, the locating/tracking equipment shall be calibrated. 3. Readings or plot points shall be recorded on every drill rod. Required readings shall be taken every 3 to 5 feet. (0.9 to 1.5 m).

Phase	Element	City of Baton Rouge, Louisiana Horizontal Directional Drilling for Sewers (2015)
	Installation	(a) The Contractor shall utilize a trailing stem (a drill rod on the trailing end of the reaming operation) during back-reaming of the borehole. (b) Maintain clean working conditions. (c) Exit and entry angles shall be between 8 and 12 degrees. Once the Contractor has begun the HDD pipe installation process, operate without intermission, including 24 hour working, weekends, and holidays, until pipe segment is completed. Pipe pulling shall immediately follow borehole drilling, reaming, and swabbing. Pipe pulling through collapsing borehole is prohibited. (d) The installed pipe shall be allowed to relax and cool the following installation, for a minimum of twelve (12) hours, prior to any reconnection of service lines or backfilling of the insertion pit. (e) Pipe pulling operations shall have a dedicated pipe handler during any pipe operations. (f) Pipe shall not come in contact with ground surface during pull back operations. (g) Deviations between the recorded position of the drill string and the plan and profile drawings shall be documented and immediately brought to the attention of the Engineer.
	Site Restoration	(a) All surfaces affected by the Work shall be restored to their preconstruction conditions. Performance criteria for restoration work will be similar to those employed in traditional open excavation work. (b) The Contractor shall immediately contain and clean up drilling fluid loss prior to continuing HDD operations. The Contractor shall prevent drilling fluids from entering streets, adjacent properties, streams or other water bodies and municipal storm or sanitary sewer lines. No additional payment shall be made for cleanup costs required by the Owner, Engineer, or regulatory agencies due to loss of drilling fluid.
	Remediation	(a) In the event that a drilling fluid fracture (frac out), inadvertent returns, or returns loss occurs during HDD operations, the Contractor shall cease operations; notify the Engineer and all appropriate regulatory agencies. (b) If mud fracture or returns loss continues, the Contractor will cease operations, notify the Engineer to discuss additional options to control or minimize the loss, and work will then proceed accordingly.
	Inspection	(a) Maintain shift logs of construction events and observation. The HDD supervisory personnel (superintendent) shall be on-site at all times any drilling operations are being conducted. The operator shall clearly print and sign their name. The Engineer shall have access to the Contractor’s daily logs with regard to the following information: 1. Location of drill head and progress of drilling operation during shift. 2. Hours worked per shift during drilling operations. 3. List of Crew Names, including full and last names, title, and hours worked for each day. 4. Completed forms or computer printouts for checking line and grade of the drilling operation, showing achieved tolerance relative to design alignment. 5. Maximum pipe loads per pull back including but not limited to torque and fluid pressures.

Phase	Element	City of Baton Rouge, Louisiana Horizontal Directional Drilling for Sewers (2015)
After Construction	Quality Control	(a) Construction Control: the Contractor shall check baselines and benchmarks shown on the Contract Documents at the beginning of the Work and report any errors or discrepancies to the Engineer. The Contractor shall use the baselines and benchmarks to establish and maintain construction control points, reference lines, and grades for locating, boring, reaming, and in relation to existing pipelines, utilities, and structures. Establish construction control points sufficiently far from the work to avoid being affected by any ground movements caused by HDD operations. (b) Temporary Bench Mark Movement: The Contractor shall ensure that if settlement of the ground surface occurs during construction which affects the accuracy of the temporary benchmarks, the Contractor shall detect and report to the Engineer such movement and reestablish temporary benchmarks. (c) Line and Grade: 1) Check and record the survey control for the boring operations against an undisturbed aboveground reference as required to accurately guide and monitor the constructed length (± 20 feet, 6.1 m). 2) At a minimum of every drill rod connection or a maximum of every 5 feet (1.5 m), record the position of the drill bit, then make immediate corrections to the alignment position before allowable tolerances are exceeded. 3) When the drill is offline, make ongoing alignment corrections to avoid major changes and keep within specified tolerances. For gravity pipe installations, a belly in the bore that will hold water and/or a reverse grade is not acceptable and shall be replaced at no additional cost to the Owner. Replacement shall include removal and replacement of the bellied pipe length by the open cut or by re-drilling on a parallel alignment as directed by Engineer. 4) Vertical Tolerance: Gravity sewer pipe (in the plan direction of flow) shall be a maximum deviation of 6 inches (15.24 cm) in downward vertical alignment for any 100 foot (30.5 m) section from plan grade but no more than 12 inches (30.5 cm) down in a 500-foot (151 m) section. Deviation of grade (in the plan direction of flow) in the upward direction is allowed only for corrective means; however, a minimum absolute grade of 0.15% in the downward direction must be maintained. A variation greater than plus (+) 0.0 feet (0 m) or minus (-) 5 feet (1.52 m) from vertical alignment designated on the Contract Documents may be allowed at the discretion of the Engineer and must be approved prior to installation. 5) Horizontal Tolerance: Gravity sewer pipe deviations in horizontal line shall be a maximum of ± 12 inches (30.5 cm) in any 100-foot (30.5 m) section but no more than ± 24 inches (61 cm) in 500 linear feet (151 m). Horizontal offsets from plan line must be corrected at manholes. A variation greater than ± 2 feet (0.6 m) from horizontal alignment designated on the Contract Documents may be allowed at the discretion of the Engineer and must be approved prior to installation. 6) The outside edge of pipe must not deviate into a 2 foot (0.6 m) space inside either edge of the servitude or right-of-way nor should it conflict with any above or below ground obstructions. 7) New pipe installed outside tolerances shall be fully grouted and abandoned or removed and all voids filled as directed by the Engineer at no additional cost to the Owner. (d) Instrumentation Monitoring: 1. Install and maintain an instrumentation system to monitor and detect movement of the ground surface and adjacent structures. Establish reference vertical control points in safe locations at a distance away from the construction areas to avoid potential disturbance due to ground settlement. 2. Installation of the instrumentation shall not preclude the Engineer, through an independent contractor or consultant, from installing instrumentation in, on, near, or adjacent to the construction work. Access shall be provided to the work for such independent installations. 3. Instruments shall be installed in accordance with the Contract Documents and the manufacturer's recommendations.
	Final Delivery	

Phase	Element	The Highways Agency, UK Guidance on the trenchless installation of services beneath motorways and trunk roads (2018)
Before Construction	Site Investigation	(a) Identification and location of all existing underground infrastructure are necessary prior to commencing any excavation or drilling activity. It should include abandoned and disused services as well as those that are active.
	Plan	(a) In all cases the Installer should identify the owners of underground infrastructure likely to be affected by the proposed crossing. All applicable records should be collected and reviewed in detail, drawings developed showing their location, and proposals submitted for avoiding damage. (b) It is recommended that the Installer appoints a Geotechnical Specialist as a focal point for all geotechnical aspects of the project. Further information is given in Site Investigation in Construction Series Documents (1993). (c) Acceptable levels of damage (if any), movement, and levels for noise and vibration at nearby structures should be agreed prior to any construction works. (d) The records, and their format, to be kept by the Installer and supplied to the Managing Agent's (MA's) coordinator should be established and agreed together with the timescale for submission prior to any construction works. (e) In compiling the Ground Investigation Report, the Installer's Geotechnical Specialist will need to consult sources of existing information, such as geological maps, memoirs, and previously completed ground investigations relevant to the site. During this time, temporary 'view-only' access to the Highways Agency Geotechnical Data Management System (HA GMDS) will be granted. The Reports Database of this system contains an inventory and downloadable copies of ground investigation reports previously undertaken on behalf of the Highways Agency.
	Design	(a) The Geotechnical Design Report should be submitted by the Installer to the Managing Agent's Geotechnical Liaison Engineer (MAGLE) for approval. Timescales for submission should be agreed with the managing agent (MA); notice periods should also comply with the relevant legislation. It is important that the Installer allows sufficient time within the construction program for this to take place.
During Construction	Materials	
	Equipment and Machinery	
	Locating and Tracking	
	Installation	
	Site Restoration	(a) Several of the methods described use drilling fluids in their operation. These materials, and all excavated materials, must be disposed of in accordance with all relevant legislation and local and national requirements for environmental protection.
	Remediation	
	Inspection	
After Construction	Quality Control	(a) Prior to any trenchless technology works, the Installer may be required to make measurements of existing ground levels. (b) The Installer should monitor the levels during construction works and record the values as agreed. Any variation from predicted values should immediately be reported to the managing agent (MA).
	Final Delivery	(a) All survey information, records, and assessments, should be included in the project Feedback Report.

Phase	Element	New York State Department of Transportation (NYSDOT) Standard Specifications Revised Section 650-Trenchless Installation of Casing (2008)
Before Construction	Site Investigation	
	Plan	(a) The Plan should show the work zone equipment configuration at the ends of the bore(s), staging areas, storage areas, location of slurry, cuttings and pit spoil-handling areas, and final placement areas.
	Design	(a) Design of entrance and exit pits shall include shoring elements, type, depth, bracing size, etc.
During Construction	Materials	(a) Materials list should include bentonite and bentonite additives proposed for use on the project, along with material safety data sheets for all other materials used in the trenchless installation method.
	Equipment and Machinery	
	Locating and Tracking	(a) Direct all drilling operations using steering and tracking systems capable of producing the required alignment within an allowable accuracy of ±1% of the bore length. Maintain the grade within 50 mm (2 in) throughout the bore length. The steering control system shall provide an angle of inclination reading and the direction in which the cutting tool is pointing.
	Installation	(a) When casing is applied, the alignment of the casing shall conform to the following requirements: 1) Choose the ground entry and exit angles such that the casing can be installed along the alignment and profile indicated on the contract plans. 2) The entrance point(s) and exit point(s) shall be approved by the Engineer and physically located in the field by the Contractor. 3) The exit point shall be no more than ±1% of the bore length left or right of the location marked in the field. 4) The vertical depth, as specified in the contract documents, is the depth to which the casing shall be installed.
	Site Restoration	
	Remediation	(a) In the event that the drill hole must be abandoned before the completion of the installation or the installation is out of tolerance, fill the abandoned drill hole with CLSM to prevent subsidence. Start pumping from the farthest point of progression of the abandoned drill hole back to the surface to eliminate encapsulating voids. The progression and restoration of the abandoned drill hole by CLSM placement will beat the Contractor's expense. The location of the new drill hole shall be approved by the DCETS prior to the progression of the operation as per NYSDOT Standard Specifications §650-3.01. Approval.
	Inspection	(a) Provide access to the Engineer at all times to all measuring or gauging devices used for the drilling operations, including drilling logs maintained by the Contractor.
After Construction	Quality Control	(a) Closely monitor the trenchless installation process to eliminate ground movements. If ground movements occur, stop work and immediately stabilize the area of concern. If it is determined during the installation process that the proposed lines and grades for the casing cannot be achieved, stop work. The Contractor shall then modify the methods of installation and submit them for review and approval as stated in NYSDOT Standard Specifications §650-3.01: Approval. Corrective stabilization actions are at the Contractor's expense.
	Final Delivery	

Phase	Element	The Plastic Pipe Institute Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe (2009)
Before Construction	Site Investigation	(a) For relatively extensive projects, such as for upgrading utility lines across a community, the owner of the facility to be placed or his representative (e.g., a geotechnical engineer), or the (potential) contractor, should perform a preliminary site investigation well in advance of the construction. (b) For projects of very limited duration, the contractor may perform only a brief study to verify the general feasibility and determine the equipment and resources required to successfully complete the task. The presence of special obstacles or situations must be considered. For example, the presence of pollutants or contaminants in the construction area must be identified, including corresponding arrangements for spoil disposal. (c) The contractor should review the construction site to verify there is sufficient room for the drill rig and auxiliary equipment, vehicles, and trailers at both ends of the bore. The drill rig working areas should be reasonably firm, level, and suitable for the movement of rubber tires or treads. For PE pipe of relatively large diameter, not provided on a reel, for which pipe prefabrication is necessary, appropriate space must be provided for the fusion equipment, as well as an area for temporarily placing the assembled pipe. (d) The presence of possible interfering aboveground structures or overhead power or telephone lines should be considered with regard to equipment movement. (e) The ability for the tracking and monitoring system to function properly may be hampered by the local conditions along the path to be bored. Conventional walkover receivers require direct overhead access, while more sophisticated systems may allow remote tracking. Potential sources of interference to the electronic locators of mini-HDD tracking systems include overhead structures or wire lines, as well as steel-reinforced concrete sidewalks, driveways, and roads. (f) The use of drilling fluids requires that a source of water, preferably potable, be available for mixing. Although drilling fluids are not considered hazardous materials, excess fluid and associated spoils must be disposed of properly. The location of an appropriate disposal area, consistent with local regulations, should be identified in advance of the construction, as part of the preliminary or planning phase. (g) Although noise levels associated with mini-HDD equipment are generally not excessive, there may be restrictions on work hours in areas near residential buildings, hospitals, or other institutions. (h) The soil investigation should attempt to evaluate conditions at the nominal placement depth of the product pipe. Mini-HDD technology is capable of placing utility lines or pipes as deep as 15 ft. In many cases, however, the desired or required depth for utility distribution lines will be relatively shallow--possibly within six feet of the surface. (Greater depths may complicate subsequent repair and maintenance procedures.) Such mini-HDD installations will also likely be in established areas, including residential communities. Thus, the relevant belowground conditions are not necessarily that of virgin soil at greater depths, but that of disturbed or filled areas, possibly including various debris or obstacles resulting from prior construction activities. (i) Possible characteristics to be evaluated include standard classification of soils, standard penetration test values, rock type and strength, and (Mohs) hardness. (ASCE 108) ASTM F 1962 provides reference ASTM test methods for soil evaluation studies, as appropriate. More extensive information is available elsewhere. (j) Locating and Marking All existing belowground facilities, including lines and structures, must be identified, located, and marked--including electrical and communications (telephone, CATV) cables, natural gas, water and sewer lines, pipes carrying other liquids, chemicals or gases, and oil tanks or other possible structures.
	Plan	(a) The size and anticipated duration of the project is an important consideration with respect to the amount of preliminary planning and investigations that may be practical. (b) Knowledge of setback distance requirements is important with respect to determining the location and position of the drill rig, consistent with available space or feasible or convenient setup locations. In order to achieve a specified depth at a particular point towards the beginning of a pilot bore operation, the front of the drill rig must be located an appropriate distance rearward from the point of interest. This setback distance depends not only upon the depth at the point of interest but also on the desired orientation (percent grade) of the bore at that point. (c) Knowledge of distance to rise to surface from level trajectory is important with respect to determining the location for feeding of the product pipe into the bore path during the pullback phase. Such locations must be compatible with available space at the far end of the bore path. If it is desired to exit the ground at a specific angle, a greater horizontal distance will generally be required. (d) Employees must be trained to prevent injuries to themselves during the operation of the equipment and be prepared to mitigate the effects of accidents. (e) To help maintain the required separation, it is recommended that the proposed bore path, including the outer edge of the cutter/reamer, be an additional 18 inches (45.7 cm) laterally offset from the outer edges of the tolerance zone, corresponding to a total 36 inches (91.4 cm) initially planned separation. For the case of the bore path crossing an exposed utility, adequate physical separation may be visually verified as the drill head or reamer passes above or beneath the existing line. The owner may place additional restrictions on the allowed deviation from the proposed bore, in both vertical and horizontal directions. (f) The combination of warning lights, traffic cones, and flagmen must be used to ensure a safe working environment for the construction personnel as well as non-construction related passersby.

Phase	Element	The Plastic Pipe Institute Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe (2009)
	Design	(a) The characteristics of the drill rods, as described, including bending capability and rod length, and the entry angle of the rod to ground surface, will essentially determine the depths achievable at the beginning of the bore path. (b) A proposed bore path plan view and profile layout should be prepared indicating the surface grade and important surface features, location of existing below ground utility lines, reference points, etc. The bore path layout should also show anticipated access pits for utility connections or lateral service lines and the bore depth of the pipe to be placed, especially at critical points such as access pits, and at other reference points along the route. In plain view, the bore path should be as direct as possible, consistent with available right-of-way, utility architecture, existing utilities, and other obstacles, as well as the capability of the mini-HDD system, considering the recommended bend radius of the drill rods and ability to steer within the soil. (c) Typical drilling fluid components are not hazardous materials, with the waste material usually considered as excavation spoils, not requiring special disposal procedures. The most common additive is bentonite, a naturally occurring type of clay. If clay represents a large component of the native soil in the construction site, a polymer additive may be more appropriate. The bentonite or polymer material used should be National Sanitation Foundation certified. The additive materials should be chemically inert, biodegradable, and non-toxic, and petroleum-based or detergent additives should not be used. (d) The owner or its representative (engineer) will provide the general requirements for the path of the product pipe, including position within the right-of-way, identification of road or local obstacle crossings (e.g., laterals or service lines to residence or building). The precise location for each segment, however, will be determined on-site, in advance of the operations, by the selected contractor and utility engineer, depending upon the location of existing utilities and other site-specific conditions. (e) A minimum depth of cover of 36 inches (91 cm) is typically desired to reduce the likelihood for surface movement, drilling fluid penetration to the surface, and the tendency for the drill head to rise to the free surface during the initial pilot boring operation, thereby complicating the steering operation. Although greater depths are generally recommended depending upon the borehole size, as discussed below, excessive depths may not be practical for future maintenance activities. (f) Typical industry guidelines recommend a minimum ratio of approximately 10-to-1 for depth of cover to final bore hole diameter to avoid surface heaving effects for a compaction process in appropriate (compatible) soil conditions. (g) The bore should attempt to follow a path at the specified nominal depth below the average surface profile. For large surface depressions or mounds (e.g., of height greater than the depth of interest and extending over a long expanse, on the order of the drill rod bend radius or greater), including peaks and valleys, the bore should attempt to follow a path at the specified depth below the local average surface grade. (h) For pipe constructed from plastic or other very flexible material, the bend radius limitation of the drill rods is sufficiently large to be compatible with that of the product pipe. In particular, PE pipe is sufficiently flexible such that the corresponding bends and path curvatures imposed on the pipe during an HDD installation will not be significant.
During Construction	Materials	(a) The pipe selection process for HDPE pipe is equivalent to determining the minimum wall thickness, or maximum DR value that is sufficient to withstand the long-term operational loads as well as the stresses due to the installation process. The appropriate pipe minimum wall thickness will be greater than the values necessary to safely withstand (1) the various long-term operational (including soil and surface) loads and (2) the short-term installation (and pre-operational) loads associated with the mini-HDD operation.
	Equipment and Machinery	(a) A drill rod may be able to withstand a single bend cycle corresponding to a relatively sharp radius of curvature, but the rotation of the rod during the boring operation results in repeated flexure which may eventually cause fatigue failure due to the cumulative effect of a large number of such cycles. The diameter of the drill rod is the primary parameter affecting its allowable bend radius and corresponding steering capability.

Phase	Element	The Plastic Pipe Institute Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe (2009)
	Locating and Tracking	(a) The recorded path information is based upon the tracking information obtained during the pilot bore operation, and assumes that the reamer closely follows the original path. In practice, however, it is not uncommon for the reamer to deviate somewhat from the pilot bore path, due to various effects, including a tendency for the reamer to cut corners as it is pulled around curves and bends. Although such discrepancies may be significant in cases of very close proximity to other utilities, it is not generally considered to be a major issue, similar to the tendency of the installed product pipe to float above (or sit below) the centerline of the final bore hole corresponding to the difference in their diameters. (b) The locator provides information to the operator on an ongoing basis to allow path corrections to follow the planned bore path as closely as possible. For systems that directly transmit the locating information to a display at the drill rig, much of this function is accomplished automatically, but communications are still required to coordinate operations and avoid hazardous situations. Radio communications should be used for distances exceeding that for convenient voice communication (e.g., 50 ft or 15.2 m) or when out of sight. If communications are disrupted, the drilling operation must be halted until communications are restored (IEEE Standard 1333). (c) Typical locating equipment and procedures are based upon the transmission of an electrical signal along an available metallic (conducting) element of the utility line of interest, in combination with an aboveground receiver. The lateral position, and to some extent, the depth, are determined by the characteristics of the received signal. For non-metallic (non-conducting) lines or facilities, a metallic tracer wire or discrete electronic markers may have been deliberately placed to facilitate future detection. In other cases, transmitting devices may be able to be placed within a plastic or another non-conducting pipe to provide an electronic signal at the surface. Improved methods continue to evolve based upon other technologies, including acoustical techniques and ground-penetrating radar.
	Installation	(a) Soil conditions, including cobbles and other encountered obstacles, as well as attempts to conform to relatively sharp bends, may result in unintentional bore path deviations. More frequent verification of the position of the drill head during the pilot bore phase will help detect potential discrepancies as soon as possible. (b) Due to the possibility of soil clogging the drilling fluid ports of the drill head or reamer, the attempt to relieve pressure at the rig may not result in an immediate loss of pressure within the drill string. In such cases, special care is required when disconnecting the rod. Clogged drill components should be cleared prior to continuing the operation, possibly requiring the drill string to be retracted or exposed. (c) Avoid supporting pipe on a surface that may cause abrasion during pullback. (d) Minimize back tension on pipe to prevent escalating effects at pulling end. (e) Avoid pulling around sharp bends to avoid pipe collapse (kinking); see comments below. (f) Pull additional 3-4% length at pipe exit to allow for temporary elongation (stretch) and subsequent recovery. (g) When exposed to sharp bends, the pipe is vulnerable to local collapse. (h) The exit point for the pilot bore represents a potentially hazardous location from which a safe distance must be maintained by all personnel. The drilling fluid pressure should be relieved as soon as the drill head emerges at the far end, as well as when the reamer emerges from the entry point at the rig end. (i) In the initial pilot hole drilling, the actual size and type drill head selected should be appropriate for the soil conditions, considering the ability to penetrate and accomplish the desired steering. Proper care and handling of the drill rods is important to avoid damage during the insertion or removal of rods from the drill string, and should conform to the manufacturer's guidelines. (j) A final hole diameter at least 50% greater than the outer diameter of the pipe (or pipe bundle) is recommended. (k) In order to maintain a neat, orderly work site, occasional small pits must be available for collecting the excess drilling fluid or slurry exiting from the borehole. A clean work site will help ensure the installation of a clean product pipe, reducing the need to later flush out mud or debris from within the pipe.
	Site Restoration	(a) After approval by the owner, the pits should be filled as soon as possible, the soil compacted, and the surface area restored, as reasonable. Surface mud and drilling fluid must be cleaned from the site and be properly disposed of. All equipment, tools, and miscellaneous debris must be removed. (b) Although the bentonite-water, or commonly used polymer water, slurry, is not inherently a hazardous material, special disposal may be required when drilling in an area known to contain toxic pollutants. In such cases, disposal must be in accordance with local laws and regulations, and it may be necessary to de-water the spoils, transport the solids to an appropriate disposal site, and treat the water to meet disposal requirements. It may also be necessary to add grouting to the drilling fluid to ensure proper sealing of the borehole to eliminate a possible passage for contaminants. In order to minimize lateral bearing loads at the front of the rig, and avoid potential difficulties in the insertion of additional rods, steering should not be attempted until one rod length (e.g., 10 ft, 3 m) has been inserted straight (while rotating) into the ground.

Phase	Element	The Plastic Pipe Institute Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe (2009)
	Remediation	(a) Potential Causes of Failure or Problems: HDD operations should only be performed by trained and experienced contractors. Nonetheless, such operations may encounter various difficulties, including: (1) Loss of drilling fluid or loss of circulation (flow); (2) Obstructions (cobbles, debris, foundations etc.); (3) Hydro lock; (4) Line and Grade Problems; (5) Bore hole collapse; (6) Failure of drill rods or downhole tooling; (7) Surface collapse or heaving; (8) Inadvertent drilling fluid returns (surface, waterways, …); (9) Striking or damaging existing utility; (10) Product pipe failure or damage; (11) Product pipe stuck in bore hole. (b) In the event of inadvertent, uncontrolled returns, there are a variety of containment measures that may prove useful, depending upon the anticipated volume, access, environmental sensitivity of the area contaminated and adjacent areas and soil and weather conditions. Possible methods include the use of silt fencing, hay or straw bales, or sand bags. If insufficient, additional techniques are available.
	Inspection	(a) It is assumed that the owner, or its representative, of the pipeline facility being installed has had an inspector on-site or has regularly visited the area to verify the progress of the operation and that the construction is consistent with recommended practices, such as those provided herein or available from the industry. (b) It is essential that the pipeline facility being installed be visibly inspected prior to filling the various pits that may be present. In particular, the route should be inspected at openings or pits provided for access, as well as any areas where existing utilities have been exposed, such as at crossings with the new pipe. The depth of the pipe may be conveniently verified at such locations.
After Construction	Quality Control	(a) Pipe Testing: Depending upon the application, the integrity of the pipes should be verified. Any mud or debris that may have entered the pipe should be expelled, and the pipe flushed if necessary. Facilities to be used to transport fluids (gas or liquid) should be checked for leakage, pressurized if necessary. For pipes or conduits to be used for the installation of cables, a mandrel or equivalent should be inserted (pulled, blown, etc.) to verify a clear passage. If necessary, a pull line may be installed simultaneously during this procedure. For a project involving the placement of a large number of pipes or conduits for cable applications such verification may be performed on a sampling basis to maintain quality control of the overall process, as specified by the owner.
	Final Delivery	(a) The information of the actual “as-built” path of the pilot bore based upon the tracking information, corresponding to the original bore plan, the deviations from the intended path in both the horizontal and vertical directions are provided, and/or related drawings and supplemental information, may be used to provide a record of the installation, to be submitted to the owner (b) The drawings should reference permanent existing structures or features (e.g., curbing), and preferably indicate the relationship to existing utilities, especially at crossings of such lines. (c) Unforeseen obstacles encountered during the drilling process should also be indicated. Software tools are available for facilitating the preparation of the drawings. (d) The actual boring operation such as steering commands (drill head orientation) and additional information related to the boring or reaming operation, such as type and size (diameter) drill head, reamer and/or compactor; drilling fluid type and volume; duration of the pilot bore and/or back-reaming operation, may be useful for subsequent operations in the project area. (e) A daily log book, or equivalent, should be maintained by the contractor to provide a permanent record of the operation, including the above information. (f) Information showing the final “as-built” location of the pipe must be submitted to the owner, who should confirm that all appropriate information is included. The information should be sufficient to create a certified record of the new utility pipe. The drawings provided by the contractor may be used to verify the pipe was placed at the proper location and depth, or within acceptable limits.

Phase	Element	American Society of Civil Engineering (ASCE) Pipeline Design for Installation by Horizontal Directional Drilling (2014)
Before Construction	Site Investigation	(a) Once it has been determined that HDD will be utilized, a surface survey is typically performed. Prior to conducting the actual survey, the design engineer should investigate the site to determine the limits of work required for equipment staging and setup, pipe layout, and areas of potential impact, such as adjacent utilities or structures. The survey should be performed in an area sufficient in size to show equipment setup and storage locations. Typical staging areas required for HDD construction projects are discussed in Section 5. The survey should be conducted along the proposed drill path center line for a width of approximately 100 ft (30.5 m). Each HDD project has specific staging requirements that should be identified by the design engineer prior to initiating the field survey. Information to be gathered during the survey should include, but not be limited to, the following: (1) Existing grade elevation data referenced to a public datum if practical; (2) Surface features such as roadways, sidewalks, utility poles, overhead power lines, fire hydrants, etc.; (3) Ledge or rock outcrops; (4) Boring/test pit locations; (5) Waterways; (6) Potentially delineated wetlands; (7) Culverts; (8) Visible subsurface utility landmarks such as manholes or valve boxes; and (9) Structures such as buildings, towers, or bridges adjacent to the proposed drilled path. (b) A typical geotechnical survey consists of taking exploratory borings to collect soil samples for classification and laboratory analysis. Methods utilized in the survey of underground utilities, as described previously, can also be incorporated into the geotechnical survey. (c) The number, location, and depth of exploratory borings should be determined taking into account site-specific conditions such as the general geology of the area, availability of access, availability of existing data, cost, etc. Borings should be located off the drilled path centerline to reduce the possibility of drilling fluid inadvertently surfacing through the borings during HDD operations. The borings should penetrate to an elevation 20 to 30 ft (6 to 9 m) below the depth of the proposed drill path to provide information for design modifications and anticipated pilot-hole deviations during construction. (d) Areas of geologic transition and/or significant contrast in physical ground properties can present unique challenges to HDD construction and should be carefully scrutinized with greater frequency of investigation. Sampling interval and technique should be set to accurately describe subsurface material characteristics taking into account site-specific conditions. (e) Sampling interval and technique should be set to accurately describe subsurface material characteristics, taking into account site-specific conditions. Typically, split spoon samples will be taken in soft soil at 5 ft (1.5 m) depth intervals in accordance with ASTM D 1586-99. Where rock is encountered, it should be cored in accordance with ASTM D 2113-99, to the maximum depth of the boring. The following data should be developed from exploratory soil borings: Standard classification of soils in accordance with ASTM D 2487-00; Gradation curves for granular soils containing gravel; Standard penetration test (SPT) values where applicable (generally unconsolidated ground); Cored samples of rock with lithologic description, rock quality designation, and percent recovery; Unconfined compressive strength for representative rock samples (frequency of testing should be proportionate to the degree of variation encountered in rock core samples); and Mohs hardness for rock samples. (f) The following data should be developed from exploratory soil borings: 1) Standard classification of soils in accordance with ASTM D2487-10 (2011); 2) Gradation curves for granular soils containing gravel; 3) Standard penetration test (SPT) values where applicable (generally unconsolidated ground); 4) Cored samples of rock with lithologic description, rock quality designation (RQD), and percent recovery; 5) Unconfined compressive strength (UCS) for representative rock samples (frequency of testing should be proportionate to the degree of variation encountered in rock core samples); 6) Mohs hardness for rock samples; 7) Unit weight; 8) Atterberg limits; 9) Cohesion coefficient; 10) Soil friction angle, and 11) Depth to water table. (g) Seismic surveys require that a small explosive charge or impact by means of sledgehammer be initiated and detected via a series of detectors or geophones spaced along the path of the utility line. A time recorder is used to record the time of origin of the wave and the time of arrival at each detector. Similar to GPR, the water table and type of subsurface material affect the data output; therefore, proper interpretation of the data is critical, and greater density contrasts tend to yield more beneficial results. Seismic surveys are generally used in uncongested areas or locations where deep utility installations exist. Once the subsurface utility information is obtained, it should be correlated to determine possible conflicts and then included in the survey base drawings.
	Plan	

Phase	Element	American Society of Civil Engineering (ASCE) Pipeline Design for Installation by Horizontal Directional Drilling (2014)
	Design	(a) Penetration angles are measured from the horizontal. Entry angles are limited by equipment capabilities and should generally be designed between 8° and 20° (Directional Crossing Contractors Association 1995; Hair and Hair 1988). Most horizontal drilling rigs are designed to function best between 10° and 12°. However, for large-diameter pipelines, entry angles may be less than 8°. (b) Exit angles should be designed to provide ease in breakover support of the pull section. High exit angles require the pull section breakover bend to be supported at an elevated position during pull back. Exit angles should generally range from 5° (for large-diameter steel pipelines) to 12°. As part of a general constructability review, the design engineer should check pull section handling requirements to evaluate the constructability of the design. (c) The radius of curvature typically used in designing HDD paths is estimated to be equal to 100 ft (30.5 m) per in. (2.5 cm) -diameter of the pipe to be installed. This connection between pipe diameter and radius of curvature is derived from established practice for steel pipe rather than from theoretical analysis. Reduction of the design radius from this standard is possible, particularly for crossings utilizing alternate pipe materials such as high-density polyethylene (HDPE) pipe, fusible polyvinyl chloride pipe (FPVC), or ductile iron pipe (DIP). For instance, the cold bending radius for HDPE pipe in HDD and other pull-in applications is usually limited to 40 to 50 times the diameter. The preferred installed radius for full-length, flexible restrained joint DIP is 100ft per in. diameter; however, the flexible restrained joint is capable of significantly reduced values. In these cases, the lower limit of the radius is generally controlled by the capabilities of the drill pipe being used. However, reduction in radius increases bending stress and pulling load on steel pipe. For flexible restrained joint DIP bending stress is not an issue, but a similar increase in pulling load is encountered. (d) The drilling fluid is usually a mixture of freshwater, bentonite (sodium montmorillonite), and benign polymers. Bentonite is a natural clay that is very hydrophilic, causing the clay particles to swell when mixed with water. This swelling increases the fluid viscosity and helps create an impervious coating on the wall of the drilled hole. Bentonite and several of its additives are non-hazardous as defined by the U.S. Environmental Protection Agency. The freshwater is mixed with drilling fluid additives to obtain specific engineered characteristics for drilling performance. (e) The depth of penetration is controlled primarily by the definition of the obstacle. However, the design engineer should also consider other factors, such as geotechnical features, when selecting a penetration elevation. A minimum of 15ft (4.5 m) of separation beneath the obstacle should be maintained (Directional Crossing Contractors Association 1995; Hair and Hair 1988). Twenty-five feet is recommended as a standard separation distance and for less favorable drilling conditions. (f) The effective weight of the pipe is the unit weight of the pull section minus the unit weight of any drilling fluid displaced by the pull section. This is typically expressed in lb/ft. The unit weight of the pull section includes not only the product pipe, but also its contents (ducts, internal water used for ballast, etc.) and external coatings if substantial enough to add significant weight (i.e., concrete coating). Calculating the weight of drilling fluid displaced by the pull section requires that the density of the drilling fluid either be known or assumed. For HDD installations, drilling fluid density ranges from approximately 8.9 lb/gal to approximately 11.0 lb/gal--water weighs 8.34lb/gal. (American Gas Association 1994; Bennett and Ariaratnam 2008). Where use of a high-end value for fluid density is warranted for a conservative analysis, 12.0 lb/gal represents a reasonable upper limit. (g) Fluidic drag between the pipe and viscous drilling fluid is determined by multiplying the external surface area of the pipe by an appropriate fluid drag coefficient. A reasonable value for fluidic drag coefficient is 0.025 lb/sq. in. (Puckett 2003). The external surface area of any segment defined in the drilled path model can easily be determined based on the segment's length and the outside diameter of the pull section. For HDPE pipe, an alternate approach is given in ASTM F1962 (2011b). (h) Frictional drag between the pipe and soil is determined by multiplying the bearing force that the pull section exerts against the wall of the hole by an appropriate coefficient of friction. A reasonable value for the coefficient of friction is 0.3 for a pipe pulled into a reamed hole filled with drilling fluid (American Gas Association 1995). However, it should be noted that this value can vary with soil conditions. A very wet mucky soil may have a coefficient of friction of 0.1, while a rough and dry soil (unlikely in an HDD installation) may have a coefficient of friction of 0.8. For HDPE pipe sliding on the ground surface, ASTM F1962 (2011b) suggests a coefficient of friction of 0.5. For straight segments, the bearing force can be determined by multiplying the segment length by the effective unit weight of the pipe and the cosine of the segment's angle relative to the horizontal. For curved segments, calculation of the bearing force is more complicated because additional geometric variables must be considered along with the stiffness of the pipe. (i) The tension imposed on a circular pipe during installation by HDD is assumed to act through the centroid of the cross-section and therefore is uniformly distributed over the cross-section. The tensile stress is determined by dividing the tension by the cross-sectional area. The maximum allowable tensile stress imposed on a steel pull section during installation should be limited to 90% of the pipe's specified minimum yield strength (American Gas Association 1995).
During Construction	Materials	(a) Pipe to be installed by HDD should be smooth and flexible and have sufficient strength to resist tension, bending, and external pressure installation loads.
	Equipment and Machinery	(a) These pits typically have a volume of at least 500 cubic ft. (14.2 m^3) To make the drilling fluid suitable for reuse during pilot-hole drilling, reaming, and hole-conditioning operations, the cuttings and spoil must be continuously removed from the fluid as it returns to the surface. The drilling fluid returns are then processed through various levels of a solids control system. This system mechanically separates most fluid from the suspended solids so the fluid can be recirculated back downhole.

Phase	Element	American Society of Civil Engineering (ASCE) Pipeline Design for Installation by Horizontal Directional Drilling (2014)
	Locating and Tracking	(a) Utility lines can have both horizontal and vertical locations identified by means of surface applied pipe locators. Pipe locators can be instruments that simply detect underground lines by means of a magnetic field application similar to a metal locator. More sophisticated locators require imposing an electric current on the utility line. Applied current travels along the utility and is detected and traced with the pipe locator. Nonmetallic pipe, such as PVC or high-density polyethylene (HDPE) that has not been installed with a tracing wire cannot be detected with a pipe locator.
	Installation	(a) Allowable deviations from the specified drilled path must be provided taking into account constraints at a particular location. This is particularly critical where HDD is being used to install a gravity sewer. The required line and grade tolerances may not be achievable or may be achievable only after multiple pilot holes have been attempted. A reasonable target at the pilot-hole exit location is 10 ft (3 m) left or right and minus 10 ft (3 m) to plus 30 ft (9.1 m) in length (Directional Crossing Contractors Association 1995). (b) When installing HDPE pipe by HDD, installation stresses can often be reduced substantially by using rollers and filling the pull section with water as it is being pulled into the reamed hole. This practice has two primary benefits. First, with a specific gravity of less than 1, HDPE pipe is extremely buoyant when submerged in drilling fluid. Filling the pull section with water decreases the buoyant force exerted by the pipe on the top of the reamed hole, thereby reducing the pulling load. Second, the pressure exerted by the water in the pipe counteracts the external hydrostatic pressure exerted by the drilling fluid in the annulus. This increases the factor of safety relative to collapse. (c) Casings are rarely used in HDD installations because they require an additional step in the construction process and thus increase cost. Where casings are employed, it is usually to provide strength to resist installation loads, as in the case of an HDPE within a steel casing. HDPE may have been selected because of its resistance to corrosion during operation, but it may not have the tensile capacity to resist installation loads over a long-drilled segment. (d) Pipe installed using either the assembled line or cartridge installation methods (Ariaratnam and Carpenter 2003) shall have either welded, fused, or, for segmented pipe, flexible restrained joints. Installation of welded or fused joint pipe sections is best accomplished by using the assembled line method where the individual pipe sections, (steel, HDPE, or FPVC) are preassembled or fabricated (welded or fused) into long pull lengths prior to pull back.
	Site Restoration	
	Remediation	
	Inspection	
After Construction	Quality Control	
	Final Delivery	

Phase	Element	American Society of Civil Engineering (ASCE) Pipeline Design for Installation by Horizontal Directional Drilling (2005)
Before Construction	Site Investigation	(a) Once it has been determined that HDD will be utilized, a surface survey is typically performed. Prior to conducting the actual survey, the design engineer should investigate the site to determine the limits of work required for equipment staging and setup, pipe layout, and areas of the potential impact such as adjacent utilities or structures. The survey should be performed in an area sufficient in size to show equipment setup and storage locations. Typical staging areas required for HDD construction projects are discussed in Section 5. The survey should be conducted along the proposed drill path centerline for a width of approximately 100 ft (30.5 m). Each HDD project has specific staging requirements that should be identified by the design engineer prior to initiating the field survey. Information to be gathered during the survey should include, but not limited to, the following: Existing grade elevation data referenced to a public datum if practical; Surface features such as roadways, sidewalks, utility poles, overhead power lines, and fire hydrants; Ledge or rock outcrops; Boring/test pit locations; Waterways; Potentially delineated wetlands; Culverts; Visible subsurface utility landmarks such as manholes or valve boxes; and Structures such as buildings, towers, or bridges adjacent to the proposed drilled path. (b) Information to be gathered during the survey should include, but not limited to, the following: Existing grade elevation data referenced to a public datum if practical; Surface features such as roadways, sidewalks, utility poles, overhead power lines, and fire hydrants; Ledge or rock outcrops; Boring/test pit locations; Waterways; Potentially delineated wetlands; Culverts; Visible subsurface utility landmarks such as manholes or valve boxes; and Structures such as buildings, towers, or bridges adjacent to the proposed drilled path. (c) Sampling interval and technique should be set to accurately describe subsurface material characteristics, taking into account site-specific conditions. Typically, split spoon samples will be taken in soft soil at 5 ft (1.5 m) depth intervals in accordance with ASTM D 1586-99. Where rock is encountered, it should be cored in accordance with ASTM D 2113-99, to the maximum depth of the boring. (d) The following data should be developed from exploratory soil borings: Standard classification of soils in accordance with ASTM D 2487-00; Gradation curves for granular soils containing gravel; Standard penetration test (SPT) values where applicable (generally unconsolidated ground); Cored samples of rock with lithologic description, rock quality designation, and percent recovery; Unconfined compressive strength for representative rock samples (frequency of testing should be proportionate to the degree of variation encountered in rock core samples); and Mohs hardness for rock samples. (e) Utility survey information is important to the planning and execution of the HDD project. Unlike conventional open-cut installations, HDD projects require the contractor to install the utility line while unable to see what obstructions he is faced with; the contractor should be given a record of potential conflicts and utility clearances as completely and accurately as may be obtained by reasonable and diligent inquiry. Guidance with respect to subsurface utility research may be found in ASCE Standard 38-02. The first step in obtaining subsurface utility information is accomplished during the surface survey by locating visible subsurface utility landmarks. Knowing where valve boxes, manholes, and other structures are located will provide a starting point for utility research. The design engineer should exercise due diligence in not only identifying what utilities are located along the proposed HDD path but also in determining their horizontal and vertical positions, especially if the existing utility was installed via HDD construction. Methods of confirming subsurface utility locations include Pipe locators, Ground penetrating radar, Probing, Manual excavation, Vacuum excavation, and Seismic survey. (f) Seismic surveys require that a small explosive charge or impact by means of sledgehammer be initiated and detected via series of detectors or geophones spaced along the path of the utility line. A time recorder is used to denote the time of origin of the wave and the time of arrival at each detector. Similar to GPR, the water table and type of sub-surface material impact the data output; therefore, proper interpretation of the data is critical, and greater density contrasts tend to yield more beneficial results. Seismic surveys are generally used in non-congested areas or locations where deep utility installations have taken place. Once the sub-surface utility information is obtained, it should be correlated to determine possible conflicts and then included on the survey base drawings. (g) Ground-penetrating radar (GPR) utilizes radio waves to detect underground lines and surfaces. When an object is detected, the radio waves reflect back to the receiver that records the information. The data are downloaded onto a computer, and a profile of the utility and geologic information is plotted for interpretation. Subsurface obstructions such as rock and groundwater surfaces are also detected by GPR and can result in misinterpretation of the gathered data. Since the interpretation of the data is a critical element in GPR surveys, this method should be used in conjunction with other subsurface survey methods to improve the accuracy of the information. Ground-penetrating radar is most useful in depths less than 20 ft (6.1 m), where the density of the object or utility in question contrasts greatly with the surrounding ground. In addition, GPR is highly dependent on soil type and moisture content, is more effective in dry sands than wet soils, and does not work well in clay soils or in identifying pipes made of clay.
	Plan	

	Design	(a) Penetration angles are measured from the horizontal. Entry angles are limited by equipment capabilities and should generally be designed between 8◦and 20◦ (DCCA 1995, para. D.2; Hair and Hair 1988, p. 18). Most horizontal drilling rigs are designed to function best between 10°and 12°. However, for large-diameter pipelines, entry angles may be less than 8°. Exit angles should be designed to provide ease in breakover support of the pull section. High exit angles will require the pull section breakover bend to be supported at an elevated position during pullback. Exit angles should generally range from 5° (for large-diameter steel pipelines) to 12°. As part of a general constructability review, the design engineer should check pull section handling requirements to evaluate the constructability of the design. (b) The radius of curvature typically used in designing HDD paths is 1,200 times the nominal diameter of the pipe to be installed (DCCA 1995, para. D.2; Hair and Hair 1988, p. 17). This connection between pipe diameter and radius of curvature is derived from established practice for steel pipe rather than from theoretical analysis. Reduction of the design radius from this standard is possible, particularly for high-density polyethylene pipe. The cold-bending radius for HDPE pipe in HDD, another pull-in application, is usually limited to 40 to 50 times the diameter. However, a reduction in radius will increase bending stress and pulling load on steel pipe. (c) The radius of curvature typically used in designing HDD paths is 1,200 times the nominal diameter of the pipe to be installed (DCCA 1995, para. D.2; Hair and Hair 1988, p. 17). This connection between pipe diameter and radius of curvature is derived from established practice for steel pipe rather than from theoretical analysis. Reduction of the design radius from this standard is possible, particularly for high-density polyethylene pipe. The cold-bending radius for HDPE pipe in HDD, another pull-in application, is usually limited to 40 to 50 times the diameter. However, a reduction in radius will increase bending stress and pulling load on steel pipe. (d) The drilling fluid is usually a mixture of freshwater, bentonite (sodium montmorillonite), and benign polymers. Bentonite is a natural clay that is very hydrophilic, causing the clay particles to swell when mixed with water. This swelling increases the fluid viscosity and helps create an im-pervious coating on the wall of the drilled hole. Bentonite and several of its additives are non-hazardous as defined by the U.S. EPA. Material safety data sheets (MSDS) are readily available. Horizontal directional drilling operations typically utilize significant quantities of freshwater. Consumption rates can range between 300 and 800 gal/min (1136 and 3028 L/min), depending on the phase of HDD operations (e.g., less during a pilot hole, more during reaming and installation). The freshwater is mixed with drilling fluid additives to obtain specific engineered characteristics for drilling performance. The drilling fluid is pumped from the drilling rig through the drill pipe to the cutters. Here it is released and circulates back to the surface in the annulus between the drill pipe and the drilled hole. At the surface, it is collected in “return pits.’’ These pits typically have a volume of at least 500 ft^3 (14.2 cubic m).To make the drilling fluid suitable for reuse, the cuttings and spoil must be removed. The drilling fluid returns are introduced to a solids control system. This system mechanically separates the fluid from the suspended solids. However, solids control systems are not totally efficient, and the spoil discharged ranges from semi-dry particulate to thick sludge. Recirculation of drilling fluid is complicated in an HDD installation because the drilling fluid actually returns to the surface on either side of the obstacle. In many cases, two separate solids control systems are incorporated, or the drilling fluid is transported to the opposite work area by truck, barge, temporary pipe, etc. (e) The depth of penetration is primarily controlled by the definition of the obstacle. However, the design engineer should also consider other factors, such as geotechnical features, when selecting a penetration elevation. A minimum of 15 ft (4.6 m) of separation beneath the obstacle should be maintained (DCCA 1995, para. D.1; Hair and Hair 1988, p. 18). Twenty-five feet (7.6 m) is recommended as a standard separation distance, especially for less favorable drilling conditions. This minimum distance provides a margin for error in surveying methods both before and during construction. It should be noted that permit requirements may exceed the values previously stated. In determining the depth of penetration, the design engineer should take into account the risks of inadvertent drilling fluid returns and surface settlement or heaving. Where questions exist, the depth of penetration should be increased as this typically has very little impact on construction costs unless more difficult ground conditions are encountered. (f) The effective weight of the pipe is the unit weight of the pull section minus the unit weight of any drilling fluid displaced by the pull section. This is typically expressed in pounds per foot. The unit weight of the pull section includes not only the product pipe, but also its contents (ducts, internal water used for ballast, etc.) and external coatings if substantial enough to add significant weight (i.e., concrete coating). Calculating the weight of drilling fluid displaced by the pull section requires that the density of the drilling fluid be either known or assumed. For HDD installations, drilling fluid density will range from ∼8.9 to ∼11.0 lb/gal (PRC 1994, p. 30; HDD Consortium 2001, pp. 3–25). Where use of a high-end value for fluid density is warranted for a conservative analysis, 12.0 lb/gal represents a reasonable upper limit. (g) Fluidic drag between the pipe and viscous drilling fluid is determined by multiplying the external surface area of the pipe by an appropriate fluid drag coefficient. A reasonable value for fluidic drag coefficient is 0.025 $lb/in.^2$(Puckett 2003, p. 1352). The external surface area of any segment defined in the drilled path model can easily be determined based on the segment’s length and the outside diameter of the pull section. (h) Frictional drag between the pipe and soil is determined by multiplying the bearing force that the pull section exerts against the wall of the hole by an appropriate coefficient of friction. A reasonable value for coefficient of friction is 0.30 for a pipe pulled into a reamed hole filled with drilling fluid (PRC 1995, p. 41). However, it should be noted that this value can vary with soil conditions. A very wet, mucky soil may have a coefficient of friction of 0.1, whereas a rough and dry soil (unlikely in an HDD installation) may have a coefficient of friction of 0.8. For straight segments, the bearing force can be determined by multiplying the segment length by the effective unit weight of the pipe and the cosine of the segment’s angle relative to the horizontal. For curved segments, calculation of the bearing force is more complicated since additional geometric variables must be considered along with the stiffness of the pipe.

Phase	Element	American Society of Civil Engineering (ASCE) Pipeline Design for Installation by Horizontal Directional Drilling (2005)
		(i) The tension imposed on a circular pipe during installation by HDD is assumed to act through the centroid of the cross-section and therefore is uniformly distributed over the cross section. The tensile stress is determined by dividing the tension by the cross-sectional area. The maximum allowable tensile stress imposed on a steel pull section during installation should be limited to 90% of the pipe's specified minimum yield strength (PRC 1995, p. 46).
During Construction	Materials	(a) Steel pipe is subject to corrosion and is therefore generally installed with an external corrosion coating. External coatings used in HDD installations should be well bonded to the pipe to resist soil stresses and have a smooth, hard surface to reduce friction and maintain the corrosion barrier (DCCA 1995). There are numerous external coating products currently on the market, some designed specifically for HDD installations. Mill-applied thin-film fusion-bonded epoxy is commonly recommended in a minimum thickness of 20 mils (0.5 mm) (DCCA 1995). It should be noted that concrete weight coating is not generally required on HDD installations as the deep, undisturbed cover provided in most cases serves to restrain buoyant pipelines (PRC 1995, p. 36).
	Equipment and Machinery	
	Locating and Tracking	(a) Utility lines can have both horizontal and vertical locations identified by means of surface-applied pipe locators. Pipe locators can be instruments that simply locate underground lines by means of a magnetic field application similar to that of a metal locator. More sophisticated locators require imposing an electric current on the utility line. Applied current travels along the utility and is detected and traced with the pipe locator. Nonmetallic pipe, such as PVC or high-density polyethylene (HDPE) that has not been installed with a tracing wire cannot be detected with a pipe locator. Some underground utility lines, such as electric and cable television lines, can produce a detectable signal as long as the current is flowing through them. Pipe locators are generally less accurate with depth but can be extremely accurate in locating utilities buried less than 8 ft (2.4 m) deep, depending on conditions.
	Installation	(a) Casings are not typically used in HDD installations because they require an additional step in the construction process and thus increase the cost. Where casings are employed, it is usually to provide strength to resist installation loads, as in the case of HDPE pipe within a steel casing. Although HDPE may have been selected because of its resistance to corrosion during operation, it may not have the tensile capacity to resist installation loads over a long-drilled segment. The steel casing provides the structural strength needed for HDD installation. From an HDD design standpoint, no differentiation is made between a casing and carrier or product pipe. HDD operations are essentially the same.
	Site Restoration	(a) Since the drill operations will result in spoil materials being produced that will require handling and disposal, soil and/or groundwater samples should be taken during the utility and geotechnical investigations. During the geotechnical and utility excavation programs, soils and groundwater should be examined by both visual and olfactory means to determine whether potential hazardous materials exist, and samples should be analyzed to determine whether hazardous waste problems are indicated. Testing will vary, depending upon the site and actual conditions encountered; however, typical analysis can include Volatile organic compounds (VOC), Base/neutral extractable organic compounds, Total petroleum hydrocarbons (TPH), RCRA 8 metal analyses, and Pesticides/PCBs. Samples should be taken and analyzed in accordance with applicable state and Environmental Protection Agency (EPA) regulations and methods.
	Remediation	
	Inspection	
After Construction	Quality Control	
	Final Delivery	

Phase	Element	Latorre et al. (2002) for US Army Corps of Engineers Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling
Before Construction	Site Investigation	(a) Prior to commencement of the project, the area should be physically walked over and visually inspected by District Geotechnical Engineer, the driller, and members of the Levee Board for potential entry/exit sites. The following should be addressed: (1) When on CE/Levee Board property, it should be established whether or not there is sufficient room at the site for entrance and exit pits; HDD equipment and its safe unimpeded operation; support vehicles; fusion machines; aligning the pipe to be pulled back in a single continuous operation. (2) Suitability of soil conditions should be established for HDD operations. (The HDD method is ideally suited for soft subsoils such as clays and compacted sands. Subgrade soils consisting of large grain materials like gravel, cobble, and boulders make HDD difficult to use and may contribute to pipe damage.) (3) The site should be checked for evidence of substructures, such as manhole covers, valve box covers, meter boxes, electrical transformers, conduits or drop lines from utility poles, and pavement patches. HDD may be a suitable method in areas where the substructure density is relatively high. (b) Projects where the product or casing is 61 cm (24 in.) or greater in diameter, or when project crosses flood control projects. A geotechnical evaluation by a qualified soil engineer is required to determine the following: (1) Subsurface strata, fill, debris, and material. (2) Particle size distribution (particularly, percent gravel and cobble). (3) Cohesion index, internal angle of friction, and soil classification. (4) Plastic and liquid limits (clays), expansion index (clays), soil density, and standard penetration tests. (5) Rock strength, rock joint fracture and orientation, water table levels, and soil permeability. (6) Areas of suspected and known contamination should also be noted and characterized. Boreholes or test pits should be undertaken at approximately 75 to 125 m (250 to 410 ft) intervals where a proposed installation greater than 305 m (1,000 ft) in length and parallel to an existing road. Additional boreholes or test pits should be considered if substantial variations in soil conditions are encountered.
	Plan	(a) The following steps should be undertaken by the permittee/contractor in order to ensure safe and efficient construction with minimum interruption of normal, everyday activities at the site: 1) Notify owners of subsurface utilities along and on either side of the proposed drill path of the impending work through USA alert (the one-call program). All utilities along and on either side of the proposed drill path are to be located. 2) Obtain all necessary permits or authorizations to carry construction activities near or across all such buried obstructions. 3) Expose all utility crossings using a hydro excavation, hand excavation, or other approved method (potholing) to confirm depth. 4) Arrange construction schedule to minimize disruption (e.g., drilling under major highways and/or river crossings). 5) Determine and document the proposed drill path, including horizontal and vertical alignments and the location of buried utilities and substructures along the path. (b) When a product line is installed in a crowded right-of-way, the issue of safe minimum separation distance arises. Many utility companies have established regulations for minimum separation distances between various utilities. These distances needed to be adjusted to account for possible minor deviation when a line product is installed using HDD technology. (c) Only operators who have "Proof of Training" by the North American Society of Trenchless Technology (NASTT) should be permitted to operate the drilling equipment in CE/Levee Board property. (d) Whenever possible, HDD installation should be planned so that back reaming and pulling for a leg can be completed on the same day. If necessary, it is permissible to drill the pilot hole and pre-ream one day, and complete both the final ream and the pullback on the following day. (e) If at all possible, the crossing should be planned to ensure that drilling proceed downhill, allowing the drilling mud to remain in the hole, minimizing inadvertent return.
	Design	(a) Drilling fluid mixture design: Drilling mud and additives to be used on a particular job should be identified in the permit package, and their Material Safety Data Sheets (MSDS) should be provided to the Permit Office. (b) Borehole pressure: There are legitimate concerns associated with the fluid pressures used for excavation during the horizontal directional drilling process and the risk of hydraulic fracturing. Reasonable limits must be placed on maximum fluid pressures in the annular space of the bore to prevent inadvertent drilling fluid returns to the ground surface. However, it is equally important that drilling pressures remain sufficiently high to maintain borehole stability, since the ease in which the pipe will be inserted into the borehole is dependent upon borehole stability. Limiting borehole pressures are a function of pore pressure, the pressure required to counterbalance the effective normal stresses acting around the bore (depth), and the undrained shear strength of the soil. (c) The drill path alignment should be as straight as possible to minimize the frictional resistance during pullback and to maximize the length of the pipe that can be installed during a single pull. (d) The radius of curvature is determined by the bending characteristics of the product line, and it is increasing with diameter. (e) Entrance angle of the drill string should be between 8 and 20 degrees, with 12 degrees being considered optimal. Shallower angles may reduce the penetrating capabilities of the drilling rig, while steeper angles may result in steering difficulties, particularly in soft soils. A recommended value for the exit angle of the drill string is within the range of 5 to 10 degrees.
During Construction	Materials	(a) Sufficient space should be allocated to fabricate the product pipeline into one string, thus enabling the pullback to be conducted in a single continuous operation. Tie-ins of successive strings during pullback may considerably increase the risk of an unsuccessful installation.

Phase	Element	Latorre et al. (2002) for US Army Corps of Engineers Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling
	Equipment and Machinery	(a) The drill rig shall have sufficient pulling capacity to meet the required installation loads determined by the detailed pipe calculations. The drill rig should have the ability to provide pull loads, push loads, and torque, and the permittee shall ensure that they are monitored during the drilling operation. The permittee shall ensure the drill rod can meet the bend radii required for the proposed installation (a general rule of thumb is 100 times, in feet, the diameter of the installed pipe in inches). (b) Sufficient space is required on the rig side to safely set up and operate the equipment. The workspace required depends on the type of rig to be used. A small rig may require as little as 3 by 3 m (10 by 10 ft) working space, while a large river crossing unit requires a minimum of 30 by 50 m (98 by 150 ft) working area. A working space of similar dimensions to that on the rig side should be allocated on the pipe side in case there is a need to move the rig and attempt drilling from this end of the crossing.
	Locating and Tracking	

Phase	Element	Latorre et al. (2002) for US Army Corps of Engineers Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling
	Installation	(a) The size of excavations for entrance and exit pits should be of sufficient size to avoid a sudden radius change of the pipe and consequent excessive deformation at these locations. Sizing the pits is a function of the pipe depth, diameter, and material. All pits, over 1.52 m (5 ft) in depth must abide by Occupational, Safety, and Health Administration (OSHA) regulations. (b) The product should be installed to the alignment and elevations shown on the drawings within the prespecified tolerances (tolerance values are application dependent, for example, in a major river crossing, a tolerance of ±4 m (13.1 ft) from the exit location along the drill path center line may be an acceptable value). This tolerance is not acceptable when installing a product line between manholes. Similarly, grade requirements for a water force main are significantly different from those on a gravity sewer project. (c) Excess drilling mud slurry shall be contained in a lined pit or containment pound at exit and entry points, until recycled or removed from the site. Entrance and exit pits should be of sufficient size to contain the expected return of drilling mud and spoils. (d) All diligent efforts should be made by the contractor to minimize the amount of drilling fluids and cuttings spilled during the drilling operation, and complete cleanup of all drilling mud overflows or spills shall be provided. (e) Excess drilling fluids shall be contained at entry and exit points until recycled or removed from the site. Entry and exit pits should be of sufficient size to contain the expected return of drilling fluids and soil cuttings. The permittee shall ensure that all drilling fluids are disposed of in a manner acceptable to the appropriate local, state, or federal regulatory agencies. (f) When drilling in contaminated ground, the drilling fluid shall be tested for contamination and disposed of appropriately. (g) To minimize heaving during pullback, the pullback rate shall be determined by maximizing the removal of soil cuttings and maximizing compaction of the ground surrounding the borehole. The pullback rate shall also minimize overcutting of the borehole during the back-reaming operation to ensure that excessive voids are not created and result in post-installation settlement. (h) Drilling mud pressure in the borehole should not exceed that which can be supported by the foundation soils to prevent heaving or a hydraulic fracturing of the soil (i.e., hydro-fracture). Allowing for a sufficient cover depth does not necessarily guarantee against hydro-fracture. Sound, cautious drilling practice minimizes the chance of hydro-fracture occurrence. Also, measuring mud pressures in the annular space behind the drill bit and comparing these mud pressures with the calculated maximum allowable pressures help minimize the occurrence of hydro-fracture. Typical bore depth of 0.75 to 1.0 m (2.5 to 3 ft) gives pipes with an Outside Diameter (O.D.) of 50–200 mm (2–7.9 in.) a minimum cover of 0.65 m (2.1 ft). While circumstances may dictate greater depths, shallower depths are not recommended. (i) It is preferable that straight tangent sections be drilled before the introduction of a long radius curve. Under all circumstances, a minimum of one complete length of drill rod should be utilized before starting to level out the borehole path. (j) Pipe installation should be performed in a manner that minimizes the over-stressing and straining of the pipe. This is of particular importance in the case of a polyethylene pipe. (k) Drilling mud should be used during drilling and back reaming operations. Using water exclusively may cause collapse of the borehole in unconsolidated soils. While in clays, the use of water may cause swelling and subsequent jamming of the product. (l) Heaving may occur when attempting to back-ream a hole that is too large. This can be avoided by using several pre-reams to gradually enlarge the hole to the desired diameter. (m) A swivel should be included between the reamer and the product pipe to prevent the transfer of rotational torque to the pipe during pullback. (n) In order to prevent over-stressing of the product during pullback, a weak link, or break-away pulling head, may be used between the swivel and die leading end of the pipe. More details regarding breakaway pulling heads can be found in the paragraph entitled "Break-away Pulling Head." (o) The pilot hole must be back-reamed to accommodate and permit free sliding of the product inside the borehole. A rule of thumb is to have a borehole 1.5 times the outer diameter of the product. This rule of thumb should be observed particularly with the larger diameter installations 250 mm (9.8 in.) O.D. (p)The conduit must be sealed at either end with a cap or a plug to prevent water, drilling fluids, and other foreign materials from entering the pipe as it is being pulled back. (q) Pipe rollers, skates, or other protective devices should be used to prevent damage to the pipe from the edges of the pit during pullback, eliminate ground drag, or reduce pulling force and subsequently reduce the stress on the product. (r) The drilling mud in the annular region should not be removed after installation but permitted to solidify and provide support for the pipe and neighboring soil. (s) In an HDD installation, the product may be exposed to extra abrasion during pullback. When installing a steel pipe, a form of coating which provides a corrosion barrier as well as an abrasion barrier is recommended during the operation, the coating should be well bonded and have a hard smooth surface to resist soil stresses and reduce friction, respectively. A recommended type of coating for steel pipes is mill applied Fusion Bonded Epoxy. (t) Trenching may be used to join sections of conduits installed by the directional boring method. An additional pipe length, sufficient for joining to the next segment, should be pulled into the entrance pit. This length of the pipe should not be damaged or interfere with the subsequent drilling of the next leg. The contractor should leave a minimum of 1 m (3 ft) of conduit above the ground on both sides of the borehole.

Phase	Element	Latorre et al. (2002) for US Army Corps of Engineers Guidelines for Installation of Utilities Beneath Corps of Engineers Levees Using Horizontal Directional Drilling
	Site Restoration	(a) All surfaces affected by the work shall be restored to their preconstruction conditions. Performance criteria for restoration work will be similar to those employed in traditional open excavation work. (b) Methods to be used in the collections, transportation, and disposal of drilling fluids, spoils, and excess drilling fluids should be in compliance with local ordinances, regulations, and environmentally sound practices in an approved disposal site. (c) The slurry should be tested for contamination and disposed of in a manner that meets government requirements when working in an area of contaminated ground. Precautions should be taken to keep drilling fluids out of the streets, manholes, sanitary and storm sewers, and other drainage systems, including streams and rivers. Recycling drilling fluids is an acceptable alternative to disposal. (d) Restoration of damage to a levee caused by hydro-fracture or any other aspect of the directional drilling operation shall be the responsibility of the permittee. Plans for all restoration or repair work shall be submitted for approval by the Levee District or Corps of Engineers District. (e) If a drill hole beneath a levee must be abandoned, the hole should be backfilled with grout or bentonite to prevent future subsidence.
	Remediation	(a) Should settlement occur, all repairs would be the responsibility of the permittee. To prevent future settlement should the drilling operation be unsuccessful, the permittee shall ensure the backfill of any void(s) with grout or backfilled by other means. Plans for all restoration or repair work shall be submitted for approval.
	Inspection	
After Construction	Quality Control	(a) During construction, continuous monitoring and plotting of pilot drill progress shall be undertaken. This is necessary to ensure compliance with the proposed installation alignment and allow for the undertaking of appropriate course corrections that would minimize "dog legs," should the bore begin to deviate from the intended bore path. (b) The actual path of the pilot hole should be plotted against the design drill path. Monitoring shall be accomplished by manual plotting based on location and depth readings provided by the onboard locating/tracking system or by hand-held walkover tracking systems. These readings map the bore path based on information provided by the locating/tracking system. Readings or plot points shall be undertaken on every drill rod. For installations where tight control of alignment and grade is required, readings shall be undertaken every 1.0 to 1.5 m (3 to 5 ft). At the completion of the bore, an as-built drawing shall be provided. Prior to commencement of a directional drilling operation, proper calibration of the sonde equipment shall be undertaken. (c) Monitoring of the drilling fluids such as the pumping rate, pressures at the drill rig and pressures in the annular space behind the drill bit (when drilling under flood control projects), viscosity, and density during the pilot bore, back reaming, and/or pipe installation stages shall be undertaken to ensure adequate removal of soil cuttings and that the stability of the borehole is maintained. (d) Subsurface monitoring points shall be established along the HDD centerline and along any flood protection project that the HDD crosses under to provide early indications of settlement since large voids may not materialize during drilling as a result of pavement bridging.
	Final Delivery	(a) If required, the permittee/contractor shall provide a set of as-built drawings including both alignment and profile. Drawings should be constructed from actual field readings. Raw data should be available for submission at any time upon request. As part of the "As-Built" document, the contractor shall specify the tracking equipment used, including method or confirmatory procedure used to ensure the data were captured.

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APPENDIX G: FIELD OBSERVATION OF SELECTED HDD INSTALLATION UNDER IDOT ROADWAYS

TABLE OF CONTENTS

G.1 QUINCY CASE HISTORY 304
G.2 HENNEPIN CASE HISTORY 319
G.3 PECATONICA CASE HISTORY 371
G.4 ELSAH CASE HISTORY 413
G.5 HIGHLAND CASE HISTORY 462
G.6 JACKSONVILLE CASE HISTORY 505
G.7 FARMER CITY CASE HISTORY 534
G.8 LITCHFIELD CASE HISTORY 560
G.9 ROCHELLE CASE HISTORY 580

LIST OF FIGURES

Figure 33. Photo. The project site. 304
Figure 34. Photo. Google Maps captures showing Quincy project location on state levels. 305
Figure 35. Photo. Google Maps captures showing Quincy project location on county levels. 305
Figure 36. Photo. Google Maps captures showing project's location on neighborhood levels. 306
Figure 37. Photo. Machinery used in the project. Ditch Witch FM5 mix. 308
Figure 38. Photo. Machinery used in the project. Komatsu PC 220 LC excavator. 308
Figure 39. Photo. Machinery used in the project. Ditch Witch JT1220 rig. 309
Figure 40. Photo. Machinery used in the project. Vac-Tron cuttings vacuum machine. 309
Figure 41. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Outside view. 310
Figure 42. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Inside view. 310
Figure 43. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Close view. 311
Figure 44. Photo. PVC pipes. 311
Figure 45. Photo. Cutting bit used for pilot boring. Close view. 312
Figure 46. Photo. Cutting bit used for pilot boring. General view. 312
Figure 47. Photo. Ditchwitch back-reamer used in this project. 313
Figure 48. Photo. Trenches on entry sides of the project. 313
Figure 49. Photo. Trenches on exit sides of the project. 314
Figure 50. Photo. Cutting bit used for pilot boring. Distant view. 314
Figure 51. Photo. Pipe after it had been pulled in place. 315
Figure 52. Photo. Using the Vac-Tron vacuum machine to remove the cuttings. 315
Figure 53. Photo. Observed ground heave. 316
Figure 54. Photo. Observed fluid flowing out at the point of entry during reaming. 316
Figure 55. Photo. Road IL-26. The traffic cones mark the area above the planned alignment. 319
Figure 56. Photo. Google Maps capture showing Hennepin project location on state levels. 320
Figure 57. Photo. Google Maps capture showing Hennepin project on county levels. 320
Figure 58. Photo. Google Maps capture showing Hennepin project location on neighborhood levels. 321
Figure 59. Photo. Road section just above the alignment showing the sealed cracks. The photo shows the excavator working on the upstream side. 321

Figure 60. Photo. Upstream side road shoulder, showing the damage due to soil loss. The location of the geotechnical investigation boring is also marked in the photo. 322

Figure 61. Graph. Stratigraphy and soil properties obtained from the boring performed. 323

Figure 62. Photo. Upstream side. 324

Figure 63. Photo. Downstream side. 324

Figure 64. Photo. Existing corrugated steel pipe from the upstream side. 325

Figure 65. Photo. Existing pipe from the downstream side. The photo includes the irregular, steep, and marginally stable slope due to the erosion. 325

Figure 66. Photo. Existing pipe from the downstream side showing its steep slope. 326

Figure 67. Graph. Stratigraphic cross-section showing the deposits within the Princeton Bedrock Valley. 327

Figure 68. Table. Generalized stratigraphic column of upper rock formations in the Hennepin project location 329

Figure 69. Graph. Cross-section of the road prior to construction. The schematic presents the slope on the downstream side undergoing erosion. 332

Figure 70. Graph. Cross-section of the road with the planned improvements. The schematic presents the elements of the first alternative (in black) and the modifications leading to the second alternative (in red). 332

Figure 71. Chart. Temperature and precipitation in Hennepin, Illinois. 334

Figure 72. Photo. Machinery used: excavator. 335

Figure 73. Photo. Machinery used: rig. 335

Figure 74. Photo. Machinery used: fluid tank and mixer. 336

Figure 75. Photo. Machinery used: pipe fusor. 336

Figure 76. Photo. Machinery used: vacuum excavator. 336

Figure 77. Photo. Equipment used: Armor Lance bit of 6.5” (16.5 cm) diameter. 337

Figure 78. Photo. Equipment used: tracking sensor housed in drill pipe. 337

Figure 79. Photo. Equipment used: pipe stand. 338

Figure 80. Photo. Equipment used: fluted reamer. 338

Figure 81. Photo. Equipment used: pull head. 339

Figure 82. Photo. Equipment used: swivel. 339

Figure 83. Photo. 24” (61 cm) HDPE pipe. 340

Figure 84. Photo. Component of Fluid Mix 1-Swim Clear pH plus (Water conditioner that adjusts its pH)..... 340
Figure 85. Photo. Component of Fluid Mix 1-ProDrill (soil stabilizer and viscofier). 341
Figure 86. Photo. Component of Fluid Mix 1-ProDyne (A non-foaming drilling detergent and water conditioner). 341
Figure 87. Photo. Component of Fluid Mix 2-MaxBore bentonite..... 342
Figure 88. Photo. Component of Fluid Mix 2-Duo-Vis. 342
Figure 89. Photo. Component of Fluid Mix 2-Platinum PAC. 343
Figure 90. Photo. Photo of pipe fusor control panel. 344
Figure 91. Photo. Photo of pipe fusing. 344
Figure 92. Photo. Roller pipe stands. 345
Figure 93. Photo. Pipe rolled over pipe stands. 345
Figure 94. Photo. Google map with illustrations showing the trajectory of the pipe movement. 346
Figure 95. Photo. Pipe handling and movement from fusing area. 347
Figure 96. Photo. Pipe handling and movement from the pipe fusing area towards the downstream entrance just past the top of the slope break between the ditch and the embankment side slope. . 347
Figure 97. Photo. Pipe handling and movement towards the downstream entrance with pipe bending as it passes the top of the slope break from the ditch and down the embankment side slope. 348
Figure 98. Photo. Pipe handling and movement in downstream area..... 348
Figure 99. Photo. Pipe handling and movement in downstream area in line with the downstream entrance and positioned for pulling. 349
Figure 100. Photo. Location of the rig. 350
Figure 101. Photo. Start of pilot boring. 350
Figure 102. Photo. Flow of fluid as the drill broke through the downstream side. 351
Figure 103. Photo. Removal of the drill bit to install the first reamer. 351
Figure 104. Photo. Dumped cobble-sized crushed stone used to stabilize part of the downstream slope. Close view. 352
Figure 105. Photo. Dumped cobble sized crushed stone used to stabilize part of the downstream slope. 352
Figure 106. Photo. Rod after removal of drill bit and before installing reamer. 354
Figure 107. Photo. 30 in. (76.2 cm) fluted reamer installed to rod and about to start reaming. 354

Figure 108. Photo. Stable boring reamed in second stage. 355
Figure 109. Photo. Reamer attached via a swivel to the pull head which is fused to the pipe. 355
Figure 110. Photo. Pulling of the pipe. 356
Figure 111. Photo. Pulling the pipe. 356
Figure 112. Photo. Pull head reaching the upstream side (the photo also shows the 24 in. (61 cm) reamer next to the 30 in. (72.6 cm) reamer attached to the pull head). 357
Figure 113. Photo. Badger vacuum truck. 357
Figure 114. Photo. Downstream end of the pipe showing traces of the fluid after the pipe has been fully pulled (the photo also shows the old pipe on the left). 358
Figure 115. Photo. Photo of the fluids collection pit (hole) at the downstream side of the bore. 358
Figure 116. Photo. Tube from the vacuum truck and the fluid retention pit (hole) located higher up the slope from the lower fluids collection pit on the downstream side of the bore within reach of the hose from vacuum truck. 359
Figure 117. Photo. Movement of the excavator over the road. (1) 359
Figure 118. Photo. Movement of the excavator over the road. (2) 360
Figure 119. Photo. Slope fixing. 360
Figure 120. Photo. Pavement cleaning. 361
Figure 121. Photo. Plan view showing survey marker points. 361
Figure 122. Photo. Typical set of survey readings. 362
Figure 123. Photo. Condition of pavement after pipe installation. 362
Figure 124. Chart. 2D plot showing the ground movement after finishing pipe installation relative to initial elevations. Dashed lines mark the alignment of the pipe culvert. 363
Figure 125. Chart. 3D plot showing the ground movement after finishing pipe installation relative to initial elevations (Pipe alignment is located at zero on the x-axis). 364
Figure 126. Chart. Plot of settlements, relative to initial elevations, at the centerline above the pipe alignment after each stage. 364
Figure 127. Photo. Fluid flowing out of the old pipe just before the drill bit broke through exit point on the downstream. 367
Figure 128. Report. The as-built profile of the drill location for the HDD pipe installation in Hennepin project. (Provided by Midwest Mole) 369
Figure 129. Report. The as-built profile of the drill location of the HDD pipe installation in Hennepin project. (Provided by Midwest Mole) 370

Figure 130. Photo. US-20 Highway. The intersecting road is the North Conger Road. 371
Figure 131. Photo. Part of the open-cut section showing the pipe before being lowered into the cut. 371
Figure 132. Photo. Google Maps capture showing Pecatonica project site on state levels. 372
Figure 133. Photo. Google Maps capture showing Pecatonica project site on county levels..... 373
Figure 134. Photo. Google Maps capture showing Pecatonica project site on neighborhood levels. 373
Figure 135. Photo. JULIE yellow and orange flags (left of photo), indicating existence of gas and communication lines..... 374
Figure 136. Photo. Closest building to the centerline of the pipeline..... 374
Figure 137. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (1)..... 375
Figure 138. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (2)..... 375
Figure 139. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (3)..... 376
Figure 140. Chart. Stratigraphy and soil properties obtained from boring B1. 377
Figure 141. Chart. Stratigraphy and soil properties obtained from boring B2. 378
Figure 142. Photo. Northern side of the road. 379
Figure 143. Photo. Southern side of the road. 379
Figure 144. Graph. Surficial geologic map of the Pecatonica area. 382
Figure 145. Graph. Plan view and cross-section of the road with the planned improvements. The schematic shows the elements of the first alternative (in black) and the modifications leading to the second alternative (in red). 383
Figure 146. Chart. Temperature and precipitation in Albertus, Illinois, close to Pecatonica, Illinois.. 384
Figure 147. Photo. Machinery used: excavator. 385
Figure 148. Photo. Machinery used: rig. 386
Figure 149. Photo. Machinery used: fluid tank and mixer..... 386
Figure 150. Photo. Machinery used: pipe fusor. 387
Figure 151. Photo. Machinery used: Equipment Storage Truck. 387
Figure 152. Photo. Equipment used: drill bit. 388
Figure 153. Photo. Equipment used: pull head. 389

Figure 154. Photo. Equipment used: 20” (50.8 cm) reamer. 389
Figure 155. Photo. Equipment used: 30” (76.2 cm) reamer. 390
Figure 156. Photo. Equipment used: swivel. 390
Figure 157. Photo. Equipment used: pipe stand. 391
Figure 158. Photo. Equipment used: tracker. 391
Figure 159. Photo. Equipment used: mud pump. 392
Figure 160. Photo. Pipe. 393
Figure 161. Photo. Morton water softener. 393
Figure 162. Photo. Max Bore Bentonite. 394
Figure 163. Photo. SlikGel Bentonite. 394
Figure 164. Photo. Assembly of the fluid recycling system. The pipe feeds the fluid from the fluid system. 396
Figure 165. Photo. Assembly of the fluid recycling system. The pipe feeds the fluid from the fluid system into the rig. 396
Figure 166. Photo. Assembly of the fluid recycling system. The used fluid is pumped back from the bore pit using the pump. 397
Figure 167. Photo. Delays were caused by rig starting issues. 397
Figure 168. Photo. The fluid pump in the bore pit. 398
Figure 169. Photo. The fluid pump being removed before being warmed using gas. 398
Figure 170. Photo. The drill bit about to start pilot drilling. 399
Figure 171. Photo. Tracking system used to track the location of the drill bit. 399
Figure 172. Photo. Traces of the inadvertent return that occurred after 40 ft (12.2 m) of pilot drilling. (1) 400
Figure 173. Photo. Traces of the inadvertent return that occurred after 40 ft of pilot drilling. (2) 400
Figure 174. Photo. The bore after the drilling rod was retracted. 401
Figure 175. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (1) 401
Figure 176. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (2) 402
Figure 177. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (3) 402

Figure 178. Photo. Drill bit exiting at the southern side of the highway. 403
Figure 179. Photo. The drilling rod connected to the swivel, which is connected to a wire rope. 404
Figure 180. Photo. The 20 in. (50.8 cm) reamer installed to the rod directly connected to the rig.... 405
Figure 181. Photo. Drilling fluid ejected from nozzles of the reamer. 405
Figure 182. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (1) 406
Figure 183. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (2) 406
Figure 184. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (3) 407
Figure 185. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (4) 407
Figure 186. Photo. The pipe with the welded pull head. 408
Figure 187. Photo. The 24 in. tri-cone roller reamer which was used during pipe pulling. 409
Figure 188. Photo. The start of the pipe pulling. The photo shows the reamer connected to the pipe pull head via the swivel. 409
Figure 189. Photo. How the pipe was handled using excavators during its pulling. 410
Figure 190. Photo. The reamer and pull head in the bore pit after the pipe pulling was concluded.. 410
Figure 191. Photo. Road IL-100 (looking west) at the location of the planned crossing in July 2018. 413
Figure 192. Photo. Google Maps capture showing planned alignment crossing the Mississippi River with the location of the boreholes. 413
Figure 193. Photo. Google Maps capture showing Elsah project location on state levels. 414
Figure 194. Photo. Google Maps capture showing Elsah project on county levels. 414
Figure 195. Photo. Google Maps capture showing Elsah project on neighborhood levels..... 415
Figure 196. Chart. Stratigraphy and rock RQD derived from MISIP-1 borings. 416
Figure 197. Chart. Stratigraphy and rock RQD derived from MISIP-2 borings. 416
Figure 198. Chart. Stratigraphy and rock RQD derived from MISIP-3 borings. 417
Figure 199 Chart. Stratigraphy and rock RQD derived from MISIP-4 borings. 417
Figure 200. Table. Geologic units in Elsah quadrangle. 420
Figure 201. Graph. Part of the elevation profile of the planned alignment, showing its relative location with respect to the road. 421
Figure 202. Chart. Full elevation profile of the planned alignment, showing the relative location of the boreholes with respect to the planned alignment. 422
Figure 203. Chart. Calculated failure pressure and the estimated pressure using the intersect method. 422
Figure 204. Chart. Temperature and precipitation in Elsah, Illinois. 425

Figure 205. Photo. The 42 in. (106.7 cm) casing housing the 14 in. (35.6 cm) casing in which the drill pipe is inserted. 432
Figure 206. Photo. The rig tripping the jetting assembly before replacing it with the mud motor assembly..... 432
Figure 207. Photo. The jetting assembly which was used for pilot drilling in soil. 433
Figure 208. Photo. The first section of the new tri-cone bit, bottom hole assembly, and mud motor being inserted into the 14 in. (35.6 cm) casing. 433
Figure 209. Photo. The second section of the bottom hole assembly showing the shock sub and gyro housing. 434
Figure 210. Photo. Good flow returning to the southern pit..... 434
Figure 211. Photo. Course cuttings falling from the shakers. 435
Figure 212. Photo. Fine cuttings falling from the centrifuge. 435
Figure 213. Photo. Dump truck being loaded with cuttings. 436
Figure 214. Photo. The large brace that was welded to the I-beam and the anchor plate. 436
Figure 215. Photo. The excavating pit at north entry point for the 42 in. (106.7 cm) casing (photo facing north). 437
Figure 216. Photo. Part of the 42 in. (106.7 cm) casing at north entry point (photo facing north). ... 437
Figure 217. Photo. Withdrawn drill bit showing it in good condition. 438
Figure 218. Photo. The installed 42 in. (106.7 cm) casing and 14 in. (35.6 cm) casing at north entry point (centralizer). 438
Figure 219. Photo. The HDD setup including the rig and the fluid system at north entry point. 439
Figure 220. Photo. The fluid mixing and recycling system at north entry point. 439
Figure 221. Photo. Pallets of the drilling fluid additive Super Gel-X Bentonite at north entry point. . 440
Figure 222. Photo. The rig set to a 16° angle. 440
Figure 223. Photo. A water truck filling the frac tanks. 441
Figure 224. Photo. I-beams being welded to the dead-man and 42 in. (107-cm) casing. 441
Figure 225. Photo. Joints being racked next to the rig. 442
Figure 226. Photo. The bottom hole assembly consisting of the drill bit, shock sub, and mud motor. 442
Figure 227. Photo. The bottom hole assembly being loaded on the rig. 443
Figure 228. Photo. Hay bales and bags of bentonite being pushed in the 14 in. (36 cm) casing. 443

Figure 229. Photo. Hay returning from the shaker. 444

Figure 230. Photo. The inadvertent return being contained using sand bags. 444

Figure 231. Photo. A “good” drilling fluid return flowing out of the 14 in. (35.6 cm) casing, indicating very little fluid loss into the geologic formation. 445

Figure 232. Photo. Inadvertent return spreading over a larger area compared with the previous day. 445

Figure 233. Photo. Location of the inadvertent return relative to site. 446

Figure 234. Photo. Rock cuttings after being separated by vibratory scalper shakers on the drilling fluid cleaning and recycling system. 446

Figure 235. Photo. Fine cuttings after being separated by hydrocyclones (de-sander left and de-silter right). 447

Figure 236. Chart. Actual profile vs planned profile. 447

Figure 237. Chart. Vertical and horizontal deviation along the profile. 448

Figure 238. Chart. Evolution of the pilot hole maximum vertical and horizontal deviations over the time of pilot drilling. Data before day 17 is not available. 448

Figure 239. Chart. Measured pressure vs estimated pressure and calculated failure pressure. 449

Figure 240. Photo. Reamer arriving at the drilling rig on the northern side after completing reaming. 451

Figure 241. Photo. The reamer turned around to start the first swabbing pass. 452

Figure 242. Photo. The 24 in. (61 cm) pipe being pulled into the 42 in. (106.7 cm) casing. 453

Figure 243. Photo. The pull head after completion of the pullback. 453

Figure 244. Photo. Handling of the pipe while being pulled into the hole. 454

Figure 245. Photo. Light scratches of the pipe coating. 455

Figure 246. Chart. Timeline of the project, showing the duration of each activity. 456

Figure 247. Graph. Surface deformation after pilot drilling. Dashed lines mark the boring alignment. Positive is heave. 457

Figure 248. Graph. Surface deformation after the end of construction. Dashed lines mark the boring alignment. Positive is heave. 457

Figure 249 Graph. Surface deformation around two years after the end of construction. Dashed lines mark the boring alignment. Positive is heave. 458

Figure 250. Document. Utility permit. 460

Figure 251. Document. Utility Permit Sheet. 461

Figure 252. Photo. Road IL-143 (photo looking West). 462
Figure 253. Photo. Google Maps capture showing Highland project on state levels. 463
Figure 254. Photo. Google Maps capture showing Highland project on county levels. 463
Figure 255. Photo. Google Maps capture showing Highland project on neighborhood levels. 464
Figure 256. Photo. Many fenced pit holes dug to locate the existing fiber cables. 465
Figure 257. Photo. A wooden lathe showing that 112 in. (284.5 cm) of cover is available for the sewer line. 465
Figure 258. Photo. A manhole next to the parking lot east of IL-143. 466
Figure 259. Chart. Stratigraphy and soil properties obtained from the boring performed. 467
Figure 260. Graph. Geologic map showing surficial geology of the area of Highland. The project location is shown on the northern part of the map. 469
Figure 261. Graph. Planned profile of the natural gas line to be installed using HDD. 470
Figure 262. Chart. Temperature and precipitation in Highland, IL. 472
Figure 263. Photo. Machinery used: 4 excavators. 473
Figure 264. Photo. Machinery used: rig. 474
Figure 265. Photo. Machinery used: fluid pump. 474
Figure 266. Photo. Machinery used: fluid recycling system. 475
Figure 267. Photo. Machinery used: vacuum excavator. 475
Figure 268. Photo. Photo for the 18” (45.7 cm) roller cone reamer. 476
Figure 269. Photo. The pull head. 476
Figure 270. Photo. The swivel. 477
Figure 271. Photo. Wood crane mats. 477
Figure 272. Photo. Bentonite (AMC Gel). 478
Figure 273. Photo. The additive (SandMaster). 478
Figure 274. Photo. Steel product pipe 12.75 in. (32.4 cm) in diameter and 0.5 in. (1.27 cm) in thickness 479
Figure 275. Photo. Pipe laid next to the eastern end of the profile, photo looking west (the far end of the photo is next to the exit pit). 480
Figure 276. Photo. Pipe laid next to the eastern end of the profile, photo looking east 480
Figure 277. Photo. Wrap used to protect the joints of the steel pipe; sealed TRENTON anticorrosive wraps 481

Figure 278. Photo. Wrap used to protect the joints of the steel pipe; the steel pipe joints wrapped with the anticorrosive wraps. 481

Figure 279. Chart. As built profile shared by Ameren, showing an excellent match of the actual and planned profile horizontally and vertically. 483

Figure 280. Photo. Some of the locations where inadvertent returns occurred (and were cleaned); photo (looking west) of the remains of the inadvertent return that occurred next to the road curb. 484

Figure 281. Photo. Some of the locations where inadvertent returns occurred (and were cleaned); photo (looking right) of the remains of the inadvertent return that occurred in the ditch of the road. 485

Figure 282. Photo. The reaming operation; photo of the reamed hole taken at the entry pit..... 485

Figure 283. Photo. The reaming operation; photo of the drill pipe being pulled by the excavator next to the exit pit. 486

Figure 284. Photo. An inadvertent return that occurred during reaming; photo of the fluid before cleaning. 486

Figure 285. Photo. An inadvertent return that occurred during reaming; photo of the fluid after cleaning, exposing that the inadvertent return was occurring through one of the pit holes that were dug to expose the location and depth of the utilities. 487

Figure 286. Photo. The end of the reaming operation; the ground heaving next to the exit pit just before the reamer arrives at the exit pit. 487

Figure 287. Photo. The end of the reaming operation; the reamer arriving at the exit pit (notice the orientation of the reamer used in forward reaming). 488

Figure 288. Photo. The swabbing operation; photo showing the reamer's orientation after being flipped. 489

Figure 289. Photo. The swabbing operation; the swivel carried by the excavator before being attached to the end of the drill pipes string. 489

Figure 290. Photo. The swabbing operation; the excavator assisting the rig with the swabbing..... 490

Figure 291. Photo. An inadvertent return that occurred during swabbing; the fluid emerging at the ground surface. 490

Figure 292. Photo. An inadvertent return that occurred during swabbing; the vacuum truck cleaning the fluid. 491

Figure 293. Photo. Cracks in the pavement of the car dealer's parking lot; the cracks observed on July 9. 491

Figure 294. Photo. Cracks in the pavement of the car dealer's parking lot; inadvertent returns coming out of the same cracks. 492

Figure 295. Photo. The reamer arriving at the entry pit after completing the swabbing pass. 492

Figure 296. Photo. Preparations for the pipe pulling; photo of the reamer and swivel attached to the drill pipe string. 494

Figure 297. Photo. Preparations for the pipe pulling; the pull head welded to the steel pipe. 494

Figure 298. Photo. The steel pipe being moved to reach the drill pipe; pipe being lifted by the three excavators. 495

Figure 299. Photo. The steel pipe being moved to reach the drill pipe; the pipe's end reaching the swivel attached to the reamer, which is attached to the drill pipe. 495

Figure 300. Photo. Measurement of the thickness of the cathodic coating as the pipe is being pulled. 496

Figure 301. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (1) 496

Figure 302. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (2) 497

Figure 303. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (3) 497

Figure 304. Photo. Some inadvertent returns that occurred in important locations; next to the manhole of the sewer line. 498

Figure 305. Photo. Some inadvertent returns that occurred in important locations; next to the western curb of the road. 498

Figure 306. Photo. Some inadvertent returns that occurred in important locations; through the ditch on the western side of the road. 499

Figure 307. Photo. An inadvertent return as it is happening. The fluid is squirting through the ground surface. 499

Figure 308. Photo. The steel pipe after finishing the pipe pulling; photo of the pull head at the entry pit. 500

Figure 309. Photo. The steel pipe after finishing the pipe pulling; photo of the end of the pipe at the exit pit. 500

Figure 310. Graph. Surface deformations after pilot drilling. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East. 501

Figure 311. Graph. Surface deformations after reaming and pipe pulling. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East. 502

Figure 312. Graph. Surface deformations around one and half years after the end of construction. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East... 503

Figure 313. Photo. Road IL-104 (photo looking east). 505

Figure 314. Photo. The railroad to the north of the road (photo looking south). 505
Figure 315. Photo. Google Maps captures showing Jacksonville project on state levels. 506
Figure 316. Photo. Google Maps capture showing Jacksonville project on county levels. 506
Figure 317. Photo. Google Maps capture showing Jacksonville project on neighborhood levels. 507
Figure 318. Photo. Minor pavement cracks that appeared before the installation of the pipe. 508
Figure 319. Photo. One of the pits that were dug to locate the fiberoptic cables after being filled with soil. 508
Figure 320. Photo. The white water main exposed while digging the entry trench. 509
Figure 321. Photo. The soil layers in the northern trench. 510
Figure 322. Graph. Plan and cross-section of the planned profile. 512
Figure 323. Chart. Temperature and precipitation in Jacksonville, Illinois. 513
Figure 324. Photo. Machinery used: rig. 514
Figure 325. Photo. Machinery used: CASE CX160 excavator. 514
Figure 326. Photo. Machinery used: CASE CX160 excavator. 515
Figure 327. Photo. Machinery used: fluid tank and mixer 515
Figure 328. Photo. Equipment used: slanted drill bit. 516
Figure 329. Photo. Equipment used: cutter-mixer reamer. 517
Figure 330. Photo. Equipment used: pull head. 517
Figure 331. Photo. Equipment used: swivel 518
Figure 332. Photo. Materials used: 10 in. (25.4 cm) steel casing. 519
Figure 333. Photo. Materials used: restrained joint 4 in. (10 cm) PVC pipe 519
Figure 334. Photo. Materials used: pipe lube. 520
Figure 335. Photo. Materials used: ProAction drilling fluid agents (ClayLock, ProDrill, and ProDyne). 520
Figure 336. Photo. Photo of the welding connection of two casing segments. 521
Figure 337. Photo. The northern trench, a receiving pit, after the end of the pilot drilling. The drill bit was removed in preparation to install the reamer. 522
Figure 338. Photo. The cutter-mixer reamer being tested before starting the reaming. 523
Figure 339. Photo. Good flow observed at the northern trench, the receiving pit. 523
Figure 340. Photo. The drill entrance pit after the end of the reaming. The reamer appears in the bottom left of the photo. Some of the drilling fluid appears in the bottom right of the photo. 524

Figure 341. Photo. A passing train. Reaming operations were paused before the arrival of the train and resumed after its departure. 524

Figure 342. Photo. The narrow trench the excavator dug to contain the steel casing while it is being pulled. 525

Figure 343. Photo. The pipe after it was pulled down into the narrow trench. 525

Figure 344. Photo. The pull head attached to the steel casing..... 526

Figure 345. Photo. The steel casing, attached to the pull head, swivel, and reamer before pipe pulling starts. 527

Figure 346. Photo. The assembly of the PVC pipe, before pushing it into the steel casing. (1)..... 527

Figure 347. Photo. The assembly of the PVC pipe, before pushing it into the steel casing. (2)..... 528

Figure 348. Photo. The steel casing after it was pulled into the bore. Photo of the steel casing end at the northern trench (the receiving pit). 528

Figure 349. Photo. The steel casing after it was pulled into the bore. Photo of the steel casing end at the southern trench (drill entrance pit)..... 529

Figure 350. Photo. The excavator removing the cuttings from the northern trench (receiving pit created for pulling the pipe) before dumping them on the side of the trench. 530

Figure 351. Photo. The excavator and bulldozer working on filling the trenches. 530

Figure 352. Graph. Comparison of road elevation before and after construction. Top: 30 ft (9.14 m) left of the alignment. Center: Along the alignment. Bottom: 30 ft (9.14 m) Right of the alignment.. 531

Figure 353. Photo. A very thick mix of the drilling fluid, which the contractor prepared to demonstrate the properties of the ProAction Fluids agents that he is using. 532

Figure 354. Photo. Interstate highway I-74. 534

Figure 355. Photo. Google Maps captures showing Farmer City project on state levels. 535

Figure 356. Photo. Google Maps captures showing Farmer City project on county levels..... 535

Figure 357. Photo. Google Maps captures showing Farmer City project on neighborhood levels. *Source: Google Maps* 536

Figure 358. Photo. Northern side of the site. 537

Figure 359. Photo. Southern side of the site. 537

Figure 360. Photo. Pavement which was repaired after the occurrence of fracking. 538

Figure 361. Graph. Diagrammatic stratigraphic column of glaciogenic sediments in east-central Illinois. 539

Figure 362. Graph. Locations of the soil borings relative to the interchange. 540

Figure 363. Chart. Soil boring logs at the north, median, and south of the interstate highway. 541
Figure 364. Graph. Original planned alignment of the water main. 542
Figure 365. Photo. Machinery used: rig. 544
Figure 366. Photo. Machinery used: fluid tank and mixer. 544
Figure 367. Photo. Machinery used: John Deere 60G excavator. 545
Figure 368. Photo. Machinery used: Case 580 series 2 backhoe loader. 545
Figure 369. Photo. Machinery used: pipe fusor. 546
Figure 370. Photo. Some of the equipment used: slanted drill bit. 546
Figure 371. Photo. Some of the equipment used: cutter-mixer reamer. 547
Figure 372. Photo. Some of the equipment used: pull head. 547
Figure 373. Photo. Some of the materials used: Mi SWACO drilling fluid agents POLY-PLUS. 548
Figure 374. Photo. Some of the materials used: PLATINUM ROD EASE. 548
Figure 375. Photo. The casing pulling. The pull head at the exit (southern) side, before pulling started. 549
Figure 376. Photo. The casing pulling. Photo of the pull head appearing at the entry (northern) side. 550
Figure 377. Photo. The casing. Photo at the entry (northern) side. 550
Figure 378. Photo. The casing at the exit (southern) side before the extra length of casing was cut. 551
Figure 379. Photo. The casing after its extra length was cut, and its elevation was lowered, forcing it down using the excavator then dumping soil on the top of it to lock it in place. 551
Figure 380. Photo. Drilling fluid appearing at the northern pressure relief holes. 552
Figure 381. Photo. Drilling fluid appearing at the southern pressure relief holes. 552
Figure 382. Photo. Drilling fluid appearing at the median pressure relief holes. 553
Figure 383. Photo. The slanted drill bit at the exit side after it was pushed through the casing. 553
Figure 384. Photo. The product pipe at the fusing machine being chained to the excavator arm before being pulled to the exit side of the boring. 554
Figure 385. Photo. The product pipe being dragged on the ground. The red arrow shows the location of the fusing machine. 554
Figure 386. Photo. The excavator orienting the pipe in the horizontal plane. 555
Figure 387. Photo. The second excavator orienting the pipe in the vertical place. 556
Figure 388. Photo. The pipe being pulled through the casing. 556

Figure 389. Photo. Road deformation due to hydro-fracturing during the HDD construction. (1) 557
Figure 390. Photo. Road deformation due to hydro-fracturing during the HDD construction. (2) 557
Figure 391. Photo. Road deformation due to hydro-fracturing during the HDD construction. (3) 558
Figure 392. Photo. Road I-55 (photo looking south). 560
Figure 393. Photo. Google Maps captures showing Litchfield project on state levels. 561
Figure 394. Photo. Google Maps captures showing Litchfield project on county levels. 561
Figure 395. Photo. Google Maps captures showing Litchfield project on neighborhood levels. *Source: Google Maps* 562
Figure 396. Photo. The entry (eastern) bore pit. 563
Figure 397. Graph. Cross section view of the initial design using the jack and bore construction method. 564
Figure 398. Graph. Cross section view of the new design using the horizontal directional drilling construction method. 565
Figure 399. Chart. Temperature and precipitation in Litchfield, Illinois. 566
Figure 400. Photo. Machinery used: rig. 567
Figure 401. Photo. Machinery used: fluid tank and mixer. 568
Figure 402. Photo. Machinery used: John Deere 310E backhoe loader. 568
Figure 403. Photo. Machinery used: Komatsu 200 LC excavators. 569
Figure 404. Photo. Some of the equipment used: walkover system. 569
Figure 405. Photo. Some of the equipment used: slanted drill bit. 570
Figure 406. Photo. Some of the materials used: HDPE casing. 570
Figure 407. Photo. Some of the materials used: RJPVC pipe. 571
Figure 408. Photo. Some of the materials used: DET CON 1 drilling fluid agent. 571
Figure 409. Photo. Pilot drilling. (1) 572
Figure 410. Photo. Pilot drilling. (2) 573
Figure 411. Photo. Police assisting with the traffic control. 573
Figure 412. Photo. The water line feeding into the rig, connected to the hydrant. 574
Figure 413. Photo. The 16 in. (40.6 cm) fly cutter reamers. 574
Figure 414. Photo. The 30 in. (76.2 cm) fly cutter reamers. 575
Figure 415. Photo. The HDPE casing fusing. 575

Figure 416. Photo. The HDPE casing welding to the pull head. 576
Figure 417. Photo. The HDPE casing being dragged to the edge of the exit pit. 576
Figure 418. Photo. The HDPE casing being pulled into the hole at the exit pit. (1) 577
Figure 419. Photo. The HDPE casing being pulled into the hole at the exit pit. (2) 577
Figure 420. Equation. An equation to calculate the fluid pumping (or drilling) rate. 578
Figure 421. Photo. Road I-39 (looking south). 580
Figure 422. Photo. Google Maps captures showing Rochelle project on state levels. 581
Figure 423. Photo. Google Maps captures showing Rochelle project on county levels. 581
Figure 424. Photo. Google Maps captures showing Rochelle project on neighborhood levels. 582
Figure 425. Photo. Planned alignment of the pipe's installation. Boreholes locations are shown in blue. 583
Figure 426. Chart. Boring log of the preliminary bore hole B-1. 584
Figure 427. Chart. Boring log of the preliminary bore hole B-2. 585
Figure 428. Chart. Boring log of the bore hole B-4 586
Figure 429. Chart. Boring log of the bore hole B-5 587
Figure 430. Graph. Initial design of the crossing under I-39, using jack and bore. 589
Figure 431. Chart. Temperature and precipitation in Rochelle, Illinois. 591
Figure 432. Photo. Pilot boring. The drilling rig in action. 592
Figure 433. Photo. Pilot boring. The rock drilling bit. 593
Figure 434. Photo. Pilot boring. Pilot boring in action as seen from the entry pit. 593
Figure 435. Photo. The walkover system. Receiver 594
Figure 436. Photo. The walkover system. Transmitter installed behind drill bit. 594
Figure 437. Photo. Reaming. The 18 in. tricone reamer 595
Figure 438. Photo. Reaming in action as seen from the entry pit. 596
Figure 439. Photo. Swabbing in action as seen from the entry pit. 597
Figure 440. Photo. Over-reaming. 24 in. (61 cm) reamer with 16 in. (40.6 cm) centralizer. 598
Figure 441. Photo. Over-reaming in action as seen from the entry pit. 598
Figure 442. Photo. Over-reaming. Interior of the 24 in. (61 cm) bore (behind the reamer). 599
Figure 443. Photo. Swabbing with the 24 in. (61 cm) reamer. 599
Figure 444. Photo. The drilling fluid agents that were used: Drill-Terge. 600

Figure 445. Photo. The drilling fluid agents that were used: Insta-Vis Plus. 601
Figure 446. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The reamer before attaching the casing to it via the swivel. 602
Figure 447. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The casing being pulled into the hole. 602
Figure 448. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The reamer entering the exit pit toward the entry pit. 603
Figure 449. Photo. The trench boxes being installed at the entry pit. 604
Figure 450. Photo. Pilot drilling for the second line. 605
Figure 451. Photo. The 24 in. (61cm) rock reamer. 606
Figure 452. Photo. The 30 in. (76.2 cm) reamer with the two centralizers. (1). 607
Figure 453. Photo. The 30 in. (76.2 cm) reamer with the two centralizers. (2). 608
Figure 454. Photo. The first of the two sinkholes that appeared on the west side of I-39. 609
Figure 455. Photo. The second of the two sinkholes that appeared on the west side of I-39. 609
Figure 456. Photo. The inadvertent returns showing in the area of the sinkhole, which was previously back-filled. 611
Figure 457. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (1) 612
Figure 458. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (2) 612
Figure 459. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (3) 613
Figure 460. Photo. Photo of the inadvertent return. 613
Figure 461. Photo. The boring operation performed after the cases were pulled. 614
Figure 462. Photo. Void on the top of the installed casing. 615
Figure 463. Photo. One of the two PVC pipes installed on the top of the casing with water flowing out of it. 616
Figure 464. Photo. The two pipes with riser pipes attached to them to enable grouting. 616
Figure 465. Chart. Boring log of the bore hole B-1. 617
Figure 466. Chart. Boring log of the bore hole B-2. 618
Figure 467. Chart. Boring log of the bore hole B-3. 619

LIST OF TABLES

Table 10. List of Key People Met during This Project, with Their Affiliations and Contact Information 307

Table 11. List of Key People Met during This Project, with Their Affiliations and Contact Information 333

Table 12. Expected Timeline of the Elsah Project 423

G.1 QUINCY CASE HISTORY

G.1.1 Project's Goal

In this project, a 12 in. (30.5 cm) PVC pipe is to be installed under Harrison Street at the east of the Cadbury Ridge Street interaction (Figure 33). This installation was under a two-lane road with curb and gutter by HDD. The total length of the pipe is 60 ft (18.3 m).



Figure 33. Photo. The project site.

G.1.2 Location and Surroundings

The project is located in Quincy, Illinois (see Figure 34, Figure 35, and Figure 36), and its GPS coordinates are: 39° 54' 42.63" N 91° 20' 59.83" W.

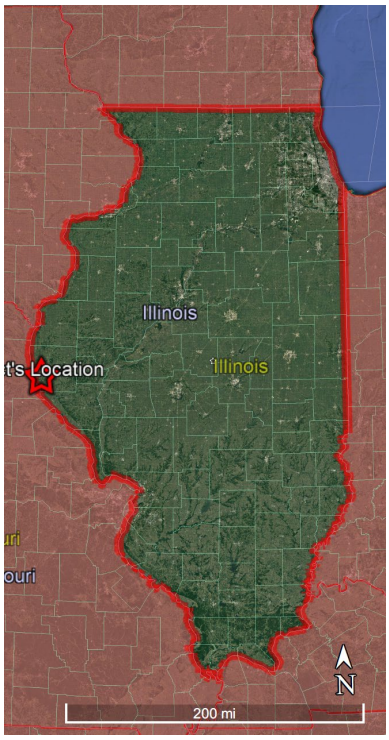


Figure 34. Photo. Google Maps captures showing Quincy project location on state levels.

Source: Google Maps.



Figure 35. Photo. Google Maps captures showing Quincy project location on county levels.

Source: Google Maps

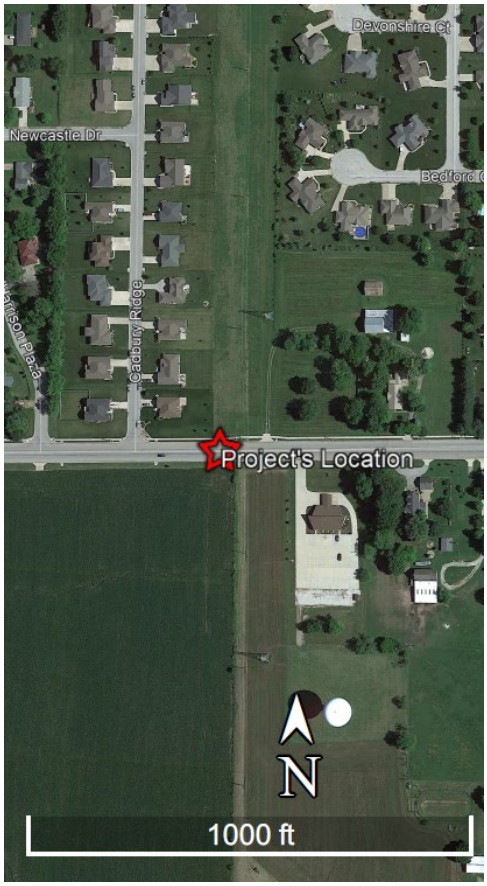


Figure 36. Photo. Google Maps captures showing project's location on neighborhood levels.

Source: Google Maps

G.1.3 Site Conditions

No borings were performed prior to the commencement of the project. With two pits excavated at the entry and exit points, visual inspection and manual field tests were possible. The soil seemed to be composed mainly of stiff brown silty clay with trace sand.

G.1.4 Designs

Not available.

G.1.5 Features and Foreseen Challenges

Not available.

G.1.6 Entities and People Engaged

Table 10 contains the list of key people met during this project, with their affiliations and contact information.

Table 10. List of Key People Met during This Project, with Their Affiliations and Contact Information

Name	Job	Affiliation	Phone Number	Email
Dave Schuster	Contractor and Driller	Schuster Pump	217-242-7916	JDSCHU@ADAMS.NET
Orlando Salazar	Drilling Fluid Expert	Baroid Industrial Drilling Products	630-277-2993	Orlando.Salazar@halliburton.com
Heather Shoup	Central Office Geotechnical Engineer	IDOT	217-785-9972	Heather.Shoup@illinois.gov
Joseph Angeli	Permit Technician	IDOT	217-782-7744	Joseph.Angeli@illinois.gov
Joseph Olson	Geotechnical Engineer	IDOT	309-671-3675	Joseph.Olson@illinois.gov

G.1.7 Executions

G.1.7.1 Settings

Preparations for installing the pipe via HDD started on May 23, 2018. On the same day, the pilot drilling was completed. The reaming and the pipe installation were performed on the following day, May 24, 2018.

G.1.7.2 Machinery, Equipment, and Materials

Machinery used in this project included the following:

- Ditch Witch FM5 mixer (see Figure 37).
- Komatsu PC 220 LC excavator (see Figure 38).
- Ditch Witch JT1220 rig (see Figure 39).
- Vac-Tron cuttings vacuum machine (see Figure 40).

Materials used in this project included the following:

- Clay Drill polymer-mix was added to water (to which some soda ash is added to fix acidity level) with a mixing ratio: 97-98% water, 3-2% polymer (see Figure 41, Figure 42, and Figure 43).
- 12 in. (30.48-cm) PVC pipes (see Figure 44).

Equipment used in this project included the following:

- 4 in. (10.2 cm) diameter slanted drill bit (see Figure 50, Figure 45, and Figure 46).
- 18 in. (45.7 cm) diameter beavertail reamer (see Figure 47).



Figure 37. Photo. Machinery used in the project. Ditch Witch FM5 mix.



Figure 38. Photo. Machinery used in the project. Komatsu PC 220 LC excavator.



Figure 39. Photo. Machinery used in the project. Ditch Witch JT1220 rig.



Figure 40. Photo. Machinery used in the project. Vac-Tron cuttings vacuum machine.



Figure 41. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Outside view.



Figure 42. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Inside view.



Figure 43. Photo. Clay-Drill polymer-mix used in this project for drilling fluid. Close view.



Figure 44. Photo. PVC pipes.



Figure 45. Photo. Cutting bit used for pilot boring. Close view.



Figure 46. Photo. Cutting bit used for pilot boring. General view.



Figure 47. Photo. Ditchwitch back-reamer used in this project.

G.1.7.3 Execution Metrics

Entry and exit pits were dug before the commencement of drilling. They were located immediately behind the curb and gutter on both sides of the road. The pits' approximate dimensions were 15 ft (4.57 m) in length, 3 ft (0.91 m) in width, and 8 ft (2.44 m) in depth (Figure 48 and Figure 49). Pilot boring was completed on May 23, 2018. The reaming started at 9:00 a.m. on May 24, 2018, and ended around 10 a.m. The pipe installation followed and was completed around 10:45 a.m. (Figure 50 and Figure 51). The pipe was installed by pushing it with the excavator from the entrance pit side at an approximate depth of 6 ft (1.83 m). Cuttings were flowing out of the entry and exit trenches and were then removed using the Vac-Tron vacuum machine (Figure 52).



Figure 48. Photo. Trenches on entry sides of the project.



Figure 49. Photo. Trenches on exit sides of the project.



Figure 50. Photo. Cutting bit used for pilot boring. Distant view.



Figure 51. Photo. Pipe after it had been pulled in place.



Figure 52. Photo. Using the Vac-Tron vacuum machine to remove the cuttings.

G.1.8 Performance Metrics

Ground cracking and heave were observed next to the rig during the back-reaming. Some drilling fluid also flowed out at the entry point as presented in Figure 53 and Figure 54.



Figure 53. Photo. Observed ground heave.



Figure 54. Photo. Observed fluid flowing out at the point of entry during reaming.

G.1.9 Important Remarks

G.1.9.1 Contractor Experience

The contractor and the drilling fluid expert shared with us some of their experiences:

- Polymer mixes are used to lubricate drilling and to mix, float, and disperse cuttings.
- Bentonite rather than polymer mix is typically used for longer installations. It is favorable because of its dispersion properties and because it prevents cuttings from depositing below the pipeline.
- Bentonite is also preferred for coarse soils.
- Using water alone without a polymer mix or bentonite may destabilize the hole. Five times more water (according to Orlando Salazar, Baroid Industrial Drilling Products) might be needed.
- Dry borings may be done for short-range applications.
- Gauges are installed on the rig to monitor how much fluid is being pumped.
- Cutting bits are also used to direct the drilling.
- Max bend achieved per rod is 8 to 10 degrees (according to Dave Schuster, Schuster Pump).
- Rule of thumb: drill a hole 1.5 times bigger in diameter than the pipe to be installed.
- It is always safer for the equipment (not to be stuck or damaged) to use drilling fluids. Its cost is only a tiny fraction of the cost of damaged or stuck equipment.
- Samples of cuttings are taken for Atterberg and hydrometer.

They also pointed out some websites that they find useful:

- https://www.ditchwitch.com/.
- https://www.vermeer.com/NA/en/N/equipment/directional_drills_pipeline.
- http://www.intpipe.com/yelomine_pipe.aspx.

G.1.10 Lessons Learned

The Quincy project taught us the following:

- A 60 ft (18.3 m) long pipe was installed at a depth of 6 ft (1.83 m) without impacting the overlying pavement. The installation was fast and did not significantly disrupt the traffic on this minor road.

- Although the HDD bore was curved, the pipe was installed only in the straight section at the full depth of this curve.

G.2 HENNEPIN CASE HISTORY

G.2.1 Project's Goal

In this project, a 24 in. (61 cm) HDPE pipe culvert is to be installed under state route IL-26 (Figure 55). The installation is next to an existing 24 in. (61 cm) corrugated steel pipe. The corrugated steel pipe was sealed because it is suspected to be broken and hence causing settlement of the road next to the downstream and cracking of the pavement by allowing soil to erode through it.



Figure 55. Photo. Road IL-26. The traffic cones mark the area above the planned alignment.

G.2.2 Location and Surroundings

The project is located two miles south of Hennepin, Illinois (see Figure 56, Figure 57 and Figure 58), and its GPS coordinates are: 41 13' 5.3" N 89 19' 7.0" W.



Figure 56. Photo. Google Maps capture showing Hennepin project location on state levels.

Source: Google Maps

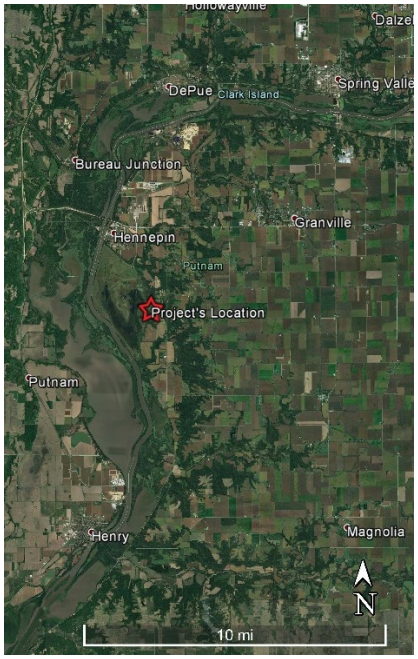


Figure 57. Photo. Google Maps capture showing Hennepin project on county levels.

Source: Google Maps

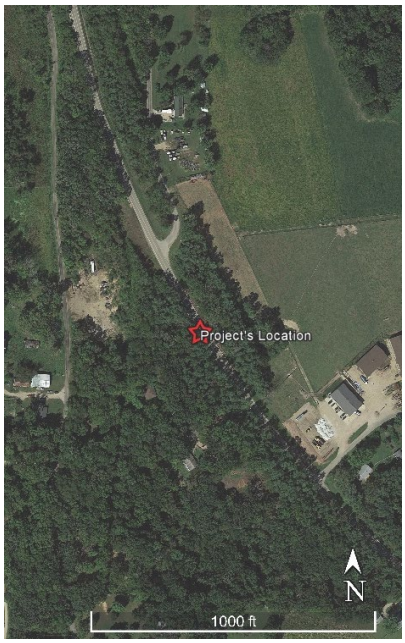


Figure 58. Photo. Google Maps capture showing Hennepin project location on neighborhood levels.

Source: Google Maps

The proposed alignment is more than 100 ft (30.5 m) away horizontally from any underground utilities. The nearest structures (small homes) are more than 300 ft (91.4 m) away from the proposed alignment. Hence, the only structure that can be impacted by the construction is road IL-26. The section of the road overlying the alignment is cracked (Figure 59). In the past year, the major cracks were sealed. At the same time, the causes of the road settlement were investigated, and resolution alternatives were proposed. A 5 in. (12.7 cm) section of the road next to the upstream end of the pipe was already lost, as presented in Figure 60.



Figure 59. Photo. Road section just above the alignment showing the sealed cracks. The photo shows the excavator working on the upstream side.



Figure 60. Photo. Upstream side road shoulder, showing the damage due to soil loss. The location of the geotechnical investigation boring is also marked in the photo.

G.2.3 Site Conditions

G.2.3.1 Soil Conditions

One 60 ft (18.3 m) deep boring was performed on November 9, 2017, by McCleary Engineering using a hollow stem auger. Standard penetration test N-values were measured using a Central Mine Equipment (CME) automatic hammer. The boring was made to find out the local stratigraphy and to check if any cavities existed beneath the road that was causing the loss of ground. The boring shows that the site is composed of thick sand layers interbedded with sandy clay layers (typically 2 ft [0.6 m] thick). Figure 61 presents the stratigraphy of the site, the SPT blow count, the unconfined compressive strength (measured via UCS tests or penetrometer), and the water content of the layers. The water surface was not encountered and hence is deeper than 60 ft (18 m), the depth of the boring.

G.2.3.2 Topography

The ground approaching the upstream end of the pipe is almost flat (Figure 62) and is around 20 ft (6.1 m) below the road level. The downstream roadway embankment (Figure 63) is much steeper and more irregular than the upstream embankment. Signs of erosion and settlement are clear in the downstream embankment (see Figure 64, Figure 65, and Figure 66). The downstream level is around 40 ft (12.2 m) below the road level.

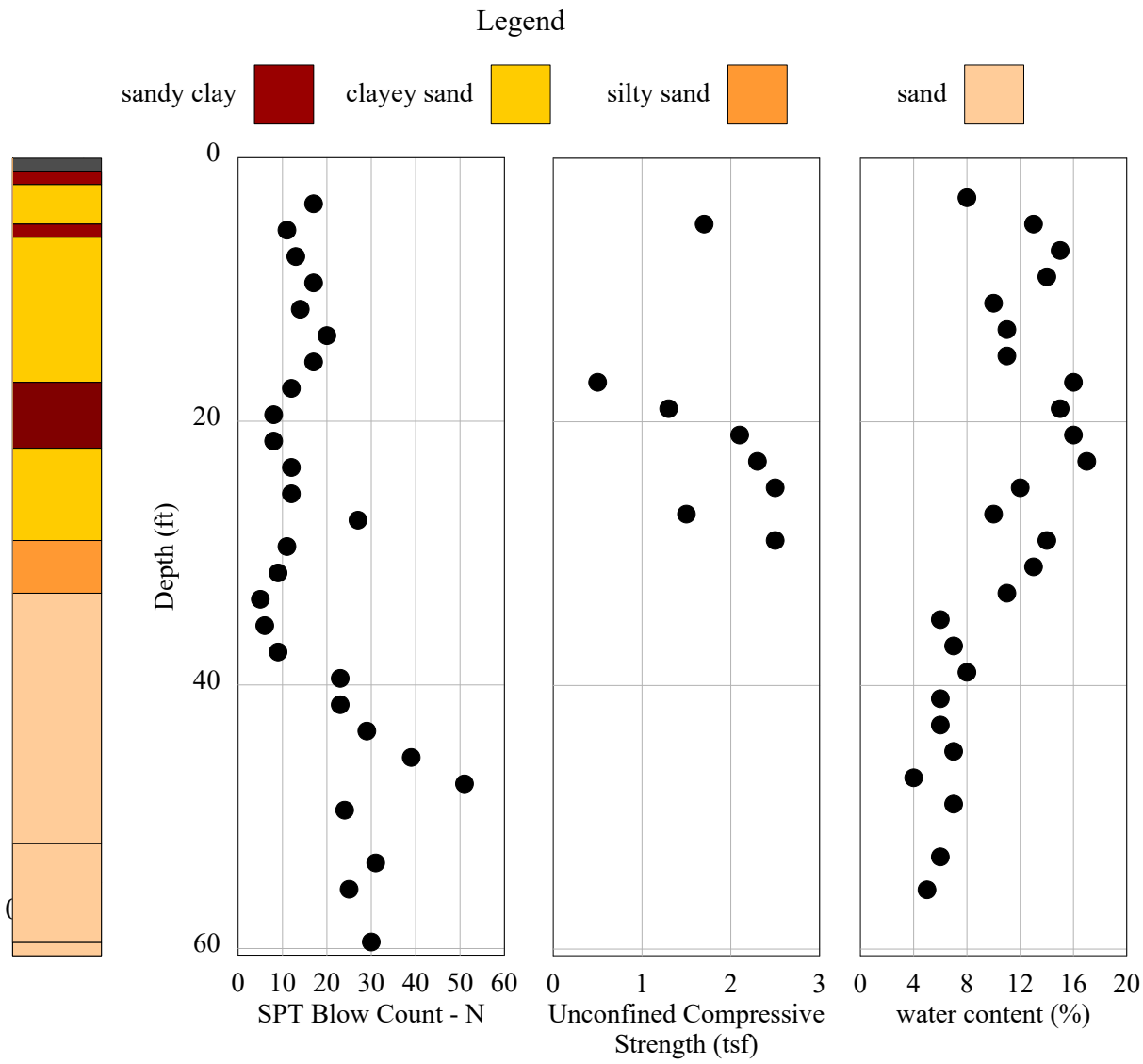


Figure 61. Graph. Stratigraphy and soil properties obtained from the boring performed.



Figure 62. Photo. Upstream side.



Figure 63. Photo. Downstream side.



Figure 64. Photo. Existing corrugated steel pipe from the upstream side.



Figure 65. Photo. Existing pipe from the downstream side.
The photo includes the irregular, steep, and marginally stable slope due to the erosion.



Figure 66. Photo. Existing pipe from the downstream side showing its steep slope.

G.2.3.3 Geology (modified from Frankie et al. [2002] and Piskin and Bergstrom [1975])

Geologic History of the Illinois River:

Hennepin is located along the eastern bank of the Illinois River in an area known as the Big Bend of the Illinois River. The development of the present Illinois River valley began during the long period of erosion following the Paleozoic Era. A system of rivers and streams developed on the pre-glacial land surface. Over time, ancient river valleys became deeply entrenched into the bedrock. One of these is the Princeton Bedrock Valley near Hennepin, presented in the cross-section in Figure 67. The entrenchment of this valley started prior to glaciation and was well established by the end of the early pre-Illinois glacial episode.

The Ancient Mississippi River flowed along the west side of the Driftless Area southward as far as Fulton in Whiteside County, then it followed the Princeton Bedrock Valley in a southeastward course to the present Big Bend of the Illinois River valley in Bureau County near Hennepin. The Ancient Mississippi River then followed the present course of the Illinois River valley southward to its confluence with the Ancient Iowa River at Grafton in Calhoun County. Illinois Episode glaciers overrode the Princeton Bedrock Valley at least three times (Willman and Frye 1970), diverting the Ancient Mississippi River to the west each time. During the Sangamon interglacial episode, the interval between the Illinois and Wisconsin Episodes of glaciation, the Ancient Mississippi River again flowed through central Illinois. Large volumes of meltwater flowed through this valley during the early stages of glaciation and deposited the thick Sankoty Sand (Figure 67). Later glaciation covered the bedrock and the sand-filled valleys with drift (Figure 67).

During the Wisconsin Episode glacial advance, the Ancient Mississippi River was again diverted to the west where it remained. This event has been dated about 21,000 years ago (Glass et al. 1964). The Wisconsin glacier (Lake Michigan Lobe) dammed the Ancient Mississippi River to produce a series of lakes in the western part of Illinois near Fulton in Whiteside County. The lakes overflowed from one

to another, and a narrow ridge of sandstone (Wyoming Hill) was eventually breached west of Rock Island, and the Mississippi River gorge was cut between Rock Island and Muscatine, Iowa. The Ancient Mississippi River was permanently diverted westward to occupy the valley of the Ancient Iowa River along the west side of what is now Illinois, a course it still follows. The abandoned Princeton Bedrock Valley was subsequently partially filled with sediments. The Princeton Lowland marks the position of this buried valley.

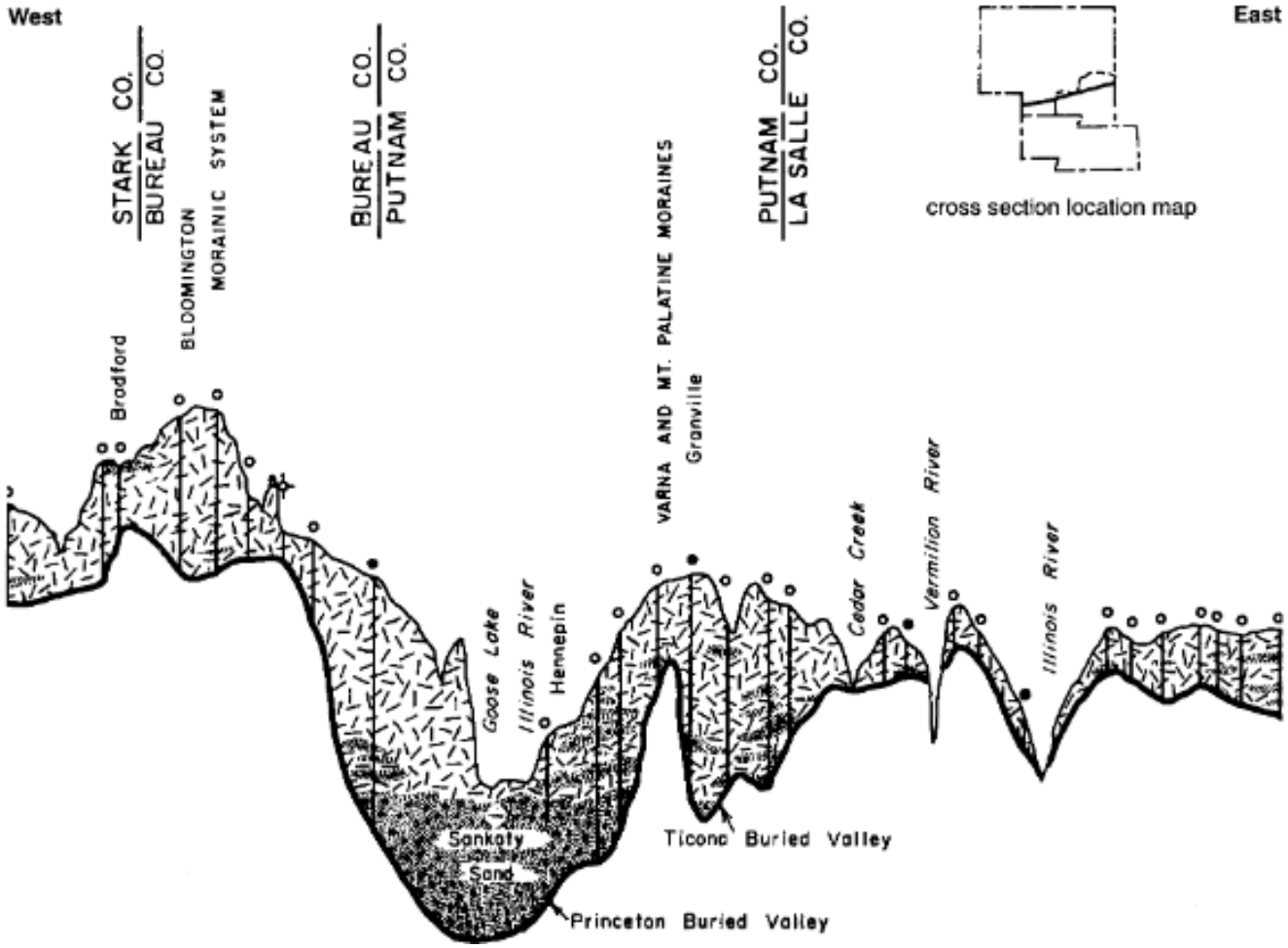


Figure 67. Graph. Stratigraphic cross-section showing the deposits within the Princeton Bedrock Valley.

Source: Modified from Piskin and Bergstrom (1975) and Frankie et al. (2002)

Glacial History of Illinois:

Glaciers of the Pleistocene have profoundly affected the present topography of Hennepin. The landscape we see today is a direct result of sediments deposited during the Pleistocene glaciations and modification of these sediments by postglacial erosion. The erosion that took place long before the glaciers advanced across the state left a network of deep valleys carved into the bedrock surface. The present topography of Illinois is significantly different from the topography of the preglacial bedrock surface. The topography of the bedrock surface throughout much of Illinois is largely hidden from view by glacial deposits except along the major streams and in the driftless areas of northwestern and southern Illinois. In many areas, the glacial drift is thick enough to completely mask the underlying bedrock surface.

In the past 1.6 million to 2 million years, during the Pleistocene Epoch of the Quaternary Period, much of northern North America was repeatedly covered by huge glaciers. These continent-size masses of ice formed in eastern and central Canada as a result of climate cooling. Their advances into the central lowland of the United States altered the landscape across much of the Midwest.

During an early part of the Pleistocene Epoch, glaciers advanced out of centers of ice accumulation both east and west of the Hudson Bay area in Canada. Glaciers flowing out of these centers into Illinois carried along rock debris incorporated into the ice as they advanced; the material was dropped out as the ice melted. The number and timing of these early episodes of glaciation are uncertain at present and are therefore unnamed, but, because they precede the first named episode of glaciation, the Illinois Episode, they are simply called pre-Illinois glacial episodes (Hansel and Johnson 1996). The pre-Illinois glacial episodes ended about 425,000 years ago. A long interglacial episode, called the Yarmouth, followed the last of the pre-Illinois glacial advances. The Yarmouth interglacial episode is estimated to have lasted approximately 125,000 years, and deep soil formation took place during that long interval (Yarmouth Geosol). On the parts of the landscape that were generally poorly drained, fine silts and clays slowly accumulated in shallow, wet depressions and formed what are called accretion gleys, which are characterized by dark gray to black, massive, dense gleyed clays.

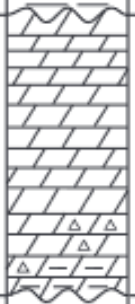
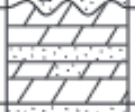
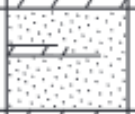
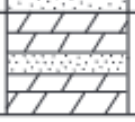
SYSTEM or SERIES	HYDROGEOLOGIC UNITS	GRAPHIC LOG	ROCK TYPE	WATER-YIELDING CHARACTERISTICS
PLEIS-TOCENE	Drift (0–300 feet)		Unconsolidated glacial deposits, loess and alluvium (drift).	Water yields variable, largest from thick basal sand and gravel deposits (Sankoty Sand) in bedrock valleys.
PENNSYLVANIAN	(280–475 feet)		Mainly shale with thin sandstone, limestone, and coal beds.	Generally unfavorable as an aquifer. Locally, domestic and farm supplies obtained from thin limestone and sandstone beds. Casing usually required.
SILURIAN	Niagaran-Alexandrian (410–505 feet)		Dolomite; argillaceous near base, lower part cherty.	Generally yields poor quality water.
ORDOVICIAN	Maquoketa (155–240 feet)		Green to blue shale with limestone and dolomite beds.	Not water yielding at most places. Casing required.
	Galena-Platteville (320–380 feet)		Dolomite, with shaly zone near the middle; some limestone in the lower part.	Not important as an aquifer, Creviced dolomite probably yields some water. Water quality good.
	Glenwood-St. Peter (115–135 feet)		Sandstone, white, clean.	Dependable source of groundwater. Water quality good.
	Shakopee (130–150 feet)		Dolomite, with some shale and sandstone.	Not important as aquifer.
	New Richmond (165 feet ±)		Sandstone, with some dolomite.	May yield some water.
	Oneota (215 feet ±)		Dolomite, with some sandstone beds.	Not important as aquifer.

Figure 68. Table. Generalized stratigraphic column of upper rock formations in the Hennepin project location.

Source: Modified from McComas (1968) and Frankie et al. (2002)

Approximately 300,000 years ago, the Illinois Episode of glaciation began. It lasted for about 175,000 years, and, during this interval, the ice advanced three times out of the northeastern center of accumulation. During the Illinois Episode, North American continental glaciers reached their southernmost position, in the northern part of Johnson County. During the first of these advances, the ice of this episode reached westward across Illinois and into Iowa.

Another long interglacial episode, called the Sangamon, followed the Illinois Episode and lasted about 50,000 years. Although shorter than the Yarmouth interglacial episode, this interval's length was sufficient for another major soil, the Sangamon Geosol, to develop. The Sangamon Geosol exhibits both well-drained and poorly drained soil profiles; although accretion gleys are not as pronounced as they are in the Yarmouth Soil, their occurrence is common across the Sangamon landscape, and they are easily identified by the same characteristics as the Yarmouth accretion gleys.

About 75,000 years ago, the Wisconsin Episode of glaciation began. Ice from the early and middle parts of this episode did not reach Illinois. Although late Wisconsin ice did advance across northeastern Illinois beginning about 25,000 years ago, it did not reach southern or western Illinois. The late Wisconsin glaciation in the project location is represented here by moraines, outwash plains, valley trains, and the windblown silts (loess) that blanket the landscape and compose the parent materials for modern soils. The maximum thickness of the later Wisconsin Episode glaciers was about 2,000 feet (610 m) in the Lake Michigan Basin, but only about 700 feet (213 m) over most of the Illinois land surface (Clark et al. 1988). The last of these glaciers melted from northeastern Illinois about 13,500 years before the present. Wisconsin Episode moraines formed in Illinois from approximately 25,000 to 13,500 years ago. The Illinois Episode glaciers may not have built morainic ridges of the size and magnitude of the later moraines of the Wisconsin Episode glaciers, and the Illinois Episode moraines were exposed to weathering and erosion for approximately 280,000 years longer than their younger Wisconsin Episode counterparts. For these reasons, Illinois Episode glacial features generally are not as conspicuous as the younger Wisconsin Episode features. In general, glacial deposits consist primarily of (1) till: pebbly clay, silt, and sand, deposited directly from melting glaciers; (2) outwash: mostly sand and gravel, deposited by the rapidly flowing meltwater rivers; (3) lacustrine deposits: silt and clay that settled out in quiet-water lakes and ponds; and (4) loess: windblown sand and silt. As glaciers advanced over the area during the major ice advances, outwash deposits of silt, sand, and gravel were dumped along the Ancient Mississippi River valley and the Illinois River valley. When these deposits dried out during the winters, strong prevailing winds from the west (the westerlies) winnowed out the finer materials, such as fine sand and silt, and carried them eastward across the unglaciated terrain.

Lacustrine deposits of the Equality Formation are found in the lower portion of the Big Bureau Creek valley. These quiet slack-water deposits formed a flat topography, which represents long periods of flooding during the melting of the last glaciation. Most of these sediments were deposited during the melting of the Wisconsin glacier from about 20,000 to 10,000 years ago. Vast amounts of meltwater poured from the ice front and caused extensive flooding in the Mississippi, Illinois, Wabash, and Ohio Valleys. Scattered along the Illinois River floodplain are several areas of sand dunes. These areas can usually be recognized by their characteristic topographic form—the random arrangement of small hills or mounds, elongated ridges, and enclosed depressions—and by close visual inspection, which

reveals that the dunes are almost made entirely of sand. Dunes are formed by the piling up of sand by the wind and can develop in any region with a readily available source of sand and occasional strong winds. Dunes are common in this region on the valley flats, old terraces, and along the margins of the bluffs bordering the valleys.

The loess that mantles the bedrock and glacial drift throughout the area was laid down by wind during the Wisconsin Episode (approximately 25,000 to 13,500 years ago). This yellowish-brown silt occurs on the uplands throughout the field trip area. The loess is generally between 10 to 15 ft (3 to 4.6 m) thick, but erosion has reduced loess thickness in scattered areas. In general, the thickness of the loess decreases to the east. The loess, which covers most of Illinois, is up to 25 ft (7.62 m) thick along the Illinois River valley and is more than 50 ft (15.24 m) thick, in some localities, along the east edge of the Mississippi River valley.

Figure 68 presents the generalized stratigraphic column of the upper rock formations in the Hennepin area. The most relevant formation is the Pleistocene formation occupying approximately the first 300 ft (91.4 m) into the ground. It consists primarily of unconsolidated glacial deposits, loess, and alluvium.

G.2.4 Design

To solve the erosion problem causing road cracking and settlements and risking the stability of the road (Figure 69), the initial proposal (Figure 70) included retaining the upstream section, then replacing the local soils on the downstream side with a granular embankment, and removing the old pipe section under the downstream. A new culvert pipe was to replace the removed section, while the unremoved section was to have a liner installed.

A value engineering proposal was made by the contractor, suggesting instead to seal the old pipe with controlled low strength material (CLSM), install a new full pipe using horizontal directional drilling (HDD), and fix the downstream slope by rebuilding it with porous granular embankment and rip-rap. The proposal showed that this would save $191,000, dropping the total cost from $549,628 of the original contract to $358,628. The value engineering proposal was approved. The final design cross-section is presented in Figure 70.

The design documents included cross-sections, calculations showing the structural adequacy of the HDPE pipe to be installed, and pipe culvert extension collar design. No estimation of the construction-induced ground response, like settlements or stresses, was made.

The HDPE pipe structural adequacy was said to be checked for accordance with ASTM F1962: “Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings” and The Plastic Pipe Institute's "Handbook of Polyethylene (PE) Pipe," which is in accordance with the ASTM standard. Design checks included: soil pressure (while considering arching effects), critical unconstrained buckling based on no side support and pipe ovaling, compressive wall stress due to installation depth, frictional pipe drag installation force versus safe pull force, and additional pipe wall compressive stress check for deep depth installation. Live

loads from traffic were considered negligible per AASHTO because fill height (26 ft [8 m]) is substantially greater than culvert diameter (2 ft [0.6 m]).

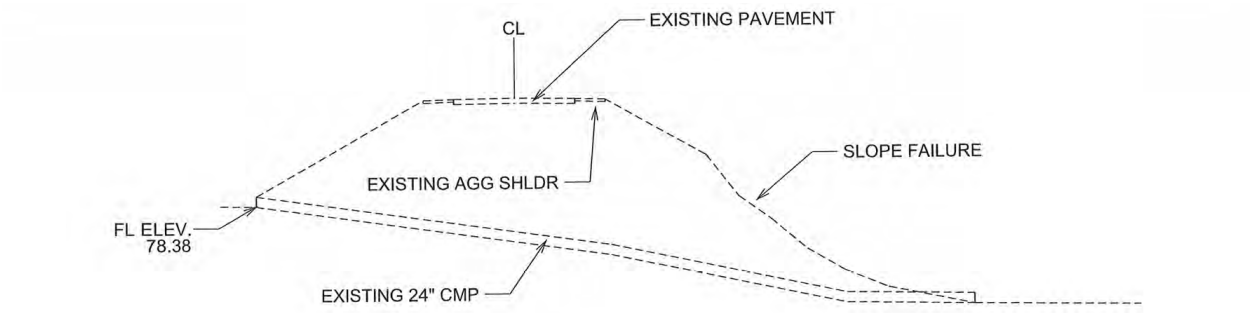


Figure 69. Graph. Cross-section of the road prior to construction.
The schematic presents the slope on the downstream side undergoing erosion.

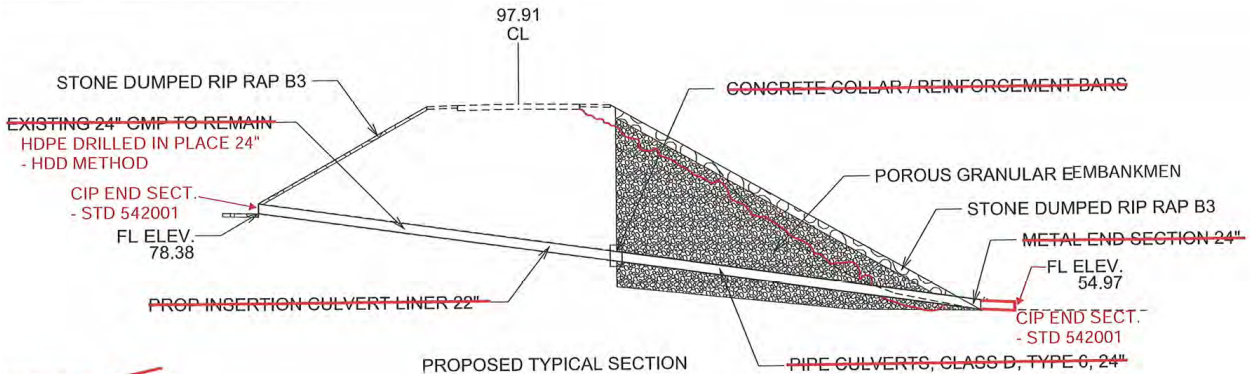


Figure 70. Graph. Cross-section of the road with the planned improvements. The schematic presents the elements of the first alternative (in black) and the modifications leading to the second alternative (in red).

G.2.5 Features and Foreseen Challenges

The following list contains some of the interesting features and challenges of this project:

- The alignment of the new pipe is close to the old pipe's alignment. In fact, this proximity encouraged shifting the location of the alignment for a few feet. This was to reduce the chance of hitting the existing pipe while drilling.
- The slope of the planned pipe (23 ft [7 m] vertically downward in 160 ft [48.7 m] horizontally), which is around 14%, was considered steep by the drillers.
- The terrain of the downstream embankment is steep and irregular, which will make access to equipment and materials harder.
- The soil is mostly sandy. This brings in threats of raveling and the consecutive ground loss.

- The space on the upstream and downstream is limited especially given the big length of the pipe (160 ft [48.7 m]).

G.2.6 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- Stark Excavating (http://starkcompanies.com/), which is the main contractor.
- Midwest Mole (https://www.midwestmole.com/), which is the subcontractor responsible for horizontal directional drilling.

Table 11 contains the list of key people met during this project, with their affiliations and contact information.

Table 11. List of Key People Met during This Project, with Their Affiliations and Contact Information

Name	Job	Affiliation	Phone Number	Email
Chad Dick	Driller	Midwest Mole	7659776182	-
Jason Schupp	Contractor	Stark Excavating	3092757032	jschupp@starkcompanies.com
Daniel Spellious	Inspector	IDOT	3095738071	daniel.spellious@illinios.gov
Dacid Kelly	Foreman	Midwest Mole	3175573574	dkelly@midwestmole.com
Eric Whiteside	Subcontractor	Midwest Mole	3179452798	ewhiteside@midwestmole.com

G.2.7 Execution

G.2.7.1 Settings

Preparations for installing the HDPE pipe via HDD started on November 19, 2018, at 8:00 a.m., and, by November 21, 2018, at 12:00 p.m., the installation was done. Temperature in Hennepin varied between 20 and 38° F (-6.7 to 3.3° C) over those three days (Figure 71). No precipitation was recorded. On the morning of the first day, around half an inch of snow was covering the soil.

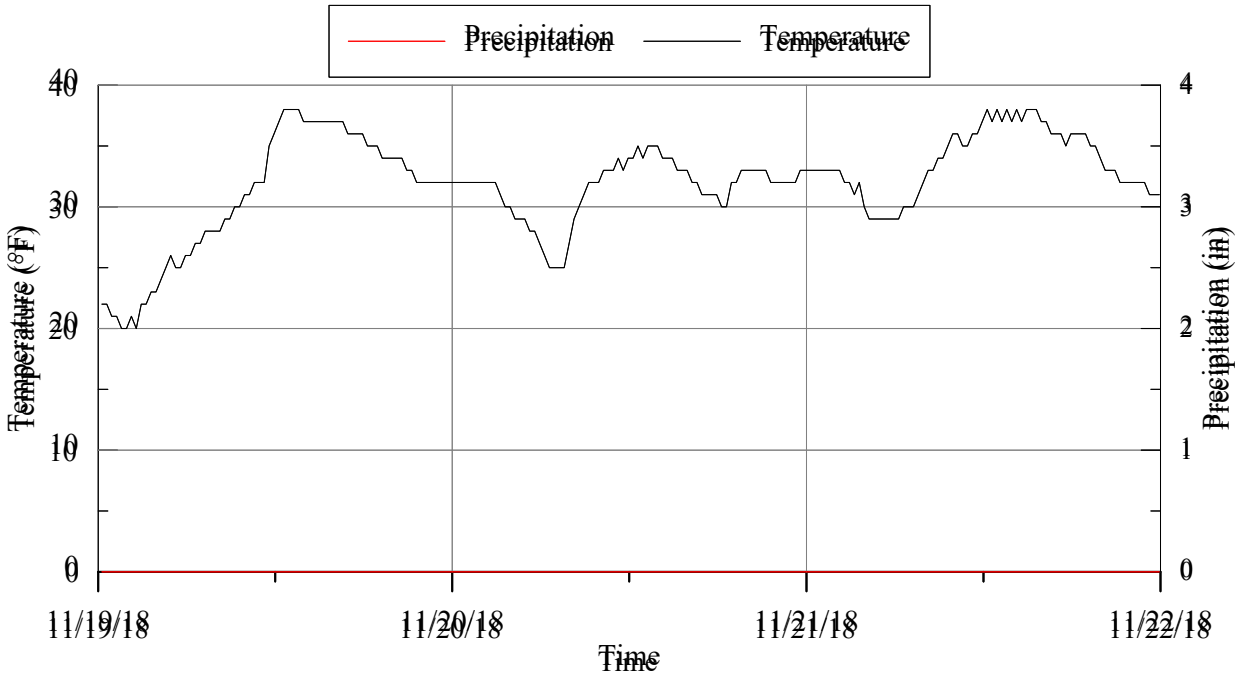


Figure 71. Chart. Temperature and precipitation in Hennepin, Illinois.

Source: ***https://www.wunderground.com/***

G.2.7.2 Machinery, Equipment and Materials

Machinery used in this project included the following (photos presented from Figure 72 to Figure 76):

- Excavator: John Deer 270 DLC.
- Rig: Vermeer D80x100. The rig uses 15 ft (4.6 m) long 3.5 in. (8.9 cm) diameter drilling rods and is characterized by a torque capacity of 10 kip-ft (13.6 kN-m), push/pull capacity of 80 kip (356 kN), and a max pumping capacity of 200 gpm (757 L/min).
- Fluid Tank and Mixer: Vermeer MX240, which is characterized by a capacity of 1000 gal (3785 L).
- Pipe Fusor: McELROY Tracstar 900 series 2.
- Vacuum Excavator: Badger's big truck

Equipment used in this project included the following (photos presented from Figure 77 to Figure 82):

- Drill bit: armor lance bit of 6.5 in. (16.5 cm) diameter.
- Reamers: 2 fluted reamers of 24 in. (61 cm) and 30 in. (76.2 cm) diameters.
- Pipe pull head.

- Swivel.
- 2 Pipe stands.
- Walkover tracking system.



Figure 72. Photo. Machinery used: excavator.



Figure 73. Photo. Machinery used: rig.



Figure 74. Photo. Machinery used: fluid tank and mixer.



Figure 75. Photo. Machinery used: pipe fusor.



Figure 76. Photo. Machinery used: vacuum excavator.



Figure 77. Photo. Equipment used: Armor Lance bit of 6.5” (16.5 cm) diameter.



Figure 78. Photo. Equipment used: tracking sensor housed in drill pipe.



Figure 79. Photo. Equipment used: pipe stand.



Figure 80. Photo. Equipment used: fluted reamer.



Figure 81. Photo. Equipment used: pull head.



Figure 82. Photo. Equipment used: swivel.

Materials used in this project included the following (photos presented from Figure 83 to Figure 89):

- Pipe: Four HDPE pipes of 24 in. (61 m) diameter, 2.18 in. (5.54 cm) thickness and 40 ft (12.2 m) unit length.
- Fluid Mix 1: ProDyne, ProDrill, and Swimclear.
- Fluid Mix 2: MaxBore Bentonite, Platinum Pac, and Platinum Duo-Vis.



Figure 83. Photo. 24” (61 cm) HDPE pipe.



Figure 84. Photo. Component of Fluid Mix 1-Swim Clear pH plus (Water conditioner that adjusts its pH).



Figure 85. Photo. Component of Fluid Mix 1-ProDrill (soil stabilizer and viscofier).



Figure 86. Photo. Component of Fluid Mix 1-ProDyne
(A non-foaming drilling detergent and water conditioner).

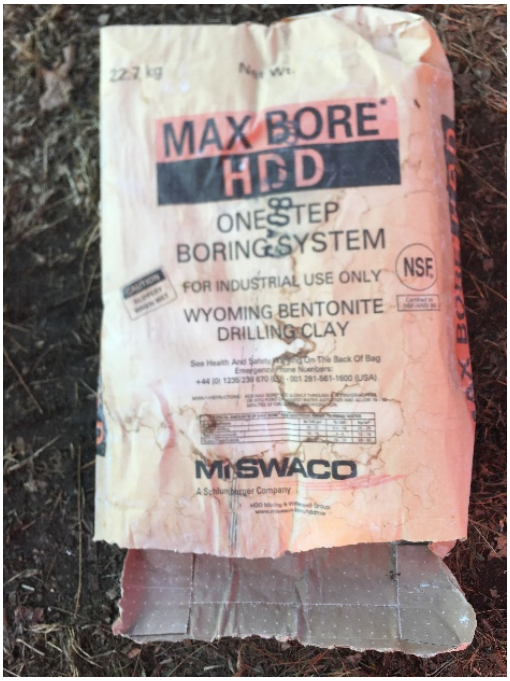


Figure 87. Photo. Component of Fluid Mix 2-MaxBore bentonite.



Figure 88. Photo. Component of Fluid Mix 2-Duo-Vis.

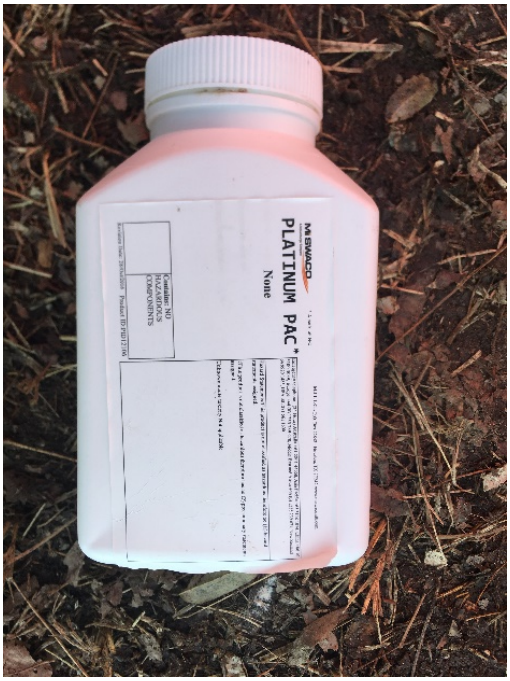


Figure 89. Photo. Component of Fluid Mix 2-Platinum PAC.

G.2.7.3 Execution Metrics

Pipe Fusing:

The execution started by fusing the four 40 ft (12.2 m) pipe segments into a single 160 ft (48.8 m) long pipe, then fusing the pull head to its end. The pipe fusor was transported to the northwestern area of the site, on the downstream side of the road, where pipes were previously placed. The area is relatively flat and has no trees. The fusing started on October 19, 2018, at 10:40 a.m. and ended at 2:00 p.m. and was performed using the pipe fuser Mc ElRoy Tracster 900 series 2. Before fusing any two segments, the faces of the segments to be fused were scraped (faced). The fusor face is pre-heated, and then its temperature is checked using a thermal radiation detecting device called pyrometer. The pipe segments are pushed against the hot surface for 9 min, 49 sec (called the heating or heat soaking stage). The hot surface is withdrawn, then the two pipes are pushed against each other at a pressure of 801 psi (5500 kPa) for 23 min, 59 sec (called fusing or cooling stage) as presented in Figure 90 to Figure 93. Once done, the fused pipe is rolled over the roller pipe stands using the excavator (John Deere 270 DLC) equipped with a textile band of 6” (15.24 cm) thickness, until the end of the fused section is next to the fusor face. A new pipe is placed next to it, and the next scrapping-heating-fusing cycle begins.



Figure 90. Photo. Photo of pipe fusor control panel.



Figure 91. Photo. Photo of pipe fusing.



Figure 92. Photo. Roller pipe stands.



Figure 93. Photo. Pipe rolled over pipe stands.

The cycle repeats until all pipe segments are fused together, then the end of the 160 ft (48.8 m) pipe is fused to the pull head using the same procedure. Two pipe stands were used to facilitate the horizontal translation of the segments and protect them from acute bend angles, which would occur if the segments were not supported except under their faces being fused. This would also help maintain the horizontal orientation of segments while being fused. The stands were placed approximately 15 ft (4.6 m) to the right and left of the fusor face; hence, the supported length of the pipes was around 40 ft (12.2 m) (including the fusor support). This seemed sufficient when two pipe segments were being fused, but as the fused pipe length was increasing by fusing new segments, the ground was used to support the remaining length, and the pipe experienced higher bending angles.

Pipe Handling:

The pipe was lifted and transported using the excavator equipped with a textile band of 6 in. (15.2 cm). Because only one excavator was available, the ground was providing support for other points. The pipe stands were only used in the pipe fusing area. The pipe was transported as presented in Figure 94. The pipe fusing area was around 3 ft (0.9 m) below the road level while the downstream level was more than 40 ft (12.2 m) below the road level. The pipe fusing area was parallel to the road while the pipe alignment was nearly perpendicular to it. Hence, to move the pipe to the location adequate for pull, the pipe had to experience significant vertical and horizontal bend angles, especially that the length of the trajectory of transportation was very limited (estimated to be around 500 ft [152.4 m]). The area downstream was not cleaned from trees and branches, and the pipe had to be moved between those trees. Figure 95 to Figure 99 present the pipe movement starting from the fusing area and ending downstream. Those bends might affect the health and integrity of the pipe, yet no signs of disintegration or cracking of the pipe or its joints were observed. The health of the pipe can be verified by the testing that is typically done after the installation is concluded.

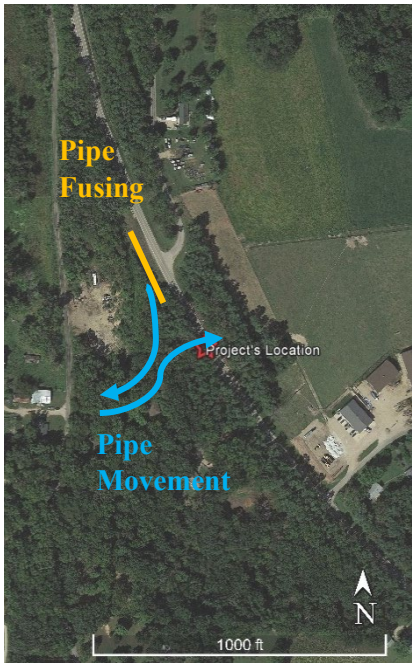


Figure 94. Photo. Google map with illustrations showing the trajectory of the pipe movement.

Source: Google Maps



Figure 95. Photo. Pipe handling and movement from fusing area.



Figure 96. Photo. Pipe handling and movement from the pipe fusing area towards the downstream entrance just past the top of the slope break between the ditch and the embankment side slope.



Figure 97. Photo. Pipe handling and movement towards the downstream entrance with pipe bending as it passes the top of the slope break from the ditch and down the embankment side slope.



Figure 98. Photo. Pipe handling and movement in downstream area.



Figure 99. Photo. Pipe handling and movement in downstream area in line with the downstream entrance and positioned for pulling.

Pilot Drilling:

The rig was moved to the upstream side of the road and placed facing the entry point of the adjusted alignment (Figure 100–Figure 103), which is a few feet to the south of the entry point of the planned alignment. This adjustment was made (apparently on site) to reduce the chance of hitting the old pipe while drilling. The area was previously cleared from trees and was almost flat. Pilot drilling started on November 19, 2018, at 1:30 p.m. and ended at 3:00 p.m. using the rig Vermeer D80x100.

This rig has three mechanical gauges and one digital gauge on its front board: a rotation pressure gauge (measuring the internal hydraulic pressure in the circuit responsible for rotating the pipe), a thrust/pullback pressure gauge (measuring the internal hydraulic pressure in the circuit responsible for thrusting/pulling the pipe), a drilling fluid pressure gauge (pressure of fluid next to the drill bit), and a fluid pumping rate digital gauge. Rotation pressure will naturally rise as the bore progresses, due to friction on the increasing length of the drill string. Thrust/pullback pressure can be affected by product size and weight, bore path lubrication, soil conditions, and bends in the bore. The drilling fluid pressure gauge is best used as an indicator that flow is occurring. Pressure can vary based on flow rates and nozzle sizes used in the tooling. A maximum indication on the drilling fluid pressure gauge could be an indicator that flow has become restricted (D9x13 Series II Navigator manual).

The first mix used for this drilling was composed of (i) four bags of ProDrill (soil stabilizer and viscofier), (ii) four bags of ProDyne (a non-foaming drilling detergent and water conditioner), and (iii) some Swim Clear (water conditioner that adjusts its pH) mixed in the fluid tank and mixer (Vermeer MX240) with 1000 gallons (3785 L) of water. The rotation pressure varied around 2200 psi (15.17 MPa), and the fluid pumping rate varied around 20 gallons (75.7 L) per minute.

The drilling was directed using the walkover system, which is composed of a receiver that receives the readings of the transmitter installed just behind the drill bit and translates them into readings of

orientation (clock), pitch (slope), and depth of the drill bit. This info is displayed on a screen placed next to the driller. The driller receives guidance from the person using the receiver who navigates the drilling and uses the readings displayed on the screen to advance the boring.



Figure 100. Photo. Location of the rig.



Figure 101. Photo. Start of pilot boring.



Figure 102. Photo. Flow of fluid as the drill broke through the downstream side.



Figure 103. Photo. Removal of the drill bit to install the first reamer.

Slope Stabilization:

Before starting the reaming, some cobble-sized crushed stone aggregates were dumped on the downstream slope that was impacted by the soil loss (Figure 104–Figure 105). This was done to protect the slope from further failure during the drilling operation. This effort was brief and limited to a relatively small section of the slope. The excavator was used to dump the aggregates, which in some instances were falling on the adjacent pavement. The excavator was used to compact those aggregates. In some instances, the excavator's arm made contact with the pavement and the adjacent guard rail. This might be responsible for some of the deformations at the edge of the shoulder after pilot boring, which is incorporated in the “After First Reaming” measurement (Figure

106–Figure 108) and might explain why the settlement at the edge of the shoulder is significantly greater than the deformation at the road's centerline.



Figure 104. Photo. Dumped cobble-sized crushed stone used to stabilize part of the downstream slope. Close view.



Figure 105. Photo. Dumped cobble sized crushed stone used to stabilize part of the downstream slope.

Reaming:

The first stage of reaming started on November 20, 2018, at 9:45 a.m. and ended at 11:35 a.m. It started by installing the 24 in. (61 cm) fluted reamer in place of the drill bit, then pulling the rod back while rotating the reamer to cut through the soil (Figure 106–Figure 108). The rotation pressure varied around 3000 psi (20.7 MPa); the pull pressure varied around 500 psi (3.45 MPa); the fluid pressure was mostly zero (indicating good flow), and the fluid pumping rate varied around 55 gallons (208.2 L) per minute.

The driller noticed that the boring was collapsing during the reaming. He could tell because, once he reamed a section, attempting to push through it required a lot of thrust, which should not be the case if he is pushing against a stable boring (pushing against void). The fluid flow on the downstream side was significantly less than expected, which pointed in the same direction. This led to the conclusion that the fluid mix being used is not adequate for the current soil conditions, and it should be replaced. The initial mix was based on an initial evaluation of the soil conditions claiming that the soil is mostly clay. Note that the site investigation boring done was not available to the drillers on site. After the reamer reached the upstream side, the drillers decided to replace the mix in the second phase of reaming. The new mix was composed of six 50 lb (22.7 kg) MaxBore bentonite bags, around 3 lb (1.36 kg) of Platinum Pac, and 3 lb (1.36 kg) of Duo-Vis mixed with 1000 gallons (3785 L) of water.

Since after the first stage of reaming the drilling rod end is on the upstream side, the rod had to be pushed through the reamed hole to the downstream side, then the second reamer was to be installed. This was more practical than moving the rig downstream characterized by its rough terrain and operating it in an upward 14% slope. Therefore, the drill bit was installed again, then pushed into the reamed hole. The push pressures were confirming that the boring had collapsed, so the drill had to be used again to drill through just like it did in the pilot boring stage. The walkover system had to be used again for navigating the drilling. Had the boring been stable, no drilling or navigation would have been required.

The second stage of reaming started on November 20, 2018, at 2:20 p.m. and ended at 3:35 p.m. It used a 30 in. (76.2 cm) fluted reamer. The rotation pressure typically varied from 2500 to 3200 psi (17.2 to 22 MPa), and the fluid pumping rate varied around 75 gallons (284 L) per minute. The boring this time was much more stable, and the fluid flow on the downstream side was significantly greater than in the first stage. The bore could be seen stable from the downstream side using the naked eye (Figure 106–Figure 108).

Once this stage of reaming was done, and the rod end reached the upstream, the time was considered too late in the day for pipe pulling. The drill bit was installed to the rod, and then pushed through the stable boring. No drilling or navigation was needed.

Due to the difficulty encountered in reaming, especially in its first stage, costing drillers more time, the fluid tank had to be refilled more than once. The reaming would be paused till the tank went to a water source and was filled with water. This refilling was also done during the pipe pulling.



Figure 106. Photo. Rod after removal of drill bit and before installing reamer.



Figure 107. Photo. 30 in. (76.2 cm) fluted reamer installed to rod and about to start reaming.



Figure 108. Photo. Stable boring reamed in second stage.

Pipe Pulling:

The pipe pulling started the next day (November 21, 2018) at 8:30 a.m. and ended at 9:35 a.m. It started by transporting the 30 in. (76.2 cm) reamer back from the upstream side to the downstream side using the excavator, then attaching it to the rod, then attaching the reamer to the pull head via a swivel that provides translational connectivity but no rotational connectivity, allowing the reamer to rotate without rotating the pipe (Figure 109–Figure 112). The rotation pressure typically varied from 2500 to 3200 psi (17.2 to 22 MPa), the pull pressure typically varied from 1300 to 1500 psi (9 to 10.3 MPa), and the fluid pumping rate varied around from 75 to 90 gallons (284 to 340 L) per minute. During the pulling, the pipe experienced bending as seen in Figure 109–Figure 112. After the reamer and pull head reached the upstream side, the pull head fusing is removed using an electric saw.



Figure 109. Photo. Reamer attached via a swivel to the pull head which is fused to the pipe.



Figure 110. Photo. Pulling of the pipe.



Figure 111. Photo. Pulling the pipe.



Figure 112. Photo. Pull head reaching the upstream side (the photo also shows the 24 in. (61 cm) reamer next to the 30 in. (72.6 cm) reamer attached to the pull head).

Vacuuming:

The fluid and cuttings flowing towards the downstream were cleaned using the Badger vacuum truck. A hole was dug in the ground just below the exit point downstream to collect the fluid. Another hole was dug up the slope of the downstream(Figure 113–Figure 116). The John Deere excavator would carry a bucket full of fluid and cuttings from the first hole and dump it into the second hole up the slope. The Badger vacuum would then suck the cuttings into its tank. The use of the John Deere excavator and the second hole was because the Badger truck had limited reach and could not make it to the downstream lower pit (hole) because of the steep slope and the irregular terrain.



Figure 113. Photo. Badger vacuum truck.



Figure 114. Photo. Downstream end of the pipe showing traces of the fluid after the pipe has been fully pulled (the photo also shows the old pipe on the left).



Figure 115. Photo. Photo of the fluids collection pit (hole) at the downstream side of the bore.



Figure 116. Photo. Tube from the vacuum truck and the fluid retention pit (hole) located higher up the slope from the lower fluids collection pit on the downstream side of the bore within reach of the hose from vacuum truck.

Machinery Movement:

During the operation, heavy equipment, including the excavator, the fluid tank, and the vacuum truck, was moving over the pavement. The latter two are equipped with rubber tires, but the excavator has steel tracks. While moving, some rubber pads were being placed on the road spaced about 4 ft (1.2 m) apart as presented in Figure 117–Figure 118. The excavator moved from the upstream to the pipe fusing area (1st cross), then to the downstream along the road (2nd cross) at the end of the road. It picked the second reamer from upstream (3rd cross), then moved to the upstream area to be cleaned and prepared to be transported. Crossings towards the downstream were occurring around 30 ft (9 m) from the area, which caused most of the ground loss. This is reported because it might be contributing to the settlement of the road.



Figure 117. Photo. Movement of the excavator over the road. (1)



Figure 118. Photo. Movement of the excavator over the road. (2)

Site Restoration:

After the drilling ceased and the pipe was installed, site restoration efforts were initiated. The excavator fixed the slope downstream, making it less steep and more accessible for equipment (Figure 119–Figure 120). This is important for later construction activities targeting fixing the slope, dumping rip rap, sealing part of the old pipe, and removing part of it. The road was cleaned using brooms and pressurized water.



Figure 119. Photo. Slope fixing.



Figure 120. Photo. Pavement cleaning.

G.2.8 Performance Metrics

G.2.8.1 Surface Deformation

Ground surface (or pavement surface) elevations were surveyed at 35 points (consisting of 5 points along the centerline above the alignment of the pipe culvert and their offsets 5, 10, and 20 ft [1.5, 3, and 6 m] away in each direction [Figure 121–Figure 123]) prior to any drilling activities. Ground elevations of the 5 points along the road centerline across the pipe culvert were measured after pilot boring, first reaming, second reaming, and pipe pulling. A final measurement of the elevations of all 35 points was taken just after the drilling activities ceased.

Photos of the pavement before and after construction (Figure 123) were taken, but since the pavement was heavily cracked before the drilling, signs of further cracking, if any, were hard to distinguish.

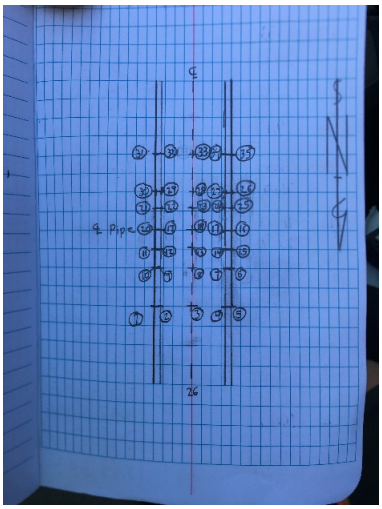


Figure 121. Photo. Plan view showing survey marker points.

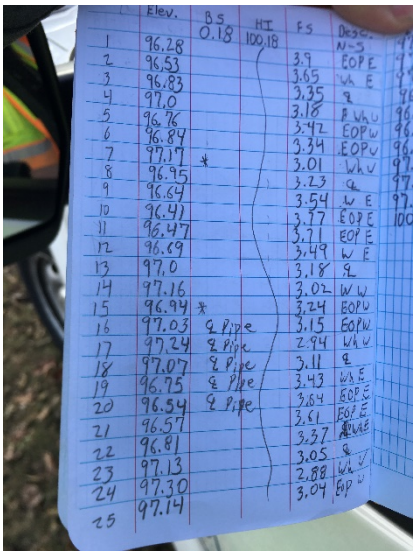


Figure 122. Photo. Typical set of survey readings.



Figure 123. Photo. Condition of pavement after pipe installation.

The ground elevations are plotted below in Figure 124 and Figure 125. Figure 124 presents that settlements up to 0.07 in. (0.18 cm) were recorded over or just next to the centerline above the alignment. Those settlements are most pronounced next to shoulder edges. The readings indicating small heave are thought to be small, within-tolerance surveying measurement errors, but might also indicate a small heave caused by the fluid pressure especially during the first stage of reaming. Figure 126 presents the settlements' development as construction stages proceed. While pilot boring did not cause any settlement, the ground settled after reaming and pipe pulling up to a max of 0.6 in. (1.5 cm). The drillers were confident that the drilling would not cause any settlement because of the large distance from the pavement level to the level of the pipe (around 30 ft [9 m]), but the measurements showed settlements have indeed occurred.

G.2.8.2 Long-Term Measurements:

Further measurements were taken on three different days months after the completion of the construction. The days of measurement are August 27, 2019, October 27, 2019, and December 12, 2019. All measurements showed very little movement compared to the measurements at the end of construction. Those calculated deformations are likely measurement errors rather than real deformations.

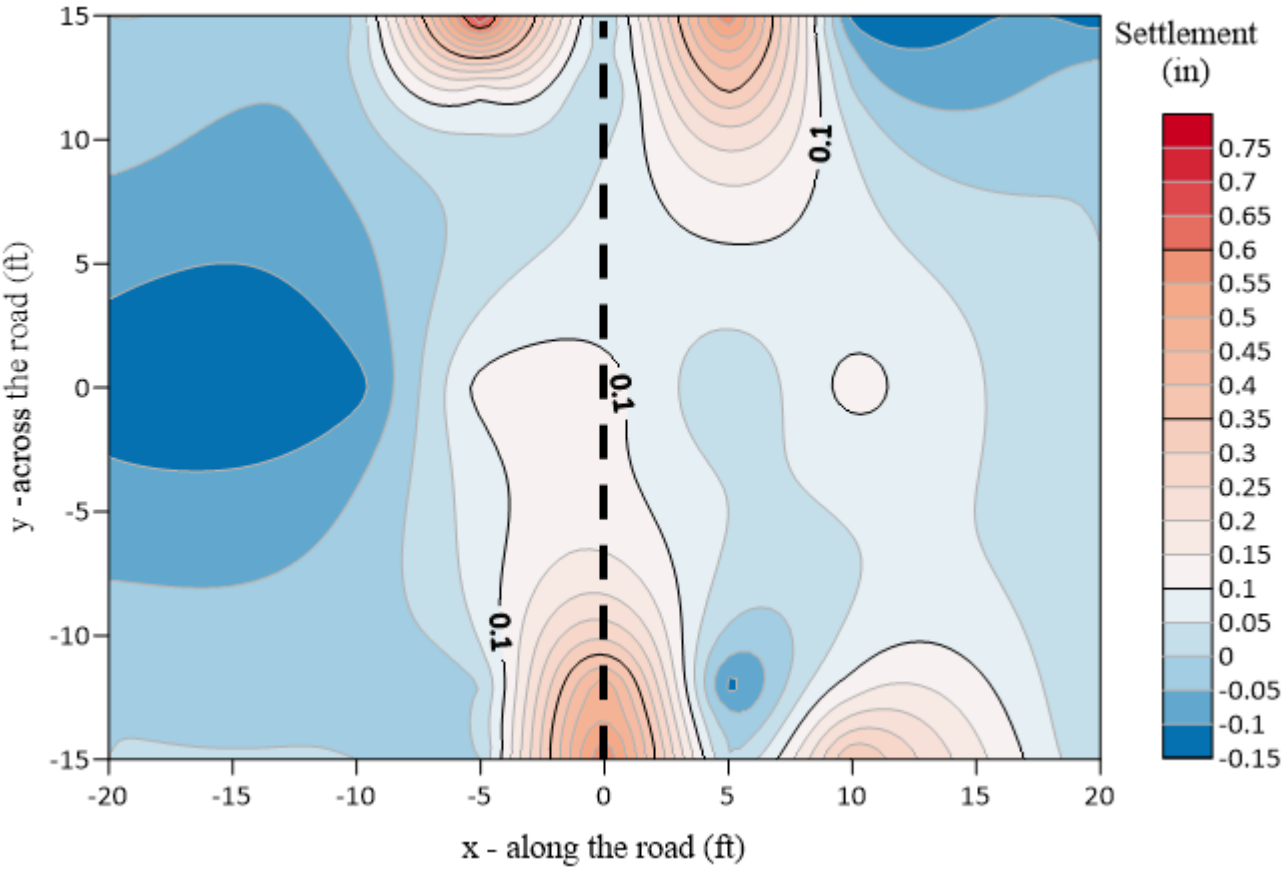


Figure 124. Chart. 2D plot showing the ground movement after finishing pipe installation relative to initial elevations. Dashed lines mark the alignment of the pipe culvert.

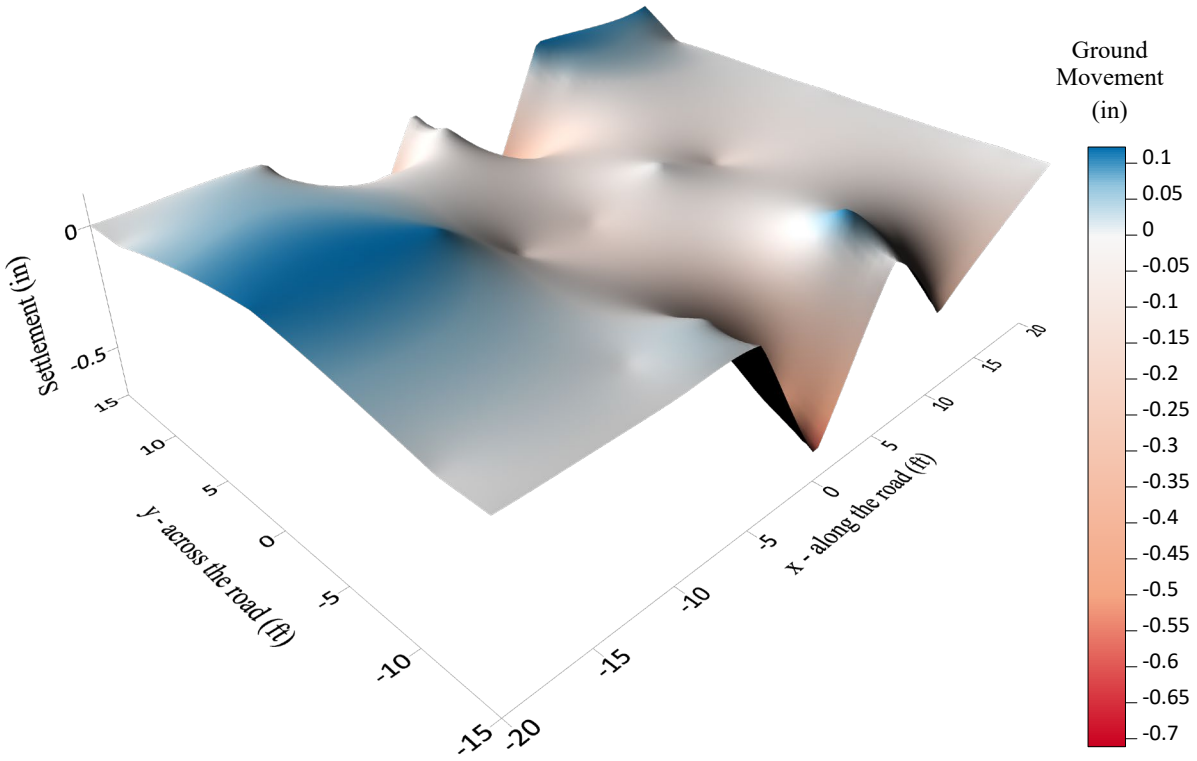


Figure 125. Chart. 3D plot showing the ground movement after finishing pipe installation relative to initial elevations (Pipe alignment is located at zero on the x-axis).

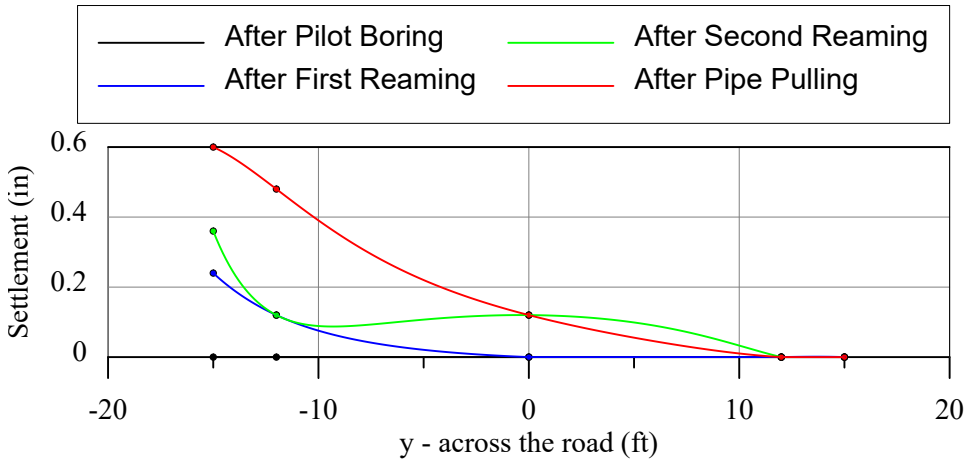


Figure 126. Chart. Plot of settlements, relative to initial elevations, at the centerline above the pipe alignment after each stage.

G.2.8.3 Pipe Testing

Pressure testing was not performed.

G.2.8.4 Pipe Alignment

The as-built profile for the HDD pipe installation of the Hennepin project is presented in Figure 128 and Figure 129. The profile was provided by Midwest Mole.

G.2.9 Important Remarks and Conclusions

G.2.9.1 Contractor's Experience

The driller stated the following, based on his experience in drilling:

- To calculate the adequate fluid rate to be used while drilling, multiply the diameter of the drill bit or reamer being used by two then add some more. For example, for the 24 in. (61 cm) reamer, the fluid rate used was 24*2+7 = 55 gallons (208 L) per minute.
- Below the 20^{o} F (-6.7^{o} C), the rig becomes slower as fluids start to freeze. This slowdown might make the drilling infeasible.
- If the reamed boring is good, just pushing the drill bit through it without drilling or navigating should be enough.
- The actual cost of the project is 10% less than the estimated cost due to efficient construction planning.

G.2.9.2 Notes on Contract Specifications

Examining the contract specifications agreed upon, the following remarks can be made:

- The document contains no specifications for handling the pipe: how the pipe should be carried and transported and what bend angles are allowed in the process.
- The document contains no specifications for fluid mixes and quantities.
- The document contains no specifications for what machinery and equipment can be used: rigs, reamers, drill bits. For example, it is known that some kinds of reamers result in less surface deformation compared to other reamers.
- The document contains no specifications for dealing with existing utilities.
- The document contains no specifications for dealing with groundwater.
- The document contains no specifications for deformation monitoring and control.
- The document contains no specifications for alignment and grade constraints.
- The document does not identify the entity responsible for site investigation.

- The document limited the damage being considered to immediate damage, while damage can occur in the long term.
- The document did not limit the ratio of the boring diameter to the pipe diameter.
- The document did not discuss the issue of collapsing bores: responsibility and mitigation.
- The document did not discuss the issue of machinery movement on structures.
- Specifications on the timing of operations should be supplemented.
- Limited reasons for damage were listed, while in fact, many more reasons can result in damage. This listing should be expanded or kept more general.

Comparing the actual execution with the contract specifications, the following deviations were observed:

- not all residual slurry was removed due to difficulty of access.
- Excavation pits were not needed.
- No resident engineer was available to give the green light for drilling to start.
- Viscosity and density of drilling fluid were not tested during operation.
- Pull rate seemed arbitrary rather than determined.
- Pipe was pulled a day after reaming.

G.2.9.3 Notes on the Existing Pipe Issue

While drilling the pilot boring, and just before the drill bit broke through the exit point downstream, some fluid started flowing out of the old pipe, as presented in Figure 127. No fluid entered the pipe from upstream. This indicates that the fluid flowed through the soil and entered the existing pipe. This strongly suggests that the existing pipe is indeed broken and is suspected to be very close to downstream, since the fluid flowed out of the pipe when the drill bit was very close to the exit point.



Figure 127. Photo. Fluid flowing out of the old pipe just before the drill bit broke through exit point on the downstream.

G.2.10 Lessons Learned

Main lessons learned from Hennepin case history include:

- The movement of heavy machinery, especially those with metal treads, on the road might cause significant distress for the pavement. Measures should be employed to protect the pavement from damage by heavy construction equipment, such as the use of neoprene pads or crane mats.

- A proper pipe layout and handling plan should be prepared prior to the commencement of construction, taking into consideration the topography of the area and the full length of the pipe. Without doing this, the pipe might be subjected to sharp angles, which might affect its integrity or reduce its final quality or durability.

- Proper soil investigation should be performed prior to the commencement of construction. This would inform the designer and contractor of the ground challenges and would likely lead them to make more adequate choices. For example, the design of the fluid mix would be significantly influenced by the type of soil to be expected.

- Choosing a fluid mix that is suitable for the soil conditions encountered is essential for a successful installation with little impact on the superstructures.

- Handling spoils might be challenging when the topography of the area makes it not easily accessible by machinery (like vacuum trucks).

G.2.11 References

Frankie, Wayne T, Russell J Jacobson, Ardith K Hansel, Myrna M Killey, Robert S Nelson, Dave H Malone, William E Shields, and Robert G Corbett. 2002. *Guide to the geology of the Hennepin area, Putnam, Bureau, and Marshall counties, Illinois*. Champaign, Ill.: Dept. of Natural Resources, Illinois State Geological Survey.

McComas, Murray R. 1968. "*Geology related to land use in the Hennepin region*." Circular no. 422.

Piskin, Kemal, and Robert E. Bergstrom. 1975. *Glacial drift in Illinois: thickness and character*. Champaign, Ill.: Illinois State Geological Survey, Prairie Research Institute.

DigiTrak LWD

DataLog® Drill Report

Job Information

	Job Location:	Client Information:	Contractor Information:
Name:	10045 Stark	Stark Excavating	
Contact:		Jason Schupp	
Phone:		309-275-7032	
Address:			
City:	Hennepin, IL		

Receiver/Job Information

10 data points collected on unit Serial Number: 30019771 in Job 11 on 11/19/2018. Flags and Pins listed below (if applicable).
All units in charts and tables are Distance in ft, Depth in ft, Pitch in %, and Pressure in PSI.
Reference Elevation is not measured.
Entry Point Relative Depth 0.00. Chart and Table zero are the Reference Elevation.
Exit Terrain not surveyed.
First Rod Length is 9.00
Typical Rod Length is 15.00
Last Rod Length is 15.00
Total number of rods 9

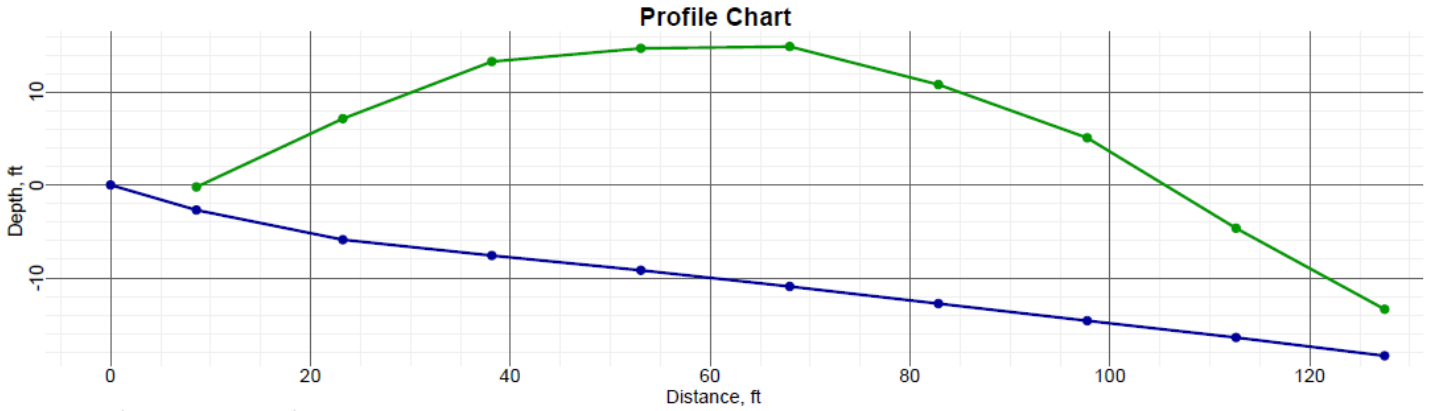
Job Comments

150' Gravity Sewer (Culvert Repair)

Figure 128. Report. The as-built profile of the drill location for the HDD pipe installation in Hennepin project. (Provided by Midwest Mole)

DigiTrak LWD

Drill Data



Blue: Drill Path -- Green: Calculated Terrain

Drill Data Points

FLP(Front Locate) - LL(Locate Line) - PO(Pitch Only) - BL(No Data) - o(override) - f(filled in) - i[*](interpolated)

Rod ID	Type	Bore Len.	X Dist.	Pitch	Rel.Depth	Depth	Rel.Elev.	L/R Offset	Deviation	Latitude	Longitude	GNSS X Dist.
0	PO	0.00	0.00	-31.5	0.00		0.00	N/A	N/A			
1	LL	9.00	8.59	-31.2	-2.69	2.48	-0.21	N/A	N/A	N/A	N/A	N/A
2	LL	24.00	23.24	-12.8	-5.89	13.05	7.16	N/A	N/A	N/A	N/A	N/A
3	LL	39.00	38.15	-10.0	-7.59	20.90	13.31	N/A	N/A	N/A	N/A	N/A
4	LL	54.00	53.06	-11.2	-9.18	23.91	14.73	N/A	N/A	N/A	N/A	N/A
5	LL	69.00	67.96	-12.1	-10.92	25.84	14.92	N/A	N/A	N/A	N/A	N/A
6	LL	84.00	82.85	-12.7	-12.77	23.59	10.83	N/A	N/A	N/A	N/A	N/A
7	LL	99.00	97.73	-12.1	-14.62	19.69	5.08	N/A	N/A	N/A	N/A	N/A
8	LL	114.00	112.62	-12.1	-16.42	11.77	-4.65	N/A	N/A	N/A	N/A	N/A
9	LL	129.00	127.49	-14.5	-18.40	5.02	-13.38	N/A	N/A	N/A	N/A	N/A

Figure 129. Report. The as-built profile of the drill location of the HDD pipe installation in Hennepin project. (Provided by Midwest Mole)

G.3 PECATONICA CASE HISTORY

G.3.1 Project's Goal

In this project, a 20 in. (50.8 cm) diameter NICOR steel gas transmission line is to be installed parallel to Conger Road replacing the existing 12 in. (30.5 cm) diameter pipe which will be abandoned in place. The pipe along the 7370 ft (2246 m) profile will be installed using open cut and horizontal directional drilling. The total length of the open-cut sections is 6735 ft (2053 m), and the total length of the HDD sections is 635 ft (193.5 m). The HDD section documented in this report runs under the US-20 Highway (Figure 130) parallel to Conger Road, with an approximate proposed length of 500 ft (152.4 m). This document does not cover the open-cut section (Figure 131).



Figure 130. Photo. US-20 Highway. The intersecting road is the North Conger Road.



Figure 131. Photo. Part of the open-cut section showing the pipe before being lowered into the cut.

G.3.2 Location and Surroundings

The project is located in Pecatonica, Illinois (Figure 132–Figure 134), and its GPS coordinates are 42°17'11.3"N 89°19 '11.3"W.

The proposed installation starts at approximately 2800 ft (853.4 m) south of the intersection of Comly Road and South Conger Road and ends at approximately 500 ft (152.4 m) north of the intersection between US Highway 20 and Conger Road.

The proposed alignment is about 10 to 15 ft (3 to 4.6 m) away from the old gas pipe, and a communication cable conduit installed next to it, as presented in Figure 135–Figure 136. The closest building is a 1-story restaurant more than 100 ft (30.5 m) away from the centerline of the pipeline (Figure 135–Figure 136). Hence, the primary structure which might be impacted by the construction is US-20. The section of the road overlying the proposed alignment is cracked (Figure 137–Figure 139).



Figure 132. Photo. Google Maps capture showing Pecatonica project site on state levels.

Source: Google Maps

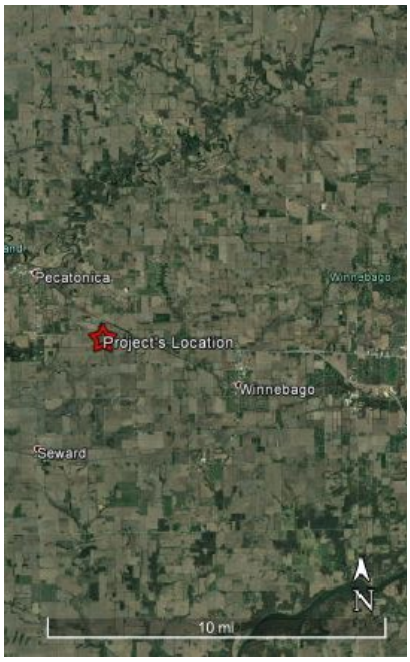


Figure 133. Photo. Google Maps capture showing Pecatonica project site on county levels.

Source: Google Maps



Figure 134. Photo. Google Maps capture showing Pecatonica project site on neighborhood levels.

Source: Google Maps



Figure 135. Photo. JULIE yellow and orange flags (left of photo), indicating existence of gas and communication lines.



Figure 136. Photo. Closest building to the centerline of the pipeline.



Figure 137. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (1)



Figure 138. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (2)



Figure 139. Photo. Road section just above the alignment showing existing cracks in the four lanes of US-20 before the start of drilling. (3)

G.3.3 Site Conditions

G.3.3.1 Soil Conditions

Four borings were performed on March 3, 2017, by SEECO consultants, using hollow stem augers. Two of those borings are within the HDD section and are 40 ft (12.2 m) deep: B1 drilled north of the intersection of US-20 with Conger Road, and B2 drilled south of this intersection. The other two borings are thousands of feet to the south, along the open-cut section. SPT blow counts were recorded, and samples were taken for the determination of natural water content and unconfined compressive strength via lab testing. Both borings showed a top fill layer of 4 ft (1.2 m) thickness, underlain by a silty clay layer of 10 to 14 ft (3 to 4.3 m) thickness, underlain by dense sand layers. Groundwater was encountered at a depth of 22 ft (6.7 m). Figure 140 and Figure 141 present the stratigraphy of the site, the SPT blow count, and the unconfined compressive strength (measured via penetrometer) at different depths.

G.3.3.2 Topography

The area of the site is almost flat. The northern side of the road, where the boring pit will be located, is only 10 ft (3 m) higher than the southern side, so the average slope is around 2% only. The terrain on both sides is regular, and the working space is vast.

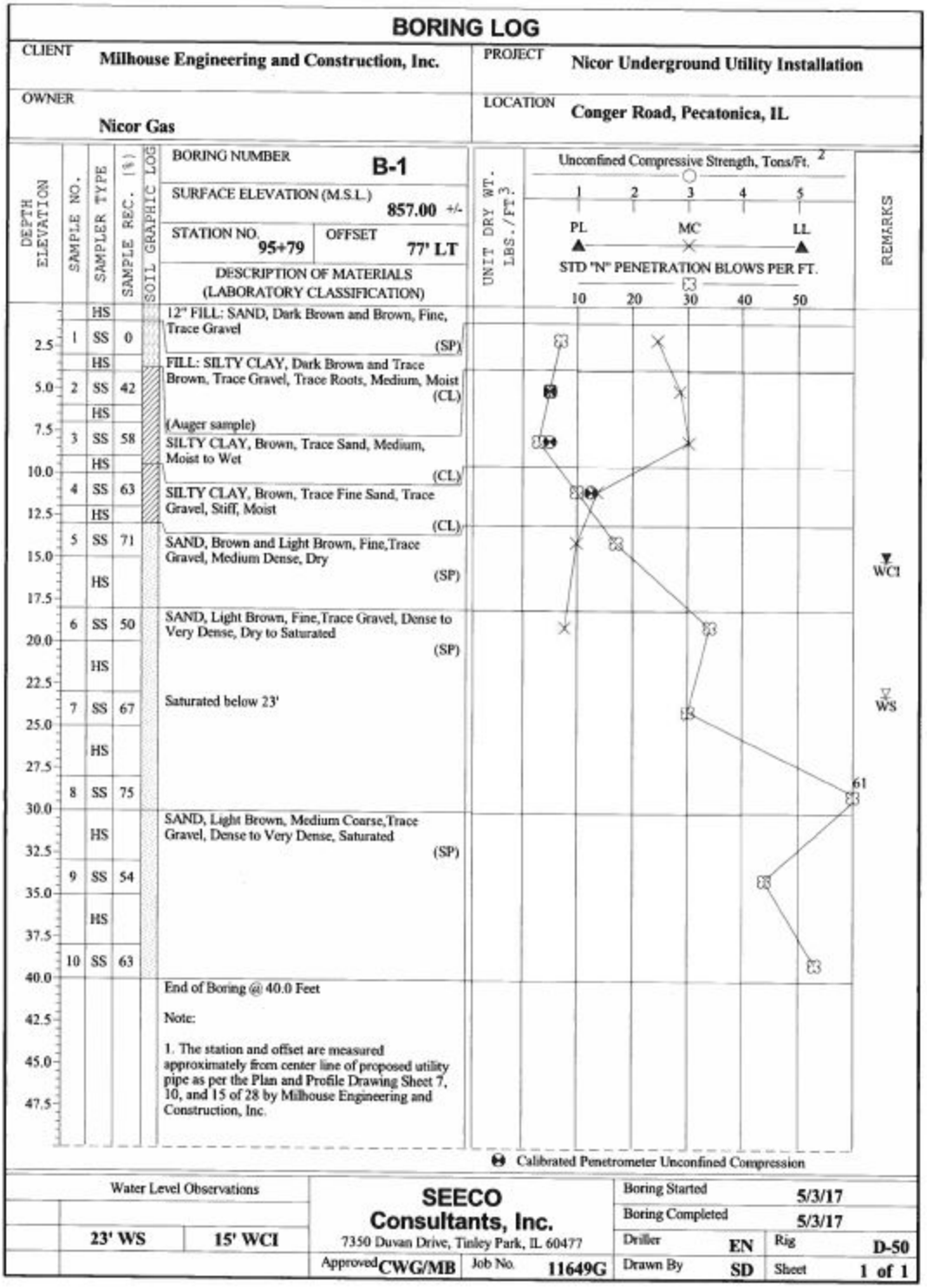


Figure 140. Chart. Stratigraphy and soil properties obtained from boring B1.

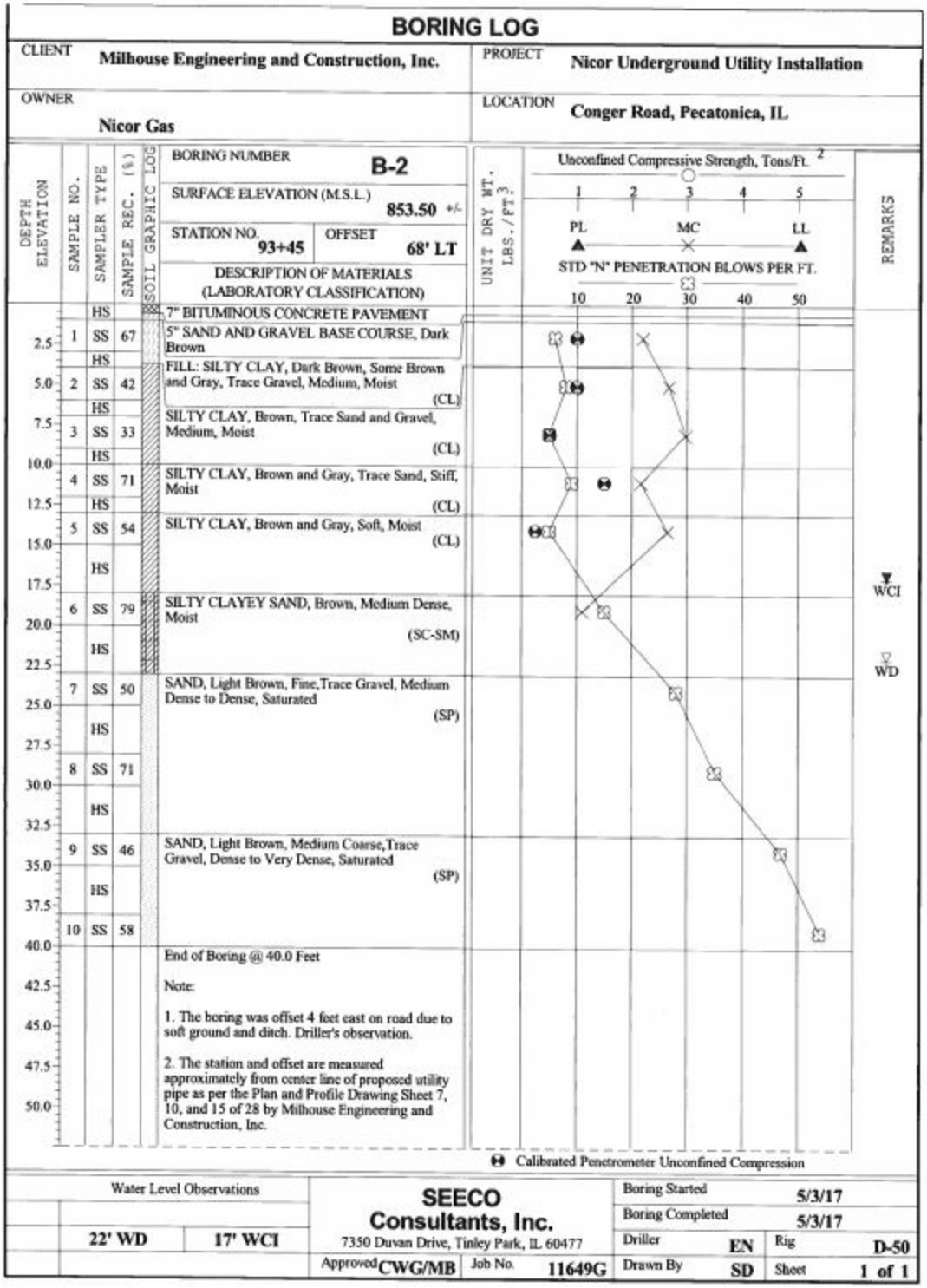


Figure 141. Chart. Stratigraphy and soil properties obtained from boring B2.



Figure 142. Photo. Northern side of the road.



Figure 143. Photo. Southern side of the road.

G.3.3.3 Geology

Blagojevich and Brunsvold (1998) assessed the geology of the Sugar-Pecatonica area and presented the following summary:

- Most of the unlithified sediments that overlie the bedrock were deposited by continental glaciers that advanced across the Sugar-Pecatonica Assessment Area during the Pleistocene Epoch, or Great Ice Age.

- Till is the major type of glacial sediment found in the region; less abundant glacial deposits include lacustrine sediments, outwash (sand and gravel), and organic-rich debris (peat, for example).

- Overlying the deposits of glacial origin is a windblown silt, or loess, from the late-glacial and post-glacial age.

Hundreds of records (logs) and samples of sediments from borings drilled throughout the assessment area are stored and cataloged at the Illinois State Geological Survey. Many borings penetrated the entire sequence of glacial sediments overlying bedrock and provided the record from which the general glacial history of the region has been interpreted. Several studies of the glacial geology of north-central and northwestern Illinois have been conducted over the past several decades: Shaffer (1956), Hackett (1960), Kempton (1963), Kempton (1968a, 1968b), Frye et al. (1969), Berg et al. (1985), Willman and Frye (1969), and Lineback (1979).

The glacial sediments in the Sugar-Pecatonica Assessment Area were deposited by glaciers of the Illinois Episode, the next to last major glacial advance into the state during the Great Ice Age (Willman and Frye 1970; Hansel and Johnson 1996). Meltwaters from these, and possibly earlier, glaciers may have deepened the bedrock valleys, such as the Pecatonica Bedrock Valley (see Bedrock Geology section). Some sand layers in the lowest parts of the valleys may also have been deposited by meltwaters of glaciers before and during the Illinois Episode.

At least three tills, representing three different pulses of the Illinois Episode glacier, underlie the loess cover of the Sugar-Pecatonica Assessment Area: from oldest to youngest, they are the Ogle, the Winslow, and the Argyle (Willman and Frye 1970; Lineback 1979).

The Ogle, found over most of the central part of the assessment area, is generally a sandy, tan to gray-brown till that is thin and discontinuous and interbedded with sand and gravel. It has been intensely eroded but can be seen in many small outcrops that include the underlying bedrock. The Winslow, found only in the northwestern part of the assessment area, is a dark gray, clayey till. The Argyle, a sandy, gravelly pinkish tan till found in the eastern and southeastern part of the assessment area, was originally thought to be deposited by a glacier during the Wisconsin Episode (Willman and Frye 1970). However, an earlier soil (the Sangarnon Soil) that developed between the Illinois and Wisconsin Episodes of glaciation was found in the Argyle, so this till is now classified as an Illinois Episode deposit (Berg et al. 1985).

The sequence of deposits, as well as their position on the landscape and their relationships to each other, has been difficult to unravel because of a combination of depositional and erosional circumstances (Berg et al. 1985). The major factors contributing to the difficulty are (1) a highly irregular bedrock surface that has a great deal of local relief, (2) a thin cover of drift with few exposures of more than one till in any one locality, (3) the similar appearance of the weathered tills in the field, and (4) the lack, due to erosion, of preserved early soils developed in the tills. Nevertheless, the glacial history of the area can be summarized as the occurrence of several pulses of ice advance during the Illinois Episode, followed by an event of widespread high-velocity meltwater that flowed across the uplands and eroded and removed some of the early soils (Berg et al. 1985). Later, deposition of windblown silt followed, which left a covering of loess across the entire area.

Drift throughout most of the assessment area is thinner than 25 ft (7.62 m), and numerous outcrops of bedrock can be observed throughout the region. However, more than 200 feet (61 m) of drift overlies the bedrock valleys near the east boundary of the assessment area (Piskin and Bergstrom 1975). The three tills in the area are each generally thinner than 20 ft (6.1 m). The Ogle and Winslow, especially, are thin and discontinuous and appear in many small outcrops capping bedrock exposures.

Sands and gravels in the bedrock valleys, where overlain by modern stream alluvium (Cahokia Alluvium), may be considerably thicker. Localized areas of lake silts (Equality Fonnation and Teneriffe Silt) that resulted when glacial meltwater temporarily backed up into small valleys tributary to the larger streams, such as the Pecatonica and Sugar Rivers, are usually several feet thick. The loess cover is as thick as 15 ft (4.6 m) in the westernmost tip of the area but thins to about 5 feet (1.52 m) at the east boundary.

The geologic map of the quaternary deposits in the area is presented in Figure 144 and is modified from (Kron 2011). The location of the project is marked on the map. The map shows that the geologic unit to be expected on site is the Argyle Till, which contains silt, clay, sand, and gravel deposited by glacial ice, and overlies bedrock. This unit is described as very sandy, brown to pinkish tan in color, massive, calcareous, and contains beds of sands and gravels.

G.3.4 Design

To extend the pipe below the US-20, the HDD method is proposed. The cross-section of the proposed drilling is presented in Figure 145. A bore pit is to be excavated around 200 ft (61 m) north of the highway, and the receiving pit will be around 150 ft (45.7 m) south of the highway, with a total straight length close to 500 ft (152.4 m). The radius of the bore will be 2000 ft (610 m).

The depth of the bore beneath the ground starts at around 4 ft (1.2 m) in the bore pit then increases to around 15 ft (4.6 m) below the centerline of the highway, then decreases back to around 4 ft (1.2 m) at the receiving pit. The angle of entry and exit is determined to be 4 degrees.

Note that the highway is about 150 ft (45.7 m) wide, but apparently, because of the limitations on steel pipes bending, the length of drilling had to be increased to 500 ft (152.4 m). The resulting proposed radius matches the rule of thumb: 1200 times the outer diameter of the steel pipe.

G.3.5 Features and Foreseen Challenges

The following list contains some of the interesting features and challenges of this project:

- The depth of drilling is relatively shallow, especially next to the entry and exit pits. Hence, the bore will be made under low confining pressure. Low covers increase the chances of fracking due to excessive fluid pressure and surface deformations (heave or settlement).

- The bore is relatively long, and no pressure relief pits are proposed in the design. This might also contribute to fracking.

- Because of the length of the bore, and hence the relatively long duration it is expected to drill, a fluid recycling system would likely be beneficial to reduce the amounts of fluid needed.

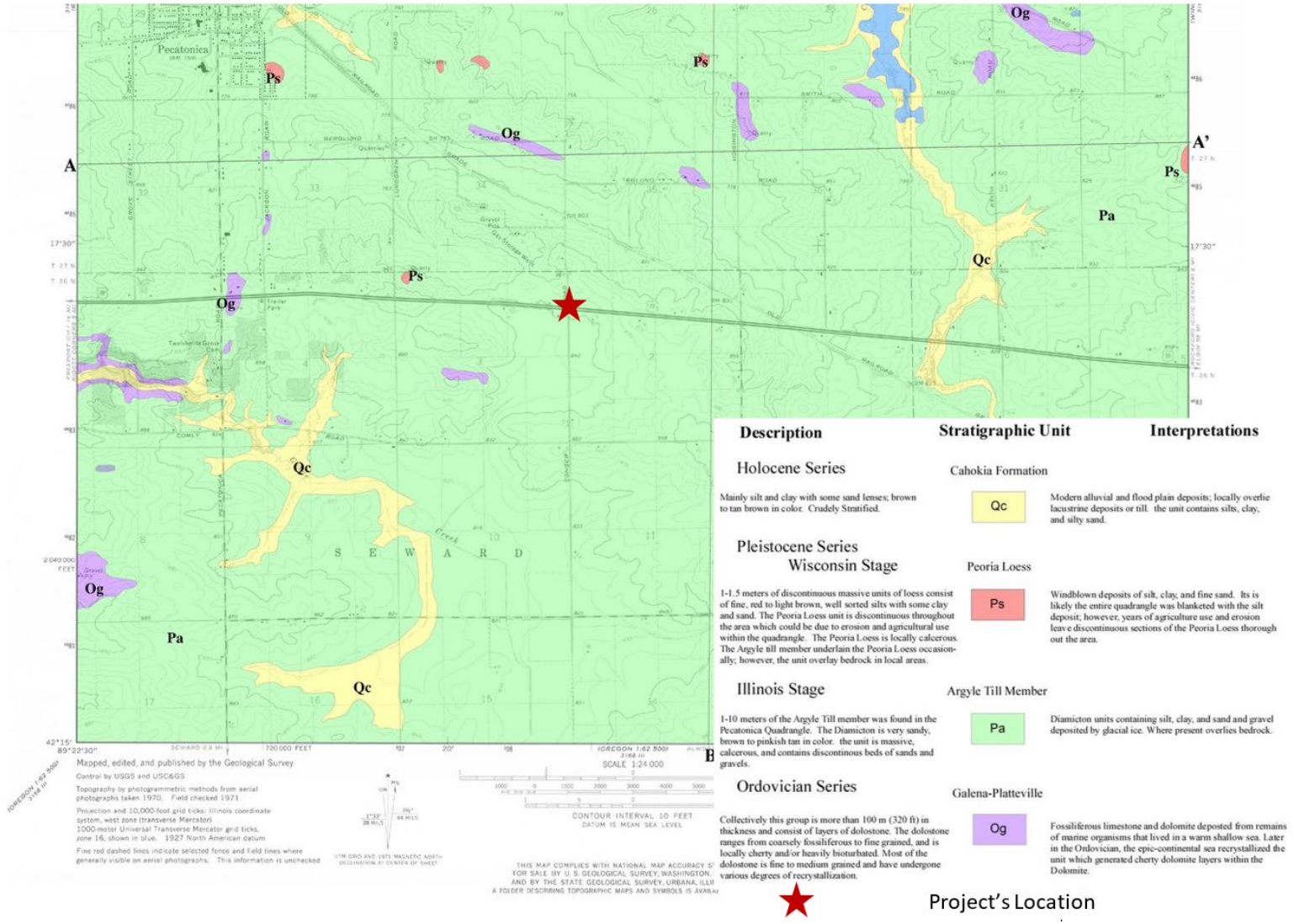


Figure 144. Graph. Surficial geologic map of the Pecatonica area.

Source: Modified from (Kron 2011)

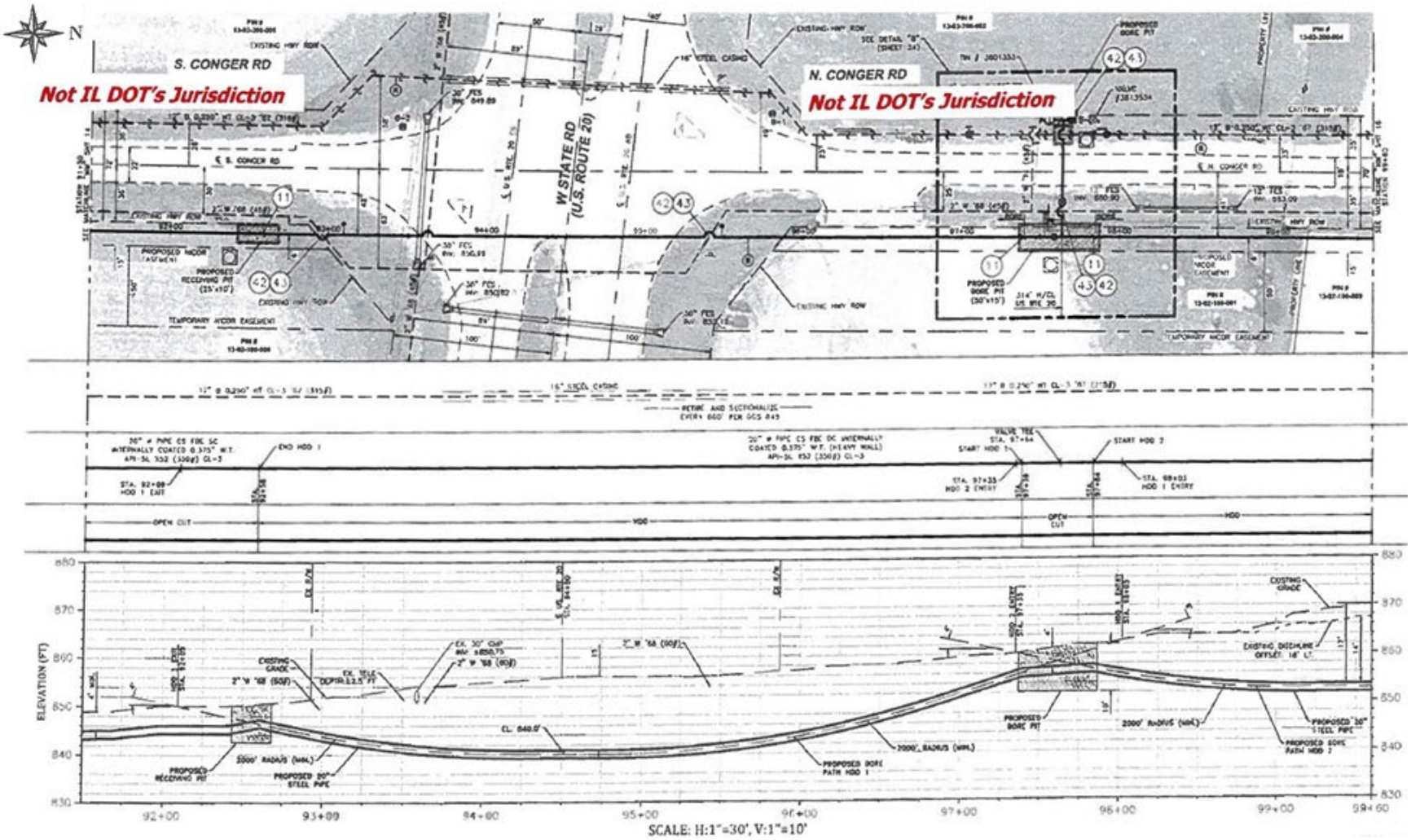


Figure 145. Graph. Plan view and cross-section of the road with the planned improvements. The schematic shows the elements of the first alternative (in black) and the modifications leading to the second alternative (in red).

G.3.6 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- NICOR Gas, which is the owner.
- Milhouse Engineering (https://milhouseinc.com/), which is the consultant.
- SEECO Consultants (https://www.seeco.com/), which carried out the soil investigation and prepared the soil report for Milhouse Engineering.
- Snelson (http://www.snelsonco.com/), which is the contractor.
- Southeast Directional Drilling (http://www.southeastdrilling.com/), which is the subcontractor that executed the horizontal directional drilling and its pipe installation.

The main point of contact during this project was IDOT's Inspector: District Geotechnical Engineer Jan Twardowski (email: Jan.Twardowski@illinois.gov; phone: +1-815-284-5429)

G.3.7 Execution

G.3.7.1 Settings

Preparations for installing the steel pipe via HDD started on January 1, 2019, and by January 26, 2019, at 4:00 p.m., the installation was done. The temperature in Pecatonica varied between -23 and 32° F over those 16 days (Figure 146). No precipitation was recorded, but snow, 4" to 8" (10 to 20 cm) thick, was covering the ground before the start of the drilling operations.

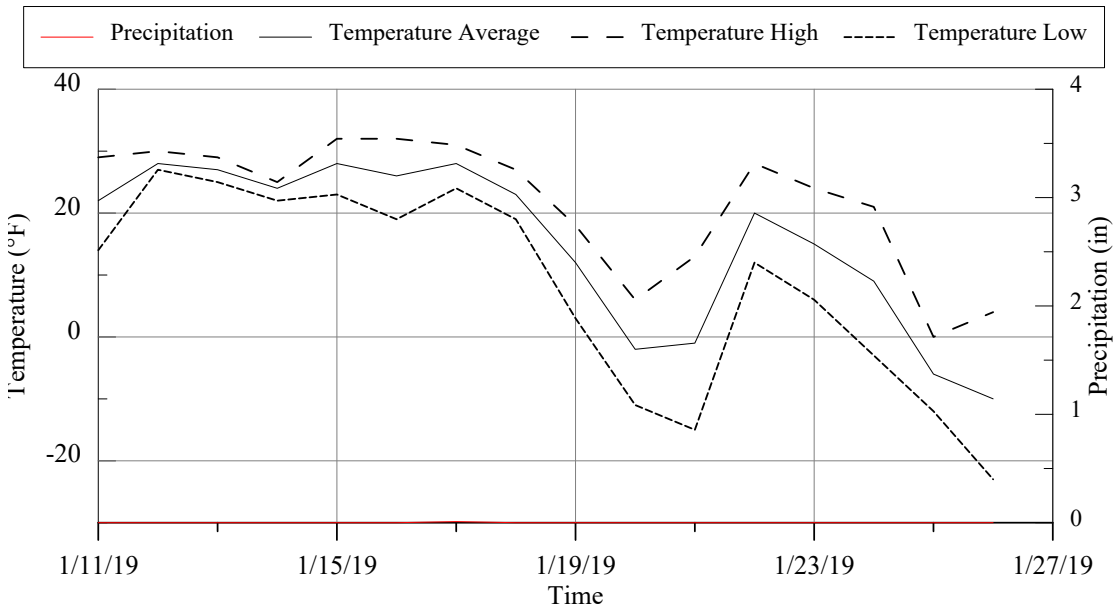


Figure 146. Chart. Temperature and precipitation in Albertus, Illinois, close to Pecatonica, Illinois.

***Source:* https://www.wunderground.com/**

G.3.7.2 Machinery, Equipment and Materials:

Machinery used in this project included the following (Photos presented in Figure 147–Figure 151):

- Excavators: Model: John Deere 210G LC.
- Rig: Vermeer D100x120 Series II NAVIGATOR. The rig uses 20-ft (6.1-m) long 4.375” (11.1 cm) thick drilling rods and is characterized by a torque capacity of 12 kip-ft (16.3 kN-m), 100 kip (444.8 kN) pull capacity, and a maximum pumping capacity of 200 gpm (757 L/min).
- Fluid Tank: of around 2500-gallon (9460-L) capacity.
- Fluid Recycling System: Kem-Tron Tango 500T.
- Equipment Storage Truck.
- Vacuum Truck.



Figure 147. Photo. Machinery used: excavator.



Figure 148. Photo. Machinery used: rig.



Figure 149. Photo. Machinery used: fluid tank and mixer.



Figure 150. Photo. Machinery used: pipe fusor.



Figure 151. Photo. Machinery used: Equipment Storage Truck.

Equipment used in this project included the following (Photos presented in Figure 152–Figure 159):

- Drill bit: armor lance bit of 6.5 in. (16.5 cm) diameter.
- Pipe pull head.
- Reamers: 2 mixer reamers of 20 in. (50.8 cm) and 30 in. (76.2 cm) diameters, and one 24 in. (61 cm) tri-cone roller reamer.
- Swivel.
- Pipe stands.
- Walkover tracking system.



Figure 152. Photo. Equipment used: drill bit.



Figure 153. Photo. Equipment used: pull head.



Figure 154. Photo. Equipment used: 20” (50.8 cm) reamer.



Figure 155. Photo. Equipment used: 30” (76.2 cm) reamer.



Figure 156. Photo. Equipment used: swivel.



Figure 157. Photo. Equipment used: pipe stand.



Figure 158. Photo. Equipment used: tracker.



Figure 159. Photo. Equipment used: mud pump.

Materials used in this project included the following (Photos shown in Figure 160 – Figure 163):

- Pipe: steel pipe of 20 in. (50.8 cm) diameter.
- For Fluid Mixes: Morton water softener, Bentonite: MaxBore or SlikGel.



Figure 160. Photo. Pipe.



Figure 161. Photo. Morton water softener.



Figure 162. Photo. Max Bore Bentonite.

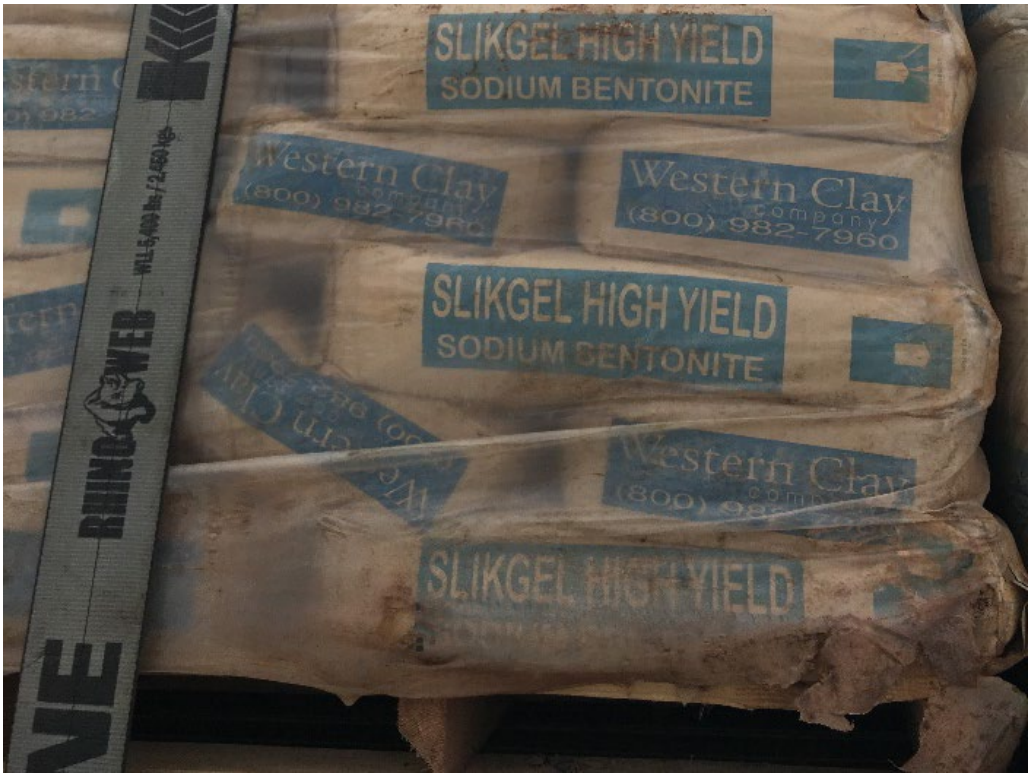


Figure 163. Photo. SlikGel Bentonite.

G.3.7.3 Execution Metrics:

The execution of this project was observed by UIUC graduate students on January 1, 2019, and January 15, 2019. The documentation of this case history after that was done by IDOT's inspector Jan Twardowski, who was sending UIUC daily updates and photos.

Pipe Preparation:

The pipe was welded and placed on pipe stands on the southern side of the road where open-cut trenches were made. This was done before the start of any drilling as presented in Figure 131.

Pilot Drilling:

The rig was placed on the northern side facing the bore pit which was previously excavated at station 98+35. Delays were caused by rig starting issues. The fluid recycling system had to be first assembled, connected to the rig then started (Figure 164–Figure 166), and the pump which was previously placed in the bore pit had to be warmed using gas (Figure 167–Figure 169). Pilot drilling started on January 14, 2019, at 2:30 p.m., with an entry angle of 14 °, and the drill bit's location was being tracked using the tracking system (Figure 170–Figure 171). The rig stopped working at 3:00 p.m. It was later started and drilled 40 ft (12.2 m) when an inadvertent return occurred, in which the ground was observed to soften under the covering snow, then a quantity of fluid estimated to be between 5 to 7 gallons (19 to 26.5 L) leaked to the surface. The drill bit was retracted (Figure 172–Figure 174).

On the morning of January 15, 2019, the drill bit was clogged and had to be open using drills and warmed using gas. The tracker monitor battery was drained and had to be recharged. The rig had issues starting again. Those issues delayed the start of drilling till 10:30 a.m. (Figure 175–Figure 177).

Around 2:00 p.m., when 160 ft (48.8 m) of pilot drilling was completed, the return of fluid was lost, and the whole string of rods had to be retracted. The IDOT Inspector Jan Twardowski suggested that the top of the underlying sand layer which boring log B1 showed to be at 13 ft (4 m) depth might have been encountered at the location where the loss of return occurred. Pilot drilling started again after 3:00 p.m., and by the end of the day, 280 ft (85.3 m) was drilled, so the drill head was approximately under the north edge of the highway, at an approximate depth of 20 ft (6 m).

On January 16, 2019, the pilot drilling was resumed. When the drill bit reached the southern edge of the highway, its depth was around 19 ft (5.8 m). At that point, the exit point was estimated to be at station 91+96. Pilot drilling continued in the southern side, and another inadvertent return occurred 100 ft (30.5 m) before the point of exit. The drilling continued till the drill bit exited at the southern side at station 91+82 (Figure 178). With 380 ft (115.8 ft) drilled on this day, the total length of the bore summed up to 660 ft (201 m), which is significantly larger than the planned 500 ft (152.4 m).



Figure 164. Photo. Assembly of the fluid recycling system. The pipe feeds the fluid from the fluid system.



Figure 165. Photo. Assembly of the fluid recycling system. The pipe feeds the fluid from the fluid system into the rig.



Figure 166. Photo. Assembly of the fluid recycling system.
The used fluid is pumped back from the bore pit using the pump.



Figure 167. Photo. Delays were caused by rig starting issues.



Figure 168. Photo. The fluid pump in the bore pit.



Figure 169. Photo. The fluid pump being removed before being warmed using gas.



Figure 170. Photo. The drill bit about to start pilot drilling.



Figure 171. Photo. Tracking system used to track the location of the drill bit.



Figure 172. Photo. Traces of the inadvertent return that occurred after 40 ft (12.2 m) of pilot drilling. (1)



Figure 173. Photo. Traces of the inadvertent return that occurred after 40 ft of pilot drilling. (2)



Figure 174. Photo. The bore after the drilling rod was retracted.



Figure 175. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (1)



Figure 176. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (2)



Figure 177. Photo. Issues with the drill bit due to mud and low temperature, which caused work delays. (3)



Figure 178. Photo. Drill bit exiting at the southern side of the highway.

Reaming:

On January 16, 2019, after the completion of the pilot drilling, a swivel was added to the exit rod, and a wire rope was attached to the swivel, then extended to the excavator. A 20 in. (50.8 cm) reamer was installed at the bore pit (Figure 179–Figure 181). The wire rope is to be used to pull the drill pipe from the southern side, while the rig is advancing rotating the reamer from the northern side. Since the alignment has changed, approval from the owner (Nicor) was required, so reaming was not started on the same day.

On January 17, 2019, the reaming started. At the start of reaming, 33 drilling rods (each 20 ft [6.1 m] long) were south of the reamer, summing up to 660 ft (201 m), which is the length of the bore, and 11 rods were in the rack of the rig. After advancing the reamer 220 ft (67 m), hence using the 11 rods, the rig was supplied with another rack of rods containing 14 rods. The drilling was slow in the section ranging between 140 and 200 ft (146.7 and 61 m) south of the rig. Gravel, part of the sand layer, was assumed to be the cause of this slow advancement.

On January 18, 2019, the reaming continued from the 220 ft (67 m) reamed the day before and advanced another 220 ft (67 m). At that point, the reamer head was pulled back to the rig and was replaced by the 30 in. (76.2 cm) reamer. Switching from the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer, short of the exit, was done to keep the mud returning to the entrance of the bore where it can be recycled and avoiding a loss of return, as shown in Figure 182–Figure 185. The fluid return was excellent with a steady flow. No inadvertent return occurred. The 30 in. (76.2 cm) reamer was advanced 40 ft (12.2 m) by the end of the day.

On January 19, 2019, the reaming was continued, from the 40 ft (12.2 m) reamed the day before. After reaming an additional 120 ft (36.6 m), the drill started chattering, indicating a denser, possibly gravelly deposit, which is consistent with the slow advancement noticed at this point in the pilot drilling and first reaming passes. With an additional 20 ft (6.1 m) reamed, the total reamed section summed up to 180 ft (54.9 m).

On January 21, 2019, the rig broke down while attempting to resume reaming. Another rig was ordered to be mobilized from a site four hours away.

On January 22, 2019, the crew was working on clearing the broken rig. Freezing rain and snow precipitated all day which prevented the delivery of the replacement rig on this date.

On January 24, 2019, reaming resumed after the delivery of the replacement rig. The new rig cannot accept the rod racks of the old rig, so the drill rods were manually loaded to the new rig. An additional 160 ft (48.8 m) was reamed. The total reamed section summed up to 340 ft (103.6 m). On this day, the drilling company started working 12-hour shifts rather than 10-hour shifts. They kept the equipment running all night.

On January 25, 2019, despite having the equipment running all night, the pump froze because of the low temperature and had to be replaced. Reaming resumed at 10:00 a.m. The remaining 320 ft (97.5 m) was completed by 6:00 p.m. The reamer was then pulled back along the whole bore towards the rig, to make sure the bore was free of cuttings or any necking or restriction. The reamer was then removed from the bore pit.



Figure 179. Photo. The drilling rod connected to the swivel, which is connected to a wire rope.



Figure 180. Photo. The 20 in. (50.8 cm) reamer installed to the rod directly connected to the rig.



Figure 181. Photo. Drilling fluid ejected from nozzles of the reamer.



Figure 182. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (1)



Figure 183. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (2)



Figure 184. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (3)



Figure 185. Photo. Switching the 20 in. (50.8 cm) reamer to the 30 in. (76.2 cm) reamer. (4)

Pipe Pulling:

At 12:00 p.m. on January 26, 2019, the pipe pulling started. A 24 in. (61 cm) tri-cone roller reamer bit was connected to the drill rod ahead of the 20 in. (50.8 cm) pull head welded to the steel pipe via a swivel (Figure 186–Figure 188). Two excavators were used to elevate the sections of the pipe, which are to be pulled underground, hence decreasing the curvature of the pipe and thus reducing the resulting bending stresses (Figure 189). The drill rig broke down after pulling approximately 360 ft (109.7 m). The rig was then repaired, and the pulling was completed by 4:00 p.m. (Figure 190).



Figure 186. Photo. The pipe with the welded pull head.



Figure 187. Photo. The 24 in. tri-cone roller reamer which was used during pipe pulling.



Figure 188. Photo. The start of the pipe pulling. The photo shows the reamer connected to the pipe pull head via the swivel.



Figure 189. Photo. How the pipe was handled using excavators during its pulling.



Figure 190. Photo. The reamer and pull head in the bore pit after the pipe pulling was concluded.

Vacuuming:

A vacuum truck and four additional tanker trucks were used to remove and dispose of approximately 10000 gallons (37,854 Liters) of the drilling mud that was expelled from the exit pit. After pulling 300 ft (91.4 m), the drilling fluid started returning to the drill rig, where it was vacuumed out of the bore pit.

G.3.8 Performance Metrics

G.3.8.1 Surface Deformations

No survey measurements were taken during the project. Relying on visual inspection, no sign of heave or settlement above the pipe was observed on the ground surface, except in the areas where inadvertent return occurred during the pilot drilling.

G.3.8.2 Long-Term Measurements

Measurements should be taken to measure the long-term effects of drilling on the surface deformations. Mechanisms like loss of arching effects, consolidation, heave, softening of clays, etc., might contribute to deformations.

The long-term measurements for the Pecatonica HDD project are not available.

G.3.8.3 Pipe Testing

Gas pipes are usually tested for their fluid pressure retaining capacity to check for any cracks that might have been caused by the pipe pulling procedure.

The pipe testing data for the Pecatonica HDD project is not available.

G.3.8.4 Pipe Alignment

Not available.

G.3.9 Important Remarks and Conclusions

The installation of this gas pipe using HDD was accomplished in around two weeks despite all the delays and challenges encountered. The installation did not obstruct the traffic along the US-20, which greatly reduced the impact of the installation on society.

Based on the performance of this project, and the incidents that occurred during it, the following conclusions can be made:

- Low temperatures cause many difficulties for HDD operations. In this project, it resulted in equipment freezing and breakdown, delays, and negatively impacted the productivity of the crew. Rescheduling the HDD work is recommended when the temperature is extremely low.

- Equipment maintenance and cleaning before any HDD job can prevent a lot of delays and financial losses.

- Drilling at shallow depths increases the risks of impacting the ground surface. This was clear when two incidents of inadvertent return occurred when the drill bit was at relatively shallow depths. The fluid pressure should be controlled in those sections to avoid such occurrences. Since reducing the fluid pressure might increase the risk of bore clogging especially in long bores, pressure relief holes should be adopted. In this 660 ft (201 m) long bore, no pressure relief holes were used.

- The reaming system that was employed made it possible for the excavators to help in the reaming process, hence reducing the thrust demand on the rig. In addition, after the pilot drilling was completed, the drill string was always present across the whole length of the bore. This system has its advantages but requires many drill rods.

- The large working areas on the two sides of the job facilitated operations and reduced disruption to adjacent roads.

G.3.9.1 Notes on contract specifications

Not available.

G.3.10 References

Blagojevich, Rod, and Joel Brunsvold. 1998. *Sugar-Pecatonia Area Assessment*. Illinois Department of Natural Resources. Springfield, IL.

Kron, Nicole D. 2011. "Visualizing the Surficial and Subsurface Geology of the Pecatonica 7.5 Minute Quadrangle Winnebago County, Illinois." Illinois State University.

G.4 ELSAH CASE HISTORY

G.4.1 Project's Goal

In this project, a 24 in. (61 cm) welded steel coated and cathodically protected natural gas pipeline is to be installed under IL-100 (Figure 191) and the Mississippi River using HDD. This installation is one of two significant river crossings along this segment of the natural gas pipeline, the other involving the Missouri River. This report will focus on the Mississippi River crossing (Figure 192).



Figure 191. Photo. Road IL-100 (looking west) at the location of the planned crossing in July 2018.
Source: Google Maps

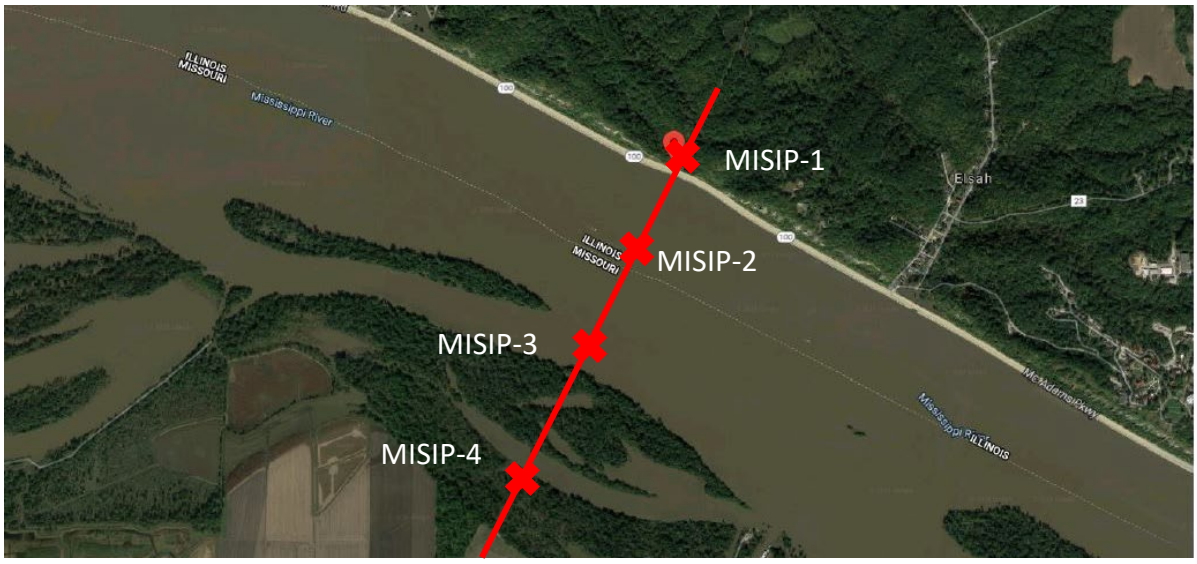


Figure 192. Photo. Google Maps capture showing planned alignment crossing the Mississippi River with the location of the boreholes.

Source: Google Maps

G.4.2 Location and Surroundings

The Illinois State Route 100 (IL-100) and Mississippi River crossing is located approximately 3400 ft (1036 m) west of Elsah, Illinois (Figure 193–Figure 195), east of Grafton, and its GPS coordinates are 38º 57’ 23.4” N 90º 22’ 28.2” W.



Figure 193. Photo. Google Maps capture showing Elsah project location on state levels.

Source: Google Maps



Figure 194. Photo. Google Maps capture showing Elsah project on county levels.

Source: Google Maps



Figure 195. Photo. Google Maps capture showing Elsah project on neighborhood levels.

Source: Google Maps

The proposed crossing is hundreds of feet away from the nearest buildings on the northern and southern sides of the crossing. Hence, the only structure in the State of Illinois that might be impacted by HDD construction is IL-100 and the utilities buried below it, if any.

G.4.3 Site Conditions

G.4.3.1 Soil Conditions

Mott MacDonald was retained by Spire Energy, the natural gas company, as part of the STL Pipeline project, to conduct a subsurface investigation program of the project area. The investigation program, as described in the geotechnical data report (GDR) submitted by Mott MacDonald, included 13 soil borings, five of which were located along the proposed Missouri River crossing, four along the proposed Mississippi River crossing, and four evenly spaced out between the crossing locations. Soil samples were recovered using a 2 in. (5 cm) outer-diameter split spoon sampler, driven continuously for the top 10 ft (3 m) of each boring, then in 5 ft (3 m) intervals thereafter. Upon split spoon or auger refusal, rock coring was performed in select borings to their proposed termination depths. Rock cores were retrieved with a double-barrel NQ2 series wireline setup. Rock core samples were measured for percent recovery and Rock Quality Designation (RQD)—a field measurement that signifies the degree of jointing or fracture in a rock mass.

The locations of the four borings/corings along the HDD alignment of the Mississippi River Crossing are presented in Figure 192, and the stratigraphy and RQD measurements derived from the obtained logs are summarized in Figure 196 and Figure 198. At the Mississippi Crossing location, groundwater was encountered in borings B-MISIP-1 and B-MISIP-4 at approximate depths of 16.5 and 11.5 ft (5 and 3.5 m), respectively. Many point load and unconfined compressive strength tests were performed on rock samples, and the results are summarized in Figure 196–Figure 201.

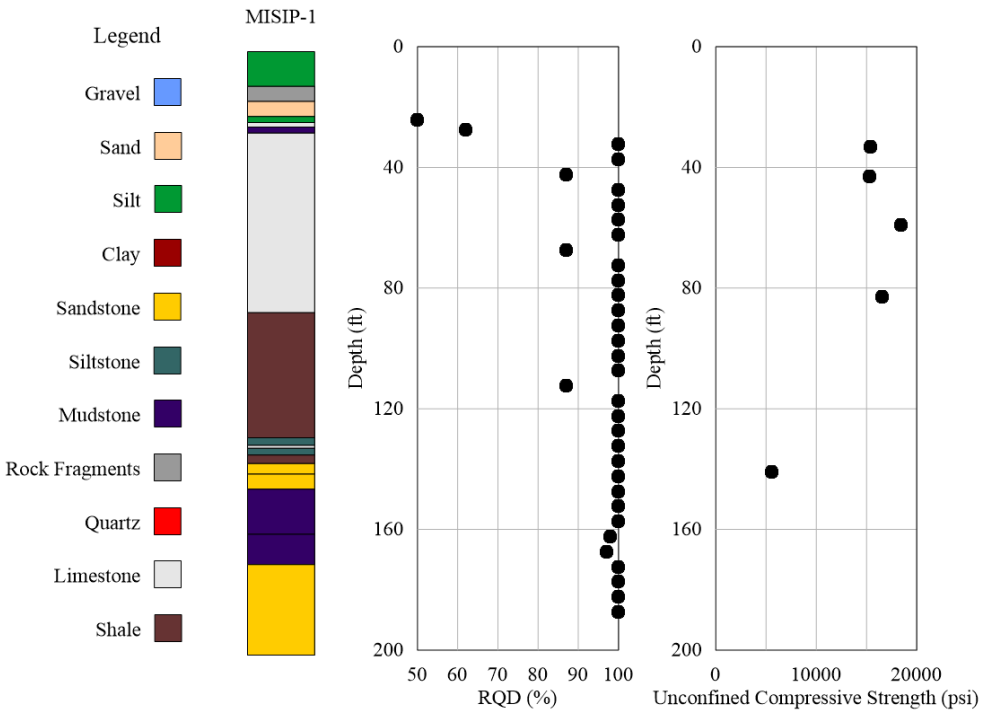


Figure 196. Chart. Stratigraphy and rock RQD derived from MISIP-1 borings.

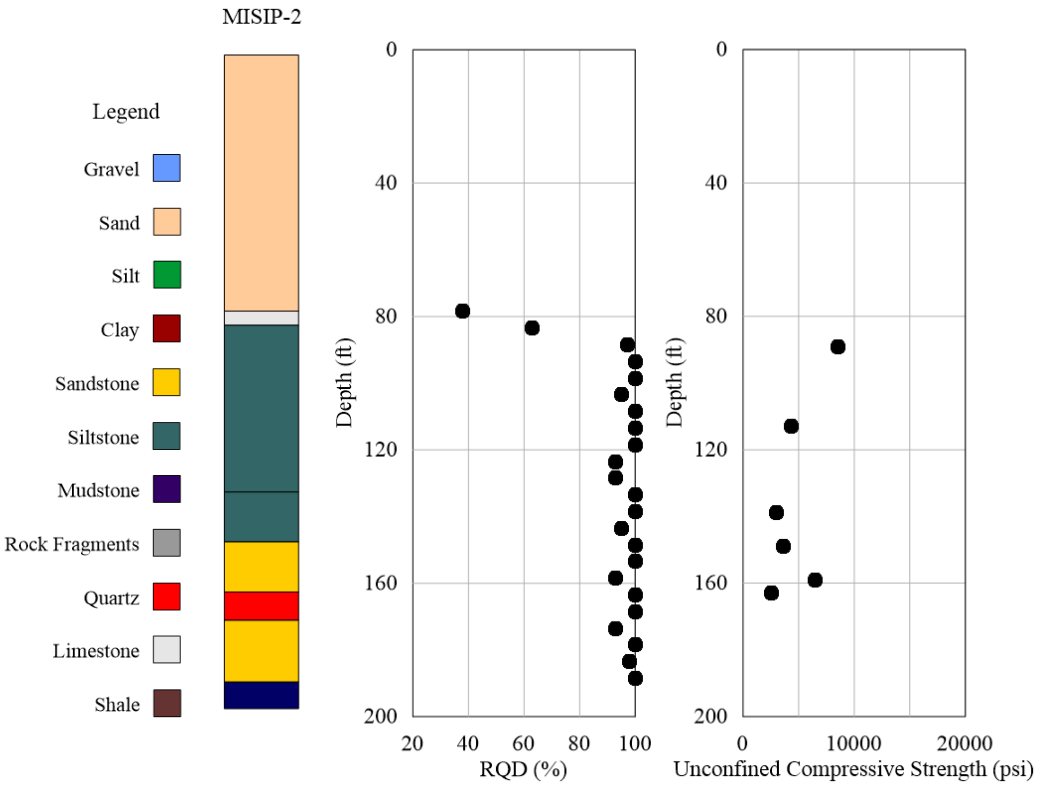


Figure 197. Chart. Stratigraphy and rock RQD derived from MISIP-2 borings.

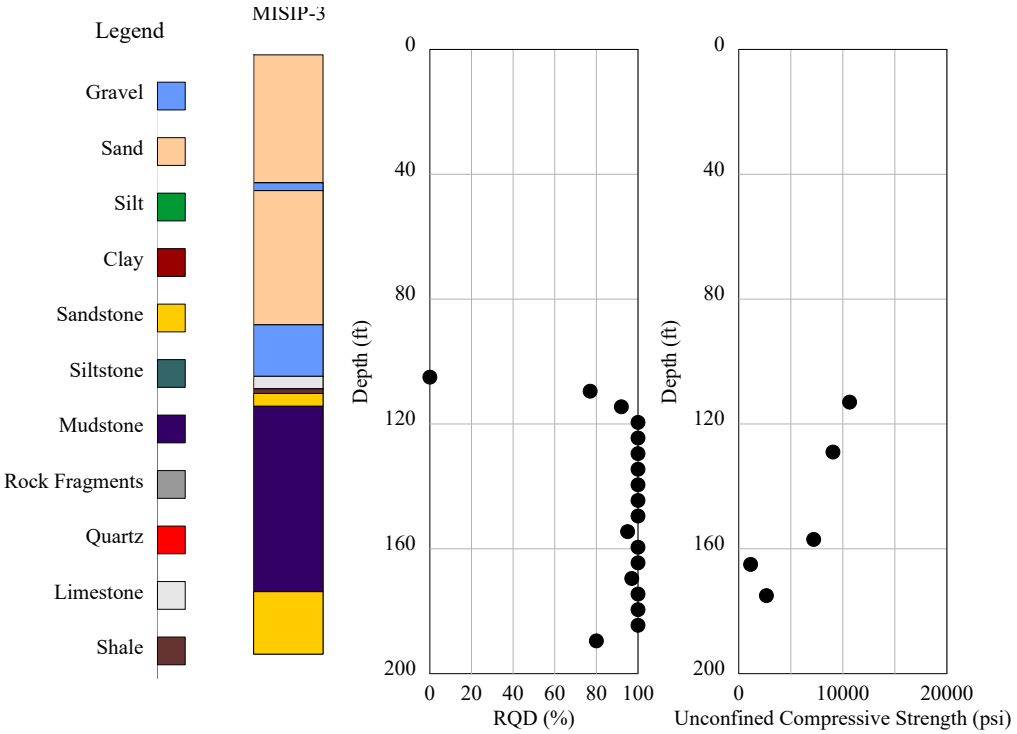


Figure 198. Chart. Stratigraphy and rock RQD derived from MISIP-3 borings.

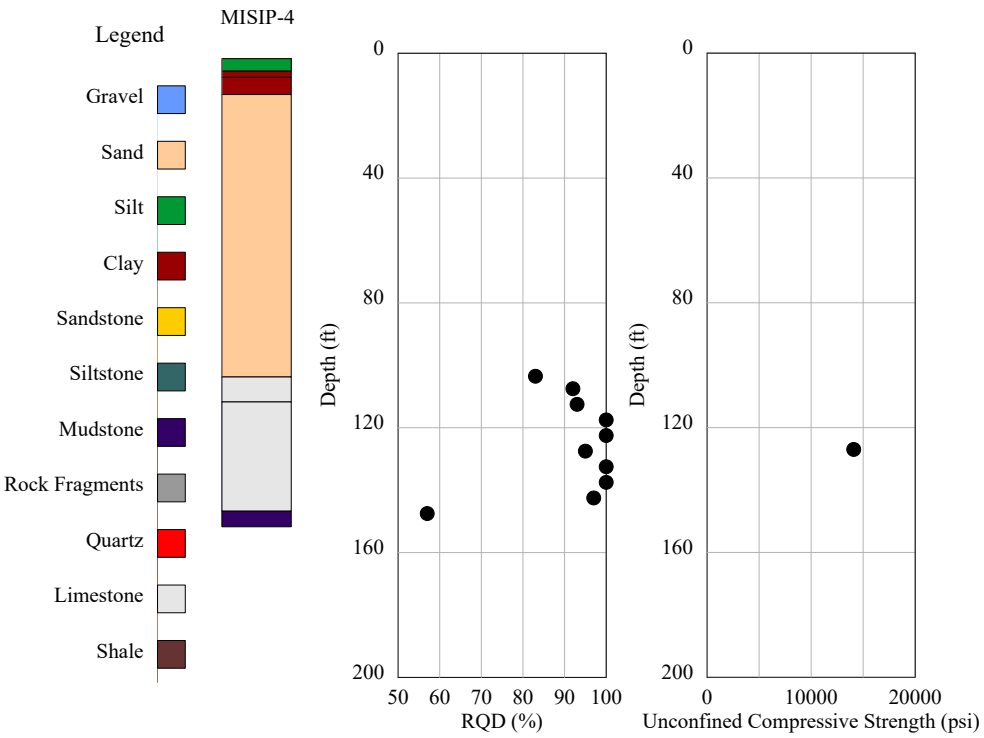


Figure 199. Chart. Stratigraphy and rock RQD derived from MISIP-4 borings.

The GDR states that the subsurface at the proposed crossing location consists of the following stratigraphic units:

- ***Silts/Clays (ML/CL):*** *This material was encountered at grade in B-MISIP-1 and B-MISIP-4 and extended down to roughly 11.5 feet (3.5 m) below ground surface (bgs). This low plasticity material ranged in consistency from soft to stiff with N-values between 3 and 10 blows per foot (bpf).*

- ***Sand (SP):*** *Very loose to dense Sand was found underlying the fine-grained material within B-MISIP- 1 and 4, and at mudline in B-MISIP-2 and 3. This Sand layer extended down to the top of bedrock in all of the Mississippi River Crossing borings with the exception of B-MISIP-3, which encountered a 16.5 foot (5 m) medium to very dense Gravel layer prior to striking bedrock. This Sand material was found to be consistent with that encountered within the Missouri River crossing bores.*

- ***Rock:*** *Bedrock material was observed to vary between each of the soil borings. Within the subsurface investigation, Mott MacDonald found many types of sedimentary rock to exist along the Mississippi River Crossing. Common rock classifications within these borings include Limestone, Mudstone, Sandstone, Shale, and Siltstone. These rock materials maintained very weak to very strong properties with fresh to high weathering. Typical recovery and RQD values ranged from 95 to 100% and 80 to 100%, respectively. Mott MacDonald notes that rock types and material properties largely varied by location within the Mississippi River Crossing, and the soil boring and rock core logs should be consulted for more accurate descriptions.* (GDR, 6)

G.4.3.2 Geology

Denny and Devera (2008) mapped the geology of the Elsah quadrangle. The geologic units identified are presented in Figure 200. The five top formations are described in (Denny and Devera 2008) as follows:

- ***Silt, clay, gravel, cobbles*** *Upland alluvial sediments composed of a mixture of sand, silt, clay, and gravel size particles. Most have been derived from the underlying bedrock, but some glacially derived gravels, cobbles of basalt, and small boulders of igneous and metamorphic rocks were observed in the uplands throughout the quadrangle. Small geodes filled with calcite and quartz derived from the Mississippian bedrock were observed in the western half of the quadrangle. Thicker sands, silts, and gravels of the Pleistocene and Holocene ages occur on the floodplain of the Mississippi River. These gravels are overlain by recent floodplain deposits of silt, sand, and clay. Additionally, outcrops of Pleistocene lakebed deposits composed of gray clay and silt with wood fragments were observed in some of the valleys at elevations near 450 feet (137 m) (Equality Formation). These lake deposits occur underneath terraces at approximately 470–480 feet (143 – 146 m) elevation along Piasa and Mill Creek valleys.*
- ***St. Louis Limestone*** *Limestone, chert, siltstone, and shale. The St. Louis Limestone is light gray to medium gray dense limestone and light gray to white wackestone, packstone, and oolitic limestone. The lighter-colored bioclastic units are coarsely fossiliferous and contain brachiopods, bryozoans, coelenterates, and echinoderms. The darker gray units are lime mudstone to wackestone, and portions may be dolomitic. The siltstone and shale are calcareous and dark gray to green-gray. Chert is dark gray and nodular. Subangular to angular limestone breccia fragments are present in portions of the lime mudstone. The brecciation may*

be a result of near surface dissolution of gypsum and anhydrite, which are known to be present in the unit. The contact with the underlying unit is unconformable.

- ***Salem Limestone*** *Limestone, dolomite, chert, siltstone, and shale. The Salem Limestone is light brown and gray mudstone to grainstone composed of rounded and broken fossil fragments. Bedding styles range from tabular to undulatory. The beds range from several inches to a few feet thick. Cross-beds are common and usually dip to the southwest. The unit is composed primarily of small rounded fragments of disarticulated echinoderms and fenestrate bryozoans that are abraded into a fossil hash. Other macrofossils are corals, brachiopods, and Pentremites. Peloidal to oolitic limestone is also present, and portions may be dolomitic. Chert is light gray, may be bioclastic, and may weather with a porous rind. Siltstone is brown to light gray and thinly bedded, typically less than 1 inch (2.54 cm) thick. The shale is blue-gray to green-gray. The foraminifera, Globoendothyra baileyi, is an index fossil for this unit. The contact with the underlying unit is unconformable but difficult to identify.*
- ***Warsaw Formation*** *Limestone, dolomite, mudstone, and siltstone. The Warsaw is medium gray and contains crinoids, brachiopods, and bryozoans. Archimedes is common and well preserved in some beds. Dolomite is gray-brown, is thinly bedded, and may contain glauconite and chlorite. Some of the thicker beds are dolomitic, while others are fairly pure limestones (packstone). The unit is dominantly shaley dolomitic limestone at the base and contains more limestone and dolomite in the upper half. The upper Warsaw is thicker bedded and contains crinoids, brachiopods, and bryozoans. The lower Warsaw is dominated by shales and siltstone with occasional thin dolomite beds. Mudstone is dark olive-brown and weathers to blue-gray. Mudstone occurs in beds as thick as 20 feet (6.1 m). Siltstone is calcareous, fossiliferous, and thinly bedded. The unit is characterized by small grains of rounded to subangular bioclastic limestone interbedded with thin shale partings. Disseminated pyrite and glauconite were observed in a few outcrops but were a very minor constituent. Geodes of calcite and quartz are common in the shale zones, particularly near the base of the formation. These geodes are excellent for collecting, and some reach diameters of over 8 inches (20.3 cm).*
- ***Burlington-Keokuk Limestones*** *Limestone, chert, siltstone, and shale. The Burlington-Keokuk Limestones are white to light gray and bioclastic to argilaceous. In places, the limestone is a light gray to white crinoidal grainstones interbedded with nodular to bedded light gray to black chert. The limestone weathers to light brown, is cross-bedded, and contains brachiopod and crinoid molds. Several well-preserved samples of the large spiriferid brachiopods were observed along with crinoids, bryozoans, and corals. The chert is usually light gray, but when weathered is white to buff with orange iron oxides on fractures. The weathered chert commonly contains bioclastic molds of crinoid stems, sponge spicules, and bryozoan debris. The chert is nodular and may coalesce along bedding planes to form beds up to 1-foot (0.3-m) thick. The unit is characterized by layers of light gray to white crinoidal grainstones with alternating beds of argillaceous limestone. This repetitive sequence of crinoidal limestone over argilaceous cross-bedded limestone was observed in the lower part of the unit. Siltstone and shale are dark gray with a greenish tint and are calcareous. Calcite- and quartz-filled round vugs from 0.5 to 2 inches (1.27 to 5 cm) in diameter were observed. The unit is conformable with the underlying unit.* (Denny and Devera 2008, 2)

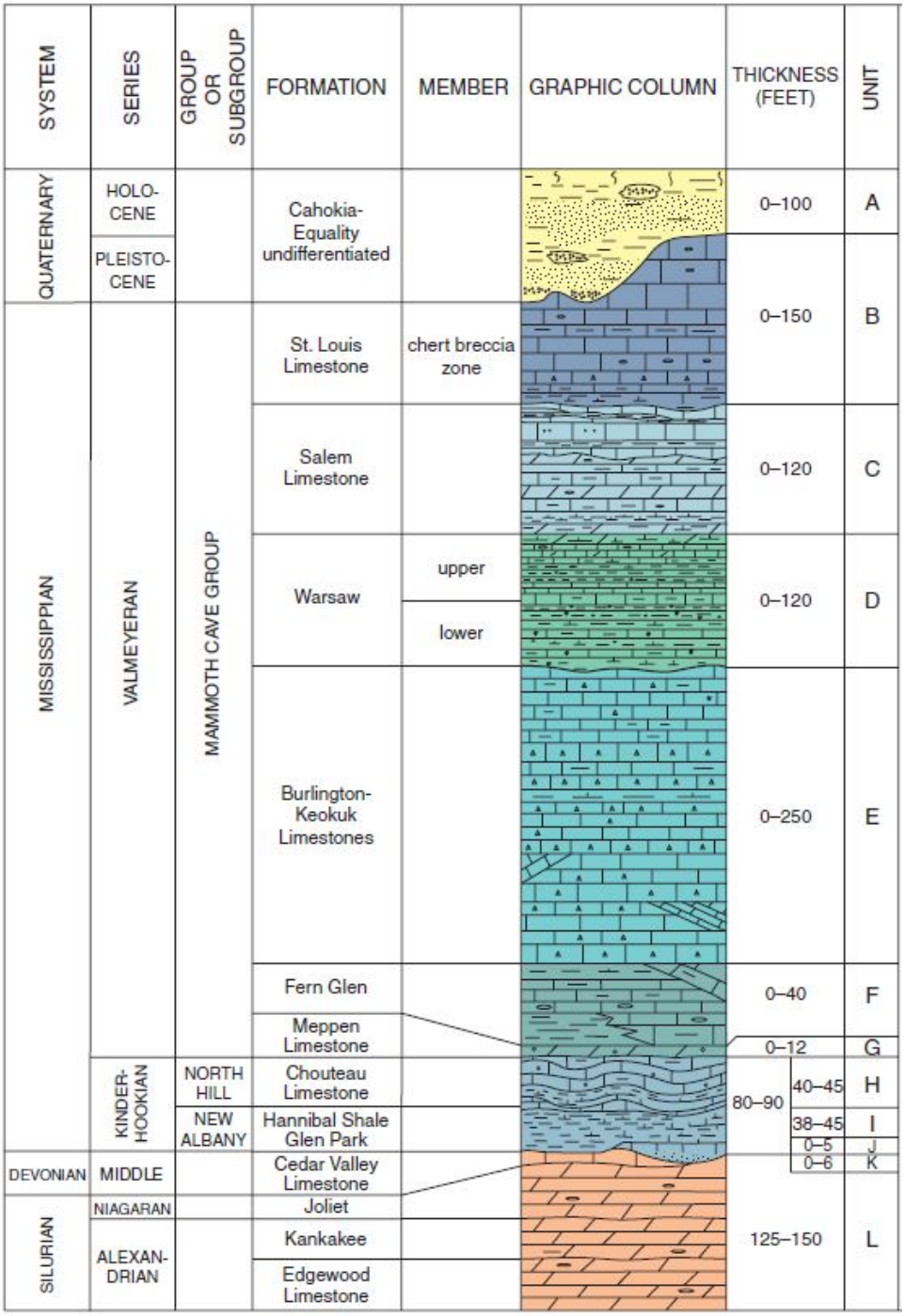


Figure 200. Table. Geologic units in Elsah quadrangle.

Source: Denny and Devera (2008)

G.4.4 Design

The crossing was first designed to pass 54 ft (16.5 m) below the centerline of IL-100 but was later modified, and the depth was increased to 127 ft (38.7 m). An existing pipeline that runs parallel with

IL-100 was located approximately 5 ft (1.5 m) below the pavement. The HDD installation will involve a reamed hole that is 1.5 times larger than the product pipe, i.e., the final diameter of the HDD borehole will be 36 in. (91.4 cm). The elevation profile of the planned alignment next to IL-100 is presented in Figure 201, and the full elevation profile is presented in Figure 202. The total projected length of the installation will be around 6250 ft (1905 m).

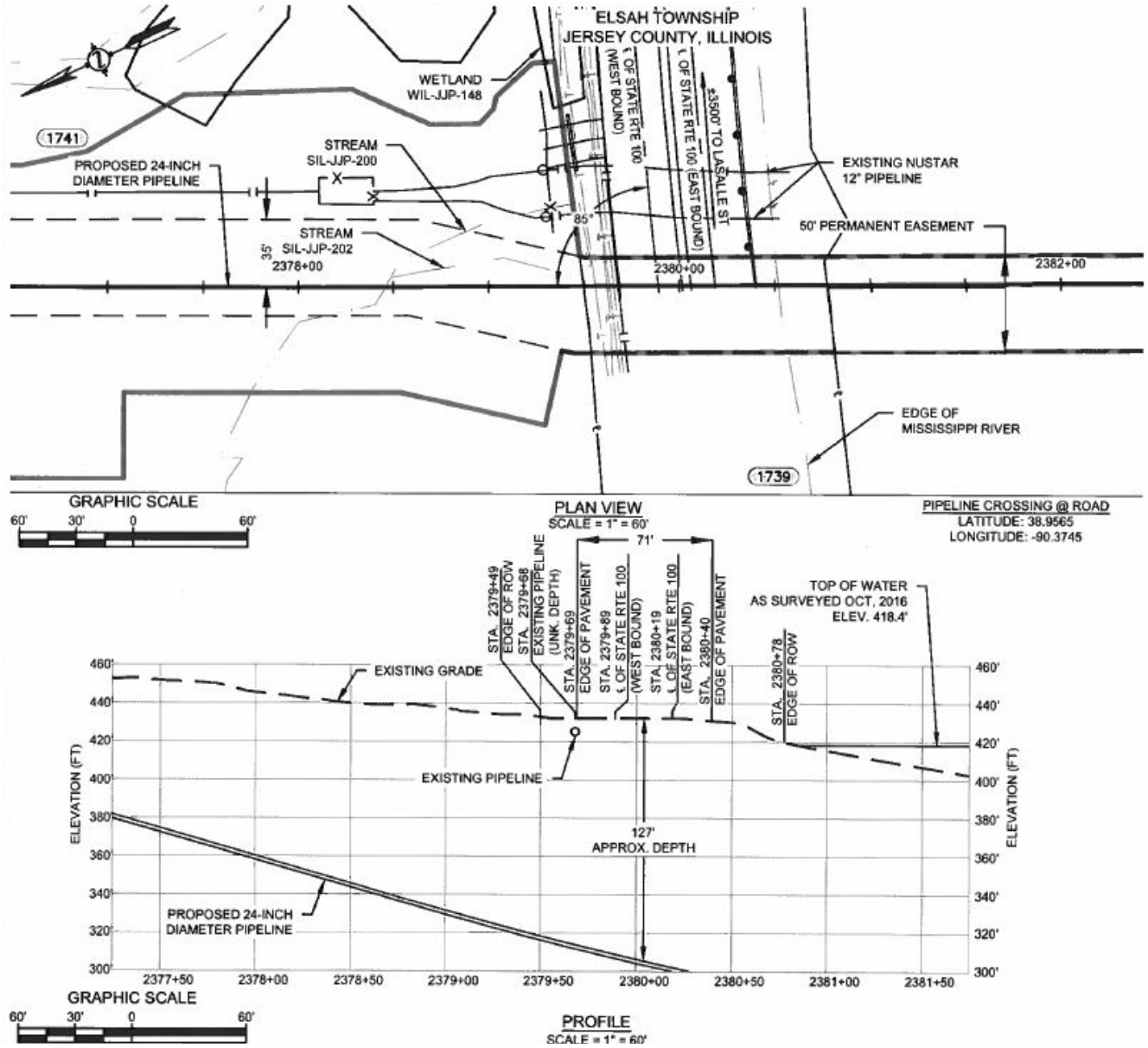


Figure 201. Graph. Part of the elevation profile of the planned alignment, showing its relative location with respect to the road.

Source: Permit Document

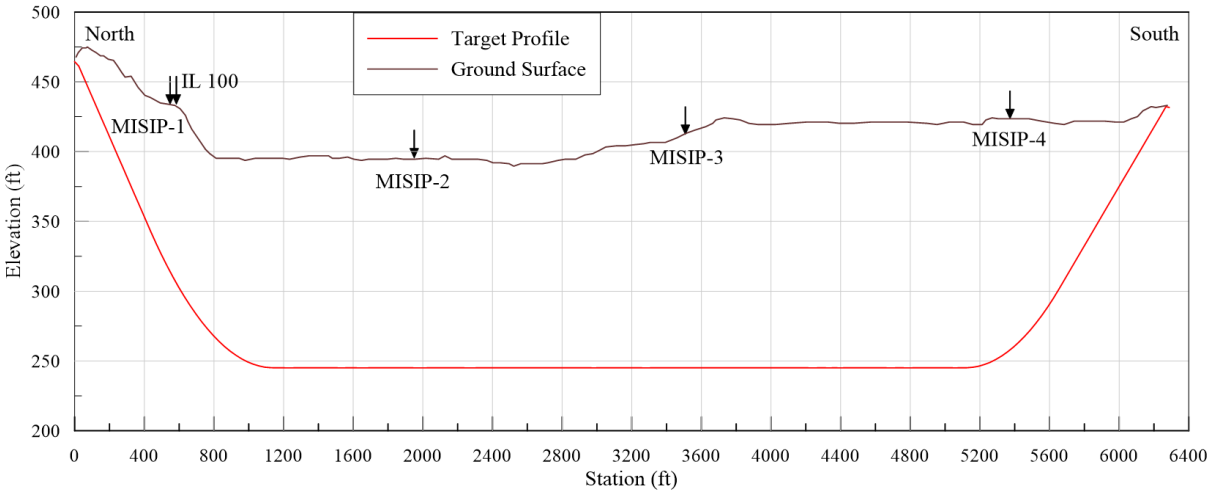


Figure 202. Chart. Full elevation profile of the planned alignment, showing the relative location of the boreholes with respect to the planned alignment.

Based on the planned depth and subsurface conditions, the confining capacity of the overlying soil and rock was calculated to evaluate the risk of inadvertent drilling fluid returns due to hydraulic fracture and to verify that the depth of the HDD design is sufficient. In general, longer and deeper crossings present a higher risk of inadvertent drilling fluid returns due to the annular pressure, which is the pressure that results due to drilling fluid in the annular space between the drill pipe and the wall of the hole that is being cut and is necessary to drill the pilot hole. To reduce the risk, the HDD intersect method was selected. In the intersect method, two HDD drilling rigs are used to complete the pilot hole, with each positioned on opposing sides of the crossing. Each rig drills a pilot hole along the designed path. The two pilot holes eventually meet. This method reduces the total length that the drilling fluid has to travel to transport the cuttings and hence reduces the required annular pressure. The decrease in annular pressure reduces the risk of hydraulic fracture and the potential for inadvertent drilling fluid returns. The estimated pressure using the intersect method in addition to the calculated failure pressure are presented in Figure 203.

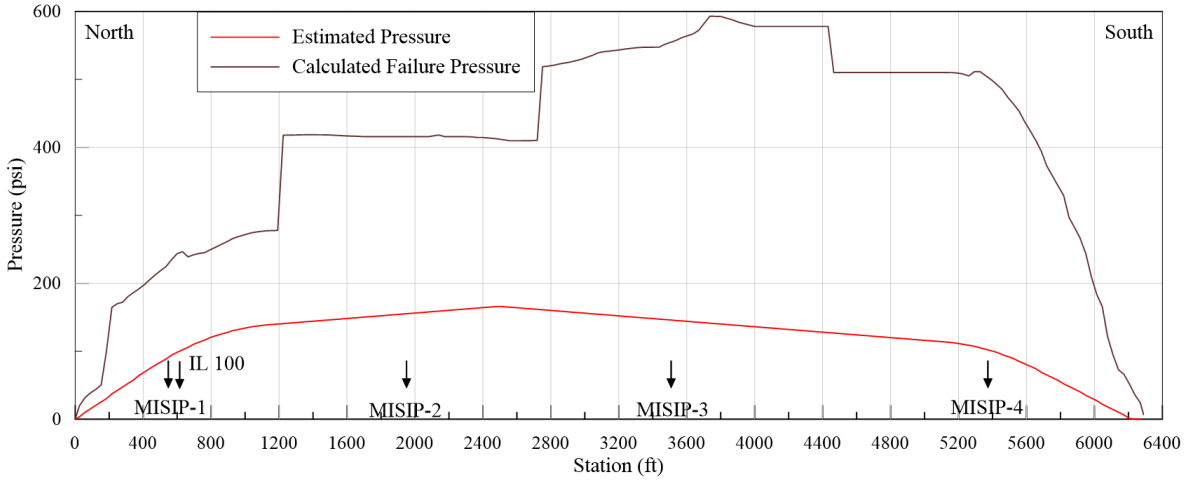


Figure 203. Chart. Calculated failure pressure and the estimated pressure using the intersect method.

Since problematic soils, which might cause boring instability and loss of fluid return, such as gravel and sand deposits, were found at the location of the entry and exit points, temporary steel conductor casings were suggested to stabilize those sections.

Table 12. Expected Timeline of the Elsah Project

Task	Number of Working Days	Date (all in 2019)
Mobilization of HDD Rig and Equipment	2	2/4–2/5
Pilot Boring and Reaming	83	2/6–5/31
Pipe Pulling	5	6/3–6/7
Completion of the HDD	1	6/10

G.4.5 Features and Foreseen Challenges

By studying this case's settings and design, many challenges can be foreseen, including the following:

- The length of this installation will require special care to avoid fracturing the overlying soil and rock strata. This results from the fact that cuttings must be transported thousands of feet during pilot hole drilling, which results in very high annular pressures. The large embedment depth selected for the HDD design will help in reducing the severity of this problem by increasing the confining capacity of the overburden material to accommodate the higher annular pressures. The use of the intersect method will also help in reducing the risk of hydro-fracture by reducing the annular pressure necessary to complete the pilot hole, which is normally the phase of HDD construction with the highest risk of hydraulic fracture. The existence of the river will not allow using pressure relief holes.

- The sand deposits, which extend more than 50 ft (15.2m), especially at the location of MISIP-4, have the potential to cause some technical difficulties instability, which sometimes results in "hole collapse", particularly during the larger reaming passes. Hole collapse closes off or plugs the annular space, which obstructs drilling fluid returns, resulting in annular pressure increases and/or loss of drilling fluid into the formation. To prevent this, temporary conductor casings will be installed to mitigate this risk.

G.4.6 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- Michels (www.michels.us), which is the HDD contractor.

- Spire Energy (www.spireenergy.com/), which is the owner of the gas line.

- Mott MacDonald (www.mottmac.com/), which carried out the soil investigation and prepared the soil report for Spire Energy.

- J. D. Hair Associates (www.jdhair.com/), which is the 3rd party engineer.
- Project Consulting Services (www.projectconsulting.com/), which is the consultant.

The main point of contact during this project was IDOT's Project Support Engineer and TRP member Rebecca Tharp (email: Rebecca.tharp@illinois.gov; phone: 618-346-3197), who was communicating with J. D. Hair Associates and Project Consulting Services.

On February 4, 2019, a preconstruction meeting was held with IDOT representatives (including Rebecca Tharp and Matthew Tebbe [Matthew.Tebbe@illinois.gov]), Project Consulting Services representatives Ben Tinnin (btinnin@projectconsulting.com) and Michael Franks (mfranks@projectconsulting.com), and the UIUC team. The Project Consulting Services representative provided some general information about the project and the method of construction that will be used. Rebecca Tharp met with J. D. Hair's vice president Jeffrey Scholl (JScholl@jdhair.com) over the phone, and Matthew Tebbe met him in person later. Jeffry Scholl later provided some technical presentations discussing HDD design.

After the project started, Russell English from Spire Energy started sharing daily progress reports prepared by J. D. Hair inspectors Dave Patonai, Kyle Wardlow, and Luke Bever. Reports available for this documentation start on February 18 (2 weeks after the beginning of construction activities) and end at the end of the project.

G.4.7 Execution

Because of the time required for this project, the documentation relied entirely on the progress reports, including photos, from J. D. Hair & Associates engineers Dave Patonai, Kyle Wardlow, and Luke Bever. Section G.4.7.2 is a synthesis and summary of those reports. Figures were prepared based on their collected data and calculations.

G.4.7.1 Settings

The construction activities for this project started on February 4, 2019, and ended on April 17, 2019. During this 2.5-month period, the average temperature fluctuated between around 10°F and 74°F (-12°C and 23°C). Snow and rain occurred frequently during this period. The temperature and precipitation records from the close-by St. Louis Lambert International Airport station are presented in Figure 204.

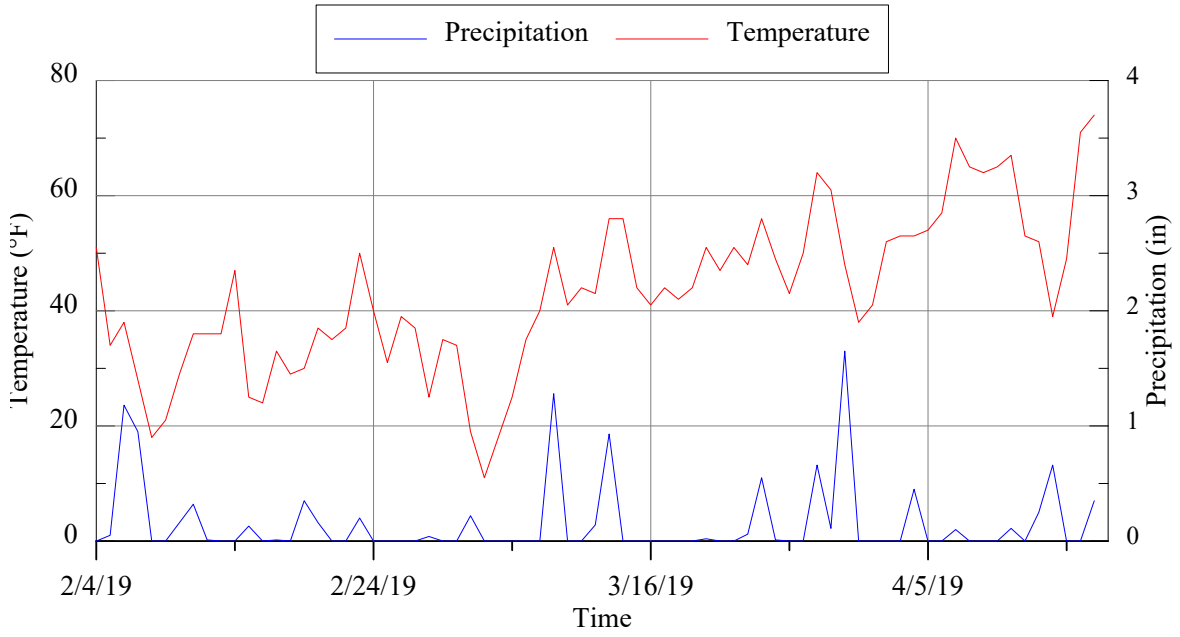


Figure 204. Chart. Temperature and precipitation in Elsah, Illinois.

Source: ***https://www.wunderground.com/***

G.4.7.2 Execution Metrics

Rigging Up, Casing Installation, and Pilot Drilling:

The first rig was mobilized to the southern end of the alignment on February 4, 2019.

Two hundred and thirty feet (70 m) of a 42 in. (106.7 cm) casing was installed by February 12, 2019. A longer, 14 in. (35.6 cm) casing was installed inside the 42 in. (106.7 cm) casing (Figure 205). Pilot boring then started. On February 15, 2019, pilot hole drilling was halted to advance the 14 in. (35.6 cm) casing to the rock interface. However, Michels made the decision to pull out the initial 14 in. (35.6 cm) casing from the hole and to add on a section with cutting teeth to help aid the casing further due to the smaller sizing of the pilot hole. By February 18, 2019, the length of the casing installed increased to 482 ft (147 m). The 14 in. (35.6 cm) casing reached the rock interface on February 19 and had a length of 515 ft (157 m).

The first 482 ft (147 m) of pilot drilling was completed by February 15, 2019, using the jetting assembly. After the 14 in. (35.6 cm) casing reached the rock interface on February 19, 2019, the jetting assembly was tripped out (Figure 206). The jetting assembly (Figure 207) was replaced by a mud motor assembly that converts hydraulic energy from the drilling fluid to mechanical energy at the drill bit. This allows for the bit to rotate without drill string rotating, aiding in quicker joint times and ease of guiding the drill bit along the designed path. The new bottom hole assembly (Figure 208–Figure 209) included a new 12.25 in. (31 cm) tricone drill bit with tungsten carbide inserts (TCI), shock sub (to reduce the vibration to the gyro steering tool), monel, and mud motor with 2.1-degree angular bend.

On February 20, 2019, drilling operations ran steadily throughout the morning averaging 35–45 minutes per joint (each 33 ft [10 m] long). They did experience minor downtime to deal with a hydraulic line on the DD-440 drill rig as well as the stops roughly every 2 hours to “north seek” the gyro (12 minutes per north seek). Till the end of the day, the total length of the pilot bore increased to 914 ft (278.6 m). No inadvertent releases or loss of drilling fluid returns were noted. A good flow of drilling fluid returns could be observed flowing back to their containment pit (Figure 210).

On February 21, 2019, four more joints were added until 10 a.m. when the mud system’s shaker motor drilling was halted to perform repairs. The drilling resumed around 2:30 p.m. and finished one more joint by the end of the day.

On February 22, 2019, it was reported from the driller that the average time per joint was just over one hour, and the drilling fluid pumping rate was averaging around 780 gpm (2950 L/min). During this day, eight more joints were added, increasing the pilot bore length to 1346 ft (410 m).

On February 23, 2019, it was reported from the surveyor that the average time per joint was 40 to 50 minutes. By the end of the day, the pilot bore length increased to 1642 ft (500.5 m). Cuttings can be observed falling from the shakers (Figure 211) and centrifuge (Figure 212). Cuttings were being loaded into dump trucks for disposal (Figure 213).

On February 25, 2019, it was reported from the onsite inspector that the average time per joint was 35 to 45 minutes. By the end of the day, the pilot bore length increased to 1875 ft (571.5 m). The northern end workspace was being prepared for the arrival of the second rig.

On February 26, 2019, it was reported from the surveyor that the average time per joint was 45 minutes. By the end of the day, the pilot bore length increased to 2174 ft (662.6 m).

On February 27, 2019, the downhole surveyor, an employee of Brownline, subcontracted by Michel to provide pilot hole navigation and tracking, discovered that they lost connection with the gyro steering tool. Due to the possible wireline break, Michels tripped the bit to the drill rig and found the wireline break near the gyro steering tool, then tripped back 27 joints into the boring (around 900 ft [274.3 m]).

On February 28, 2019, tripping back into the boring was continued till the bottom of the hole, which was encountered at 2:20 p.m. Ninety-nine more feet (30.2 m) were drilled after that.

On March 1, 2019, the average time per joint was observed to be 30 to 50 minutes. Following the drilling of each joint, the driller was swabbing the joints multiple times to help flush the cutting back to the containment pit. It was reported from the surveyor that the driller was having a slight difficulty trying to steer the bit down. This was concerning because the upper limits of the elevation tolerance were being approached. During the second half of the shift, steerability improved, and the bit began to steer a little deeper. By the end of the day, the pilot bore length increased to 2,605 ft (794 m).

On March 2, 2019, the average time per joint was observed to be 30 to 40 minutes. After installing eight more joints (around 260 ft [79.2 m]), the electronic connection to the bottom hole assembly

was lost. Six joints had to be tripped back to make a limited fix, and the connection was recovered. However, after resuming drilling, the connection was lost again, and it was decided to trip back the bottom hole assembly to the drill rig.

On March 4, 2019, the link to the gyro, part of the bottom hole assembly used for steering, was reestablished after all the bottom hole assembly was tripped back to the drill rig, and the wireline was fixed. For the remainder of the day, the bottom hole assembly was being tripped back into the boring averaging approximately 6 minutes per joint. Fifty-three joints were tripped back by the end of the day.

On March 5, 2019, tripping back into the boring was continued till the bottom of the hole, which was encountered at 1:30 p.m. Shortly after, at 1:50 p.m., drilling fluid circulation was lost, and Michels swabbed the joint to help clear any debris that may have been obstructing the bore. After once more swabbing the joint, drilling fluid was again observed flowing from the casing at the containment pit. The driller estimated that they were receiving 70% returns. After adding one more joint, the frac tank onsite was empty, and a load of water would have to be trucked in before drilling could continue. The water truck arrived at the site at 4:00 p.m., and no additional drilling was done this day.

On March 6, 2019, drilling continued, and the average time per joint was observed to be 25 minutes. Drilling fluid returns were approximated to be at about 90%. The pump rate was consistently around 720 gpm (2,725.5 L/min) while drilling. Around noon, a water truck arrived at the site to refill water levels in the frac tank. This would be the first of three loads of water delivered to the site that day to replenish the drilling fluid lost to the formation while drilling. In the afternoon, drilling time per joint slightly increased to roughly 30-40 minutes. Michels was using Cetco Super Gel-X bentonite as the only drilling fluid additive. Around 390 ft (103 m) of pilot hole drilling was completed throughout this day.

On March 7, 2019, although a strong flow of drilling fluid could be seen exiting the casing at the containment pit, the driller estimated that they were still losing approximately 10% to 20% of the drilling fluid pumped downhole. A water truck continually made trips into the site every couple of hours in order to replenish the drilling fluid levels. Drilling time per joint ranged from 30 to 45 minutes in the morning. Due to the length of the HDD and the diminished returns, the driller increased hole cleaning efforts by spending more time swabbing and circulating drilling fluid in between drilling each joint. After installing six joints, the driller swabbed the bore for 15 minutes to get cuttings moving back to the exit point. Most of the cuttings returning from the bore are being filtered out as sand-sized particles. As drilling continued into the afternoon and early evening, drilling time per joint decreased to an average of 20 minutes. Around 390 ft (103 m) of pilot hole drilling was completed throughout this day.

On March 8, 2019, drilling fluid returns were approximated to be fluctuating between 80% and 90%. In between each joint, the driller would swab multiple times to promote drilling fluid flow and help clean the bore. The driller noted that the formation had been deflecting the bit downward during the latter half of the shift on the day before and while drilling this morning. Throughout the afternoon, the driller and steer hand were able to counter the formation with an upward steering bias to level out the drilled path and start the bit back up in elevation towards the designed path. Around 390 ft

(103 m) of pilot hole drilling was completed throughout this day, bringing the total pilot hole length to approximately 4,135 ft (1092.4 m).

On March 9, 2019, no drilling was performed due to thunderstorms.

On March 11, 2019, the average time per joint was observed to be around 20 minutes. Drilling fluid returns were approximated to be fluctuating between 80% and 90%. At the northern end workspace, a survey crew was finishing up and moving out equipment preparing for mobilizing the second rig. A large 42 in. (107 cm) conductor casing was staged onsite to be installed prior to the start of drilling. Around 459 ft (140 m) of pilot hole drilling was completed throughout this day, bringing the total pilot hole length to approximately 4,594 ft (1400 m).

On March 12, 2019, after drilling in half the length of a joint, progress was halted due to a crack developing in the anchor plate in front of the rig. This issue was causing difficulty in steering. The steer hand was having a hard time deflecting the bit through the second horizontal curve section of the designed path because the crack in the anchor plate was allowing too much movement in the rig while drilling. The Michels crew stopped drilling to weld a small brace between the I-beam attached to the 42 in. (107 cm) casing and the anchor plate. Drilling continued at around 1:00 p.m. After adding three more joints, the drilling stopped again due to the same issue as before. This time crew members were welding a larger brace (Figure 214) between the I-beam and the anchor plate. At the north entry site, a small crew was busy digging a pit into the gravel at the designed entry point (Figure 215). The plan was to install 42 in. (107 cm) surface casing (Figure 216) at the entry point as deep as the excavator could clear out the rock and gravel. A majority of the HDD equipment, including the rig, had already been staged onsite in preparation for rig up. There were still a few trailers of equipment at the southern site that would be transported over to the northern site before rig up would begin. Around 200 ft (61 m) of pilot hole drilling was completed throughout this day.

On March 13, 2019, the average time per joint was observed to be around 20 minutes. Drilling fluid returns were around 85%. When the length of the pilot hole reached 5,087 ft (1,550 m) (154 joints), it was decided to stop pilot drilling from the southern side. At this point, the bit was estimated to be approximately 10 ft (3 m) below the designed path and 0.17 ft (0.05 m) to the left. The driller started tripping out the drill bit towards the rig in order to install the radar system for the intersection. The tripping continued at a rate of one joint per minute. Meanwhile, trucks made trips from the southern site to the northern site transporting additional equipment required for rig up, including the drillcab and power unit. At 3:30 p.m., the last joint was removed from the rig, and the bottom hole assembly was set aside on a trailer. The crew then worked on making up the new bottom hole assembly to be used for the pilot hole intersection. The BHA consisted of a monel, radar tool, and bit. The withdrawn drill bit showed signs of wear on the outer edges but was in overall good condition with the cones firmly in place (Figure 217).

On March 14, 2019, the preparations for starting the pilot drilling from the northern end continued. All of the necessary HDD equipment was staged at the north entry, and the crew worked that day to arrange the site and hook up equipment. A pit was excavated at the entry point and a 42 in. (107 cm) casing was buried. The casing extends approximately 51.4 ft (15.7 m) from the ground surface and a 14 in. (35.6 cm) centralizer casing was placed inside of the 42 in. (107 cm) casing (Figure 218). This is

short of the planned 213 ft (65 m) of surface casing noted in Michels drill plan; however, the casing was being driven into the bedrock. The dead-man, which consists of an 8 ft (2.4 m) by 20 ft (6.1 m) steel plate, was buried vertically in front of the rig. By the end of the shift, Michels had all of the equipment in place and the power unit connected to the rig (Figure 219–Figure 221).

On March 15, 2019, the rig up on the north side of the crossing continued in the morning. The back of the rig was elevated to achieve a 16-degree angle (Figure 222). Water trucks were in and out of the site all day in order to fill the frac tanks onsite (Figure 223). Generators were fueled, and the power unit was connected to the rig and drill cab. A survey crew arrived onsite to survey the position and elevation of the entry point. The side boom crane, track hoe, and excess equipment used for rig up were loaded up and transported from the site. I-beams were welded to the dead-man and attached to the 42 in. (107 cm) surface casing close to the end of the shift.

On March 16, 2019, rig up commenced at the entry site in the morning as welders continued to install I-beams between the dead-man and the 42 in. (107 cm) surface casing in front of the rig (Figure 224). Water trucks made multiple trips in and out of the site to continue to fill frac tanks. Racks were placed next to the rig, and drill pipe was loaded onto the racks (Figure 225). Containment was built around and underneath the rig using tarp and sandbags. By late afternoon, the rig was up and running. At around 5:00 p.m., the bottom hole assembly consisting of a 12.25 in. (31 cm) bit, shock sub, and mud motor (Figure 226) was loaded onto the rig and pushed down into the casing (Figure 227).

On March 18, 2019, add bolts were added through the I-beam in order to support the welds on each side. Then, the bit was pushed down, and drilling started just after 10:30 a.m. The driller started pumping drilling fluid at around 700 gpm (2650 L/min). No drilling fluid was observed exiting the casing at the entry point while drilling. It takes approximately 3,700 gallons (14,000 L) of drilling fluid to fill the empty 42 in. (107 cm) and 14 in. (35.6 cm) sections of casing. A crew member was able to look down into the 42 in. (107 cm) casing and see the level of drilling fluid slowly rising, although with a pump rate of 700 gpm (2650 L/min), the casing should theoretically be filled and flowing out into the containment pit in under 6 minutes. Drilling was halted so that the crew member at the hopper could catch up on mixing drilling fluid. After drilling the second joint into the ground, there was still no drilling fluid return exiting the casing, and the drilling was halted. The crew monitored the alignment and closely walked the east edge of the workspace looking down into the creek for any signs of surficial drilling fluid. If an inadvertent return were to occur at this point it was likely that it would flow out into the low valley to the east of the workspace. No signs of surficial drilling fluid were observed. The bit was tripped back to the drill rig, and hay bales and full bags of bentonite were pushed into the casing to be utilized as lost circulation material (Figure 228) and were then packed in with the bit. This process was repeated a few times before starting the trip back to the bottom of the bore. After pushing down the first joint the driller started the pump, drilling fluid started to flow from the 14 in. (35.6 cm) casing intermittently and was enough to fill the containment pit in front of the rig. Hay started to return also with the fluid (Figure 229). The second joint was added, and the bit reached the cutting face and started drilling. Flow from the 14 in. (35.6 cm) casing stopped, and, with no returns the final third, the second joint was completed. The runoff creek to the east was closely monitored while drilling, and, again, no signs of inadvertent drilling fluid returns were observed. After

completing the second joint, Michels again started the trip back out of the bore. The bit emerged from the casing a few minutes after 5:00 p.m., and Michels shut down the site for the day.

On March 19, 2019, the 14 in. (35.6 cm) centralizer casing had been removed from the 42 in. (107 cm) casing. The bottom hole assembly was removed, and an 18 in. (45.7 cm) reamer was attached instead. The plan was to move forward with the 18 in. (45.7 cm) reamer approximately 60 ft (18.3 m) past the 42 in. (107 cm) casing and install 14 in. (35.6 cm) casing into the reamed hole. The deeper 14 in. (35.6 cm) casing should seal off the porous zone near the surface where gravel had been used to bury the 42 in. (107-cm) casing because it looked like the drilling fluid was being lost at the end of the 42 in. (107 cm) casing. The AMC GEL drilling fluid additive, which is a high yield bentonite that aids in fluid loss, was used to mix drilling fluid. While reaming, a pool of drilling fluid surfaced on the HDD alignment directly above where the 42 in. (107 cm) casing ended. This inadvertent return was contained using sandbags so that it would not spread and affect other areas of the site (Figure 230), and the low-lying creek to the east was heavily monitored throughout the shift. The plan for the next day was for the bottom hole assembly to be tripped back in with the gyro to survey the position of the reamed hole before installing the 14 in. (35.6 cm) casing deeper into the bedrock.

On March 20, 2019, it was reported from the onsite inspector that the drilling fluid was largely returning, although the inadvertent return was still occurring at the same location. Four joints of pilot hole drilling were added throughout this day, bringing the total pilot hole length from the northern side to approximately 191 ft (58.2 m).

On March 21, 2019, the average time per joint was observed to be around 30 minutes, which includes the time for swabbing. A prominent flow of drilling fluid returns was observed flowing from the 14 in. (35.6 cm) casing (Figure 231). The contractor reported that both the previous inadvertent return location and the 42 in. (107 cm) casing were receiving some extent of flow as well. The inadvertent return had spread over a larger area compared with the day before (Figure 232 and Figure 233). Although flow to the inadvertent return location was small, additional sandbags were added around the area as a precaution. Measured annular pressures were well below estimated failure pressures. By the end of the day, the length of the northern section of the pilot bore increased to 555 ft (169.16 m). Cuttings were observed accumulating in the fluid recycling system dump areas after being separated via vibratory scalper shakers (Figure 234) and hydrocyclones (Figure 235).

On March 22, 2019, around 390 ft (118.9 m) of pilot hole drilling was completed throughout this day, making the northern bore less than 350 ft (106.7 m) away from the southern bore.

On March 23, 2019, the average time per joint was observed to be around 30 minutes. Some drilling fluid was still flowing to the surface at the previous inadvertent return location. By late afternoon, the northern pilot hole was advanced to the vicinity of the existing south bore. Utilizing passive magnetic ranging (PMR), the north pilot hole was revealed to be roughly 1 ft (0.3 m) above and 3 ft (1 m) left of the south pilot hole. Upon establishing where in proximity the two pilot holes were to one another, the north pilot hole was advanced forward as the south pilot hole was retracted. Periodically, ranging surveys were conducted to gauge the degree of offset from one drill string to the other and to assess what corrections were to be made. By the end of the day, the pilot holes were overlapped by

approximately 3-4 joints. The plan was to continue to advance the northern pilot hole forward attempting to intersect the existing south borehole.

On March 25, 2019, a wireline break within the northern pilot hole occurred before any drilling took place. The bit was tripped to the rig to fix the wireline. By the end of the day, the bottom hole assembly was tripped back to the bottom of the hole.

On March 26, 2019, the contractor began advancing the north pilot hole forward while attempting to correct the known offset. Advancement was heavily steering-oriented. Steering efforts were unable to produce the desired deviation leftwards. Due to proximity to the crossing's horizontal curve, the leftward movement was necessary as a function of forward advancement. A PMR survey was done to establish what, if any, progress had been made on the prior completed joints. Unsatisfied with steering performance, the contractor decided to trip back shortly after 10:00 a.m. Once the bottom hole assembly was returned to the surface, two adjustments were made: the drill bit was exchanged for a new TCI tri-cone bit, and the bent sub was increased to an angle of approximately 2.7 degrees. It was discovered that the gyro was malfunctioning as it failed the calibration/roll test. A new gyro had to be mobilized.

On March 27, 2019, after the new gyro steering tool and probe housing arrived at the site and was calibrated and installed in the bottom hole assembly, the assembly was tripped back to the bottom of the hole at a rate of 6 to 8 minutes per joint. At the southern site, the respective drill string was being retracted, and PMR surveys were taken often. By the end of the shift, five new joints were installed advancing the northern pilot hole to a new distance to date of 1,647ft (502 m). Despite chasing the southern pilot hole into the crossing's horizontal curve, the final PMR survey taken this evening revealed that the separation between the two bores was closing.

On March 28, 2019, the intersection of the northern and southern pilot bores occurred after tripping down the first 10 ft (3 m) of one additional joint. Following confirmation of the intersection, the contractor sized the area and began advancing both drill strings to the north. Upon reaching the northern end, the bottom hole assemblies were removed and set aside. The north drill rig was then connected to the southern drill string, establishing a continuous segment of drill pipe from end point to end point. The plan was to remove the 14 in. (35.6 cm) casing at the southern side to enable the initial reaming pass which would be conducted using a 36 in. (91.4 cm) reamer in a south to north direction.

Throughout the pilot drilling, measurements were taken to log the actual drilled profile and compare it to the planned profile. This guided the pilot drilling steering and helped in keeping deviations within the allowable tolerances. By the end of pilot drilling, the actual drilled profile was calculated from the measurements taken and compared to the planned profile as presented in Figure 236. The deviations from the actual profile and their evolution in time are presented in Figure 237 and Figure 238.

In addition, throughout the pilot drilling, the annular pressure was measured and compared to the estimated pressure and the calculated failure pressure. By the end of pilot drilling, the fluid pressure comparison was completed and is presented in Figure 239.



Figure 205. Photo. The 42 in. (106.7 cm) casing housing the 14 in. (35.6 cm) casing in which the drill pipe is inserted.



Figure 206. Photo. The rig tripping the jetting assembly before replacing it with the mud motor assembly.



Figure 207. Photo. The jetting assembly which was used for pilot drilling in soil.



Figure 208. Photo. The first section of the new tri-cone bit, bottom hole assembly, and mud motor being inserted into the 14 in. (35.6 cm) casing.



Figure 209. Photo. The second section of the bottom hole assembly showing the shock sub and gyro housing.



Figure 210. Photo. Good flow returning to the southern pit.



Figure 211. Photo. Course cuttings falling from the shakers.



Figure 212. Photo. Fine cuttings falling from the centrifuge.



Figure 213. Photo. Dump truck being loaded with cuttings.



Figure 214. Photo. The large brace that was welded to the I-beam and the anchor plate.



Figure 215. Photo. The excavating pit at north entry point for the 42 in. (106.7 cm) casing (photo facing north).



Figure 216. Photo. Part of the 42 in. (106.7 cm) casing at north entry point (photo facing north).



Figure 217. Photo. Withdrawn drill bit showing it in good condition.



Figure 218. Photo. The installed 42 in. (106.7 cm) casing and 14 in. (35.6 cm) casing at north entry point (centralizer).



Figure 219. Photo. The HDD setup including the rig and the fluid system at north entry point.



Figure 220. Photo. The fluid mixing and recycling system at north entry point.



Figure 221. Photo. Pallets of the drilling fluid additive Super Gel-X Bentonite at north entry point.



Figure 222. Photo. The rig set to a 16° angle.



Figure 223. Photo. A water truck filling the frac tanks.



Figure 224. Photo. I-beams being welded to the dead-man and 42 in. (107-cm) casing.



Figure 225. Photo. Joints being racked next to the rig.



Figure 226. Photo. The bottom hole assembly consisting of the drill bit, shock sub, and mud motor.



Figure 227. Photo. The bottom hole assembly being loaded on the rig.



Figure 228. Photo. Hay bales and bags of bentonite being pushed in the 14 in. (36 cm) casing.



Figure 229. Photo. Hay returning from the shaker.



Figure 230. Photo. The inadvertent return being contained using sand bags.



Figure 231. Photo. A "good" drilling fluid return flowing out of the 14 in. (35.6 cm) casing, indicating very little fluid loss into the geologic formation.



Figure 232. Photo. Inadvertent return spreading over a larger area compared with the previous day.



Figure 233. Photo. Location of the inadvertent return relative to site.



Figure 234. Photo. Rock cuttings after being separated by vibratory scalper shakers on the drilling fluid cleaning and recycling system.



Figure 235. Photo. Fine cuttings after being separated by hydrocyclones (de-sander left and de-silter right).

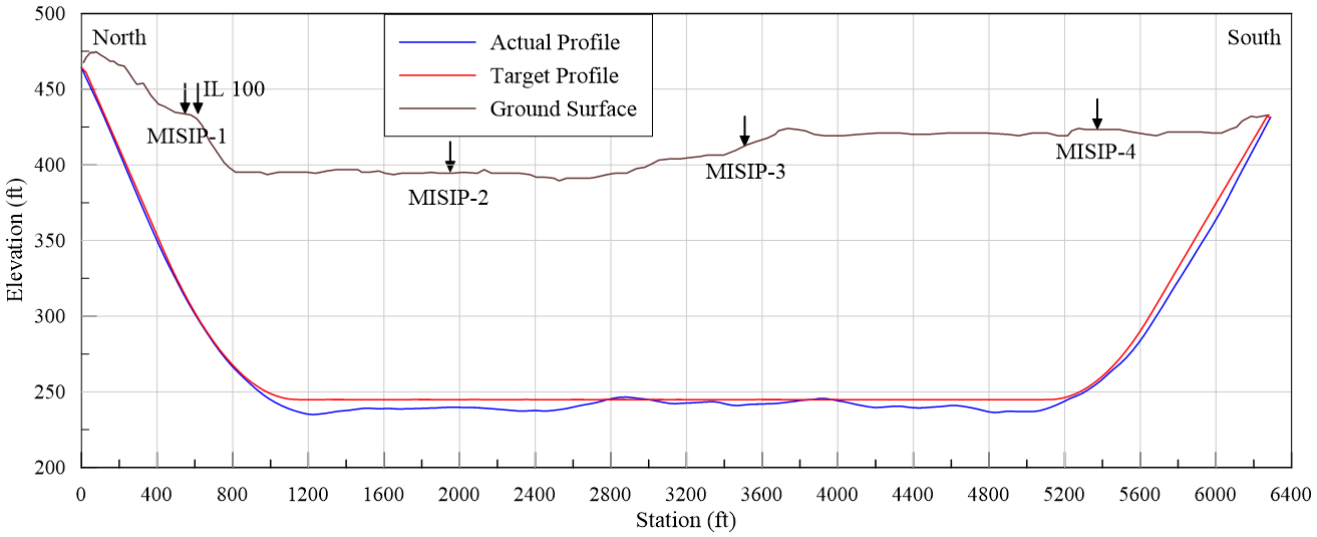


Figure 236. Chart. Actual profile vs planned profile.

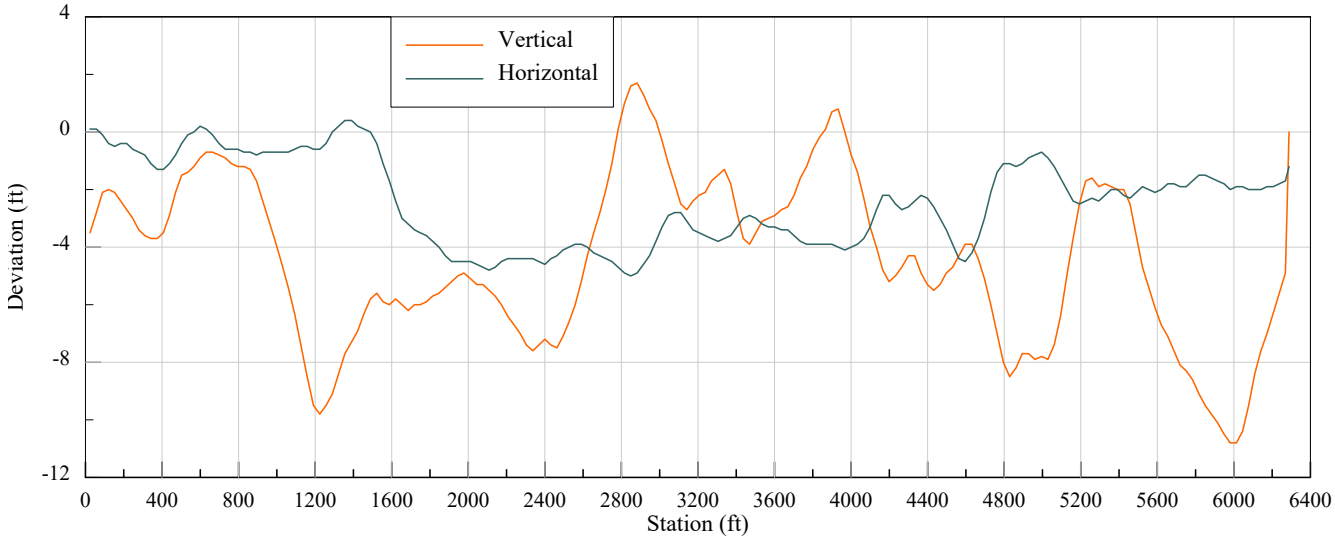


Figure 237. Chart. Vertical and horizontal deviation along the profile.

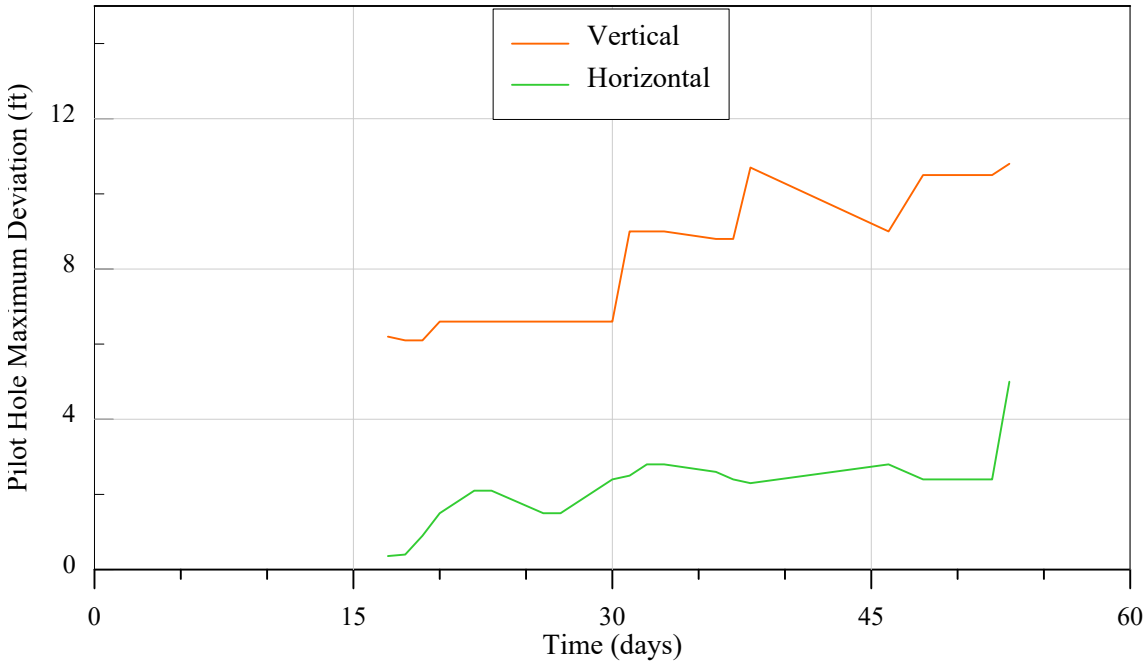


Figure 238. Chart. Evolution of the pilot hole maximum vertical and horizontal deviations over the time of pilot drilling. Data before day 17 is not available.

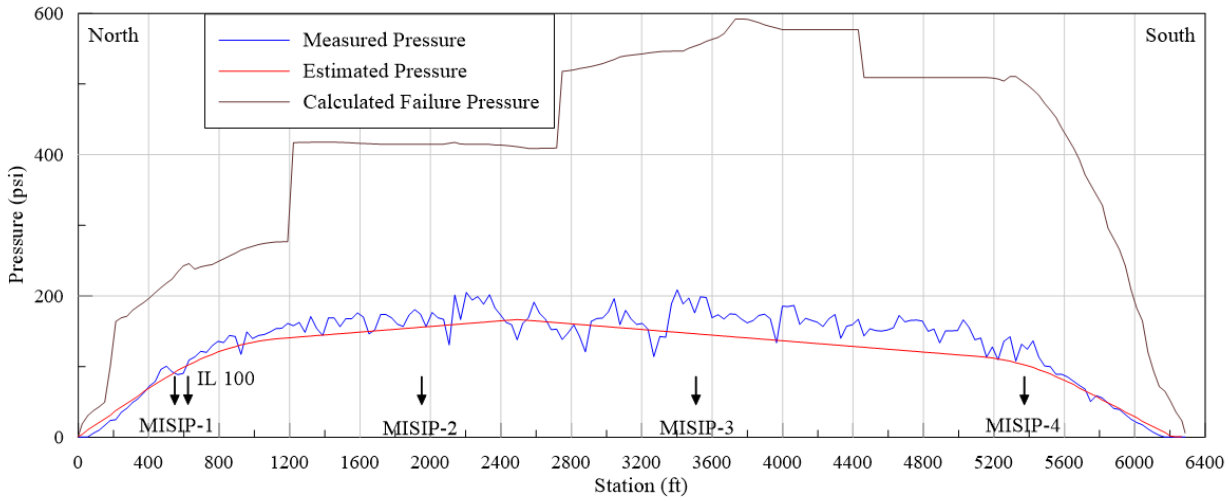


Figure 239. Chart. Measured pressure vs estimated pressure and calculated failure pressure.

Reaming:

On March 29, 2019, the 14 in. (35.6 cm) casing on the southern ends was removed. Reaming, using the 36 in. (91.4 cm) reamer, was initiated from the south, and completed 12 joints by the end of the day. Reaming was anticipated to continue the following day and to slow considerably upon reaching bedrock.

On March 30, 2019, reaming continued until 3:00 p.m., when it was stopped due to bad weather. The total length reamed by the end of the day increased to 621 ft (190 m).

On April 1, 2019, the construction schedule was adjusted to a 24-hour schedule (nonstop). The average time per joint was around 2 hours and 30 minutes. The total length reamed was increased by 7:00 p.m. to 751 ft (229 m).

On April 2, 2019, the total length reamed increased to 1013 ft (314 m) by the end of the day. No loss of drilling fluid was reported.

On April 3, 2019, the total length reamed increased to 1079 ft (329 m) by the end of the day. Delays were caused by equipment maintenance and repair.

On April 4, 2019, the total length reamed increased to 1706 ft (520 m) by the end of the day. No issue regarding drilling fluid circulation was reported.

On April 5, 2019, the average time per joint was around 45 minutes. The total length reamed increased to 2385 ft (727 m) by the end of the day.

On April 6, 2019, the total length reamed increased to 3101 ft (945 m) by the end of the day.

On April 7, 2019, the average time per joint was around 30 to 40 minutes. The drilling fluid pumping rate was averaging around 900 gpm (3400 L/min). Mud circulation continues to flow back in good amounts through the 42 in. (107 cm) surface casing. With the strong returns, good amounts of rock cuttings were observed falling from the drilling fluid recycling system into the collection bins. The total length reamed increased to 4093 ft (1247 m) by the end of the day.

On April 9, 2019, the total length reamed increased to 4765 ft (1452 m) by the end of the day.

On April 10, 2019, the total length reamed increased to 5565 ft (1969 m) by the end of the day. The drilling fluid returns are being reported to be flowing to both entry and exit locations, and, as a result, the contractor began pumping drilling fluid from both drill rigs as needed to keep the 800–900 gallons (3000–3400 L) per minute flow.

On April 11, 2019, the average time per joint decreased to around 2 hours as the reamer transitioned into what is believed to be a clay-like stratum.

On April 12, 2019, the average time per joint was around 1.5 hours. After reaming about 6240 ft (189 joints, 1902 m), the contractor began pulling the 14 in. (35.6 cm) centralizer casing at the north end using the excavator and help from the drill rig. The centralizer section was pulled out roughly 30 feet (9 m) at a time and cut up into smaller segments to remove it from the hole. Around 10:30 a.m., reaming operations resumed. After another hour of reaming, completing two additional joints, the driller felt the 36 in. (91.4 cm) hole opener against the 42 in. (107 cm) surface casing. Both drillers worked together in attempts to climb the reamer into the casing. Unfortunately, the hole opener appeared to catch the edge of the casing and would not enter inside. At 11:50 a.m., the contractor made the decision to add in one 40 ft (12.2 m) section of casing with “centralizer wings” to help centralize or lift the drill sting and reamer in efforts to get the hole opener into the casing. Around 1:30 p.m. reaming was completed, as presented in Figure 240.



Figure 240. Photo. Reamer arriving at the drilling rig on the northern side after completing reaming.

Swabbing

On April 12, 2019, after the first reaming pass was completed, the reamer was removed then turned around to be used for the first swab pass, as presented in Figure 241. By the end of the day, 18 joints were added.

On April 13, 2019, the first swab was completed around 1:15 p.m. with the 36 in. (91.4 cm) hole opener arriving at the south side drill rig. It was reported from the northern side superintendent that the fluid returns continued to flow over to the northern side containment pit through joint 103 (3,400 ft [1,036 m], approximately), at which time the circulations began flowing primarily to the south side location. The reamer was removed then turned around to be used for the second swab pass. Swabbing rates averaged 5 to 6 minutes per joint. The north side driller mentioned they were getting lots of cuttings during both swab passes. By the end of the day shift, 51 joints (1,680 ft [512 m], approximately) were installed.

On April 14, 2019, the second swabbing pass was completed before 10 a.m.



Figure 241. Photo. The reamer turned around to start the first swabbing pass.

Pipe Pulling:

The plan was to pull the first segment of product pipe roughly 700 ft (213 m) downhole, to within bedrock, before conducting welding operations. Pullback operations following the weld are anticipated to take upwards of 14 hours.

On April 15, 2019, 653 ft (199 m) of product pipe was pulled, and in doing so, the pull section was advanced to within bedrock.

On April 16, 2019, the second pull section was advanced and positioned for welding operations; then at 2:00 p.m., the pullback was resumed. Breakout tensile forces required to initiate movement of pipe were reportedly on the order of 200,000 lbs (90,718 kg). No major issues were encountered. Drilling fluid returns were observed present and exclusive to the exit pit. Pullback continued into the late afternoon hours at a rate of approximately 4-5 minutes per joint (Figure 242). Fluid returns would slowly transition northwards. Near the end of the day shift, fluid returns were readily apparent at the entry site. Pulling loads by this point in time had risen to approximately 330,000 lbs (149,685-158,757 kg). Torque readings, as they have been for the vast majority of pullback, remained negligible, suggesting that no obstructions were interacting with the pullback assembly downhole. It is worth noting that the second segment of product pipe was plumbed for buoyancy control. However, the contractor noted that ballast water would not be introduced unless pulling loads warranted.

On April 17, 2019, the pullback was completed around 4:30 a.m. (Figure 243). It was reported from the contractor that pullback during the night shift progressed smoothly until its ultimate completion. Pulling loads during the night were around 300,000-350,000 lbs (136,077-158,757 kg). Buoyancy

control measures were not implemented to the pull section as loads reportedly did not warrant such efforts.



Figure 242. Photo. The 24 in. (61 cm) pipe being pulled into the 42 in. (106.7 cm) casing.



Figure 243. Photo. The pull head after completion of the pullback.

Pipe Handling:

During pullback, the pipe was supported at different points using multiple side booms as presented in Figure 244.



Figure 244. Photo. Handling of the pipe while being pulled into the hole.

Pipe Examination:

The pull section was exposed at the entry site, although only a limited amount of coating was visible for examination. Due to the presence of surface casing, only approximately 8-10 ft (2.4–3 m) of product pipe was readily visible (not including the length of the pull head). The leading edge of the pull section looked to be in good condition. Some amounts of scratches and scuffs were evident but nothing that can be characterized as unusual for a crossing installed through rock, especially one of this length (Figure 245).



Figure 245. Photo. Light scratches of the pipe coating.

Timeline Summary:

Based on the daily update reports, the timeline of this project was summarized. The duration of each activity and the number of feet installed every day are presented in Figure 246.

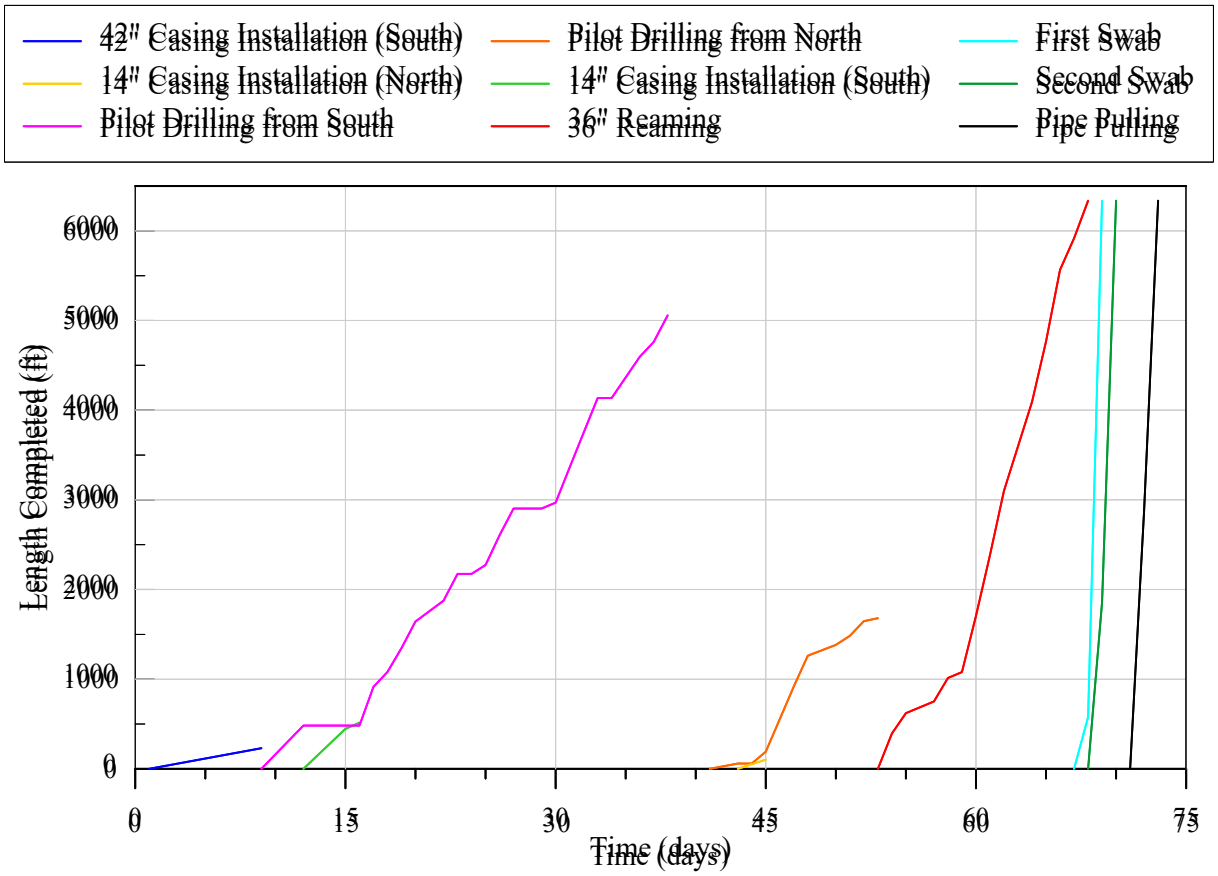


Figure 246. Chart. Timeline of the project, showing the duration of each activity.

G.4.8 Performance Metrics

The project performance can be evaluated by considering surface deformations, pipe performance, pipe profile, fluid pressures used, and the schedule.

G.4.8.1 Surface Deformation

A surveying crew from IDOT District 8 took an initial survey of the surface of IL-100 on January 29, 2019, before the beginning of construction. Blasting on the northern side of the project, estimated to be 600 ft (182.88 m) away from IL-100 to clear a pad required for the equipment. It was planned to have 14 consecutive blasts, one per day. Because of this blasting, another survey was taken on March 11, 2019, before pilot drilling. The latter set of measurements is taken as the baseline. After pilot drilling (on March 28, 2019), another set of measurements was taken. Around three months after the end of construction (on July 8, 2019), another set of measurements was taken. The surface deformations are plotted and presented in Figure 247 and Figure 248. The plots show deformations less than 0.5 in. (1.27 cm) after both stages. Because of the random patterns of deformation, it is very likely that those measured deformations are measurement errors rather than real deformations.

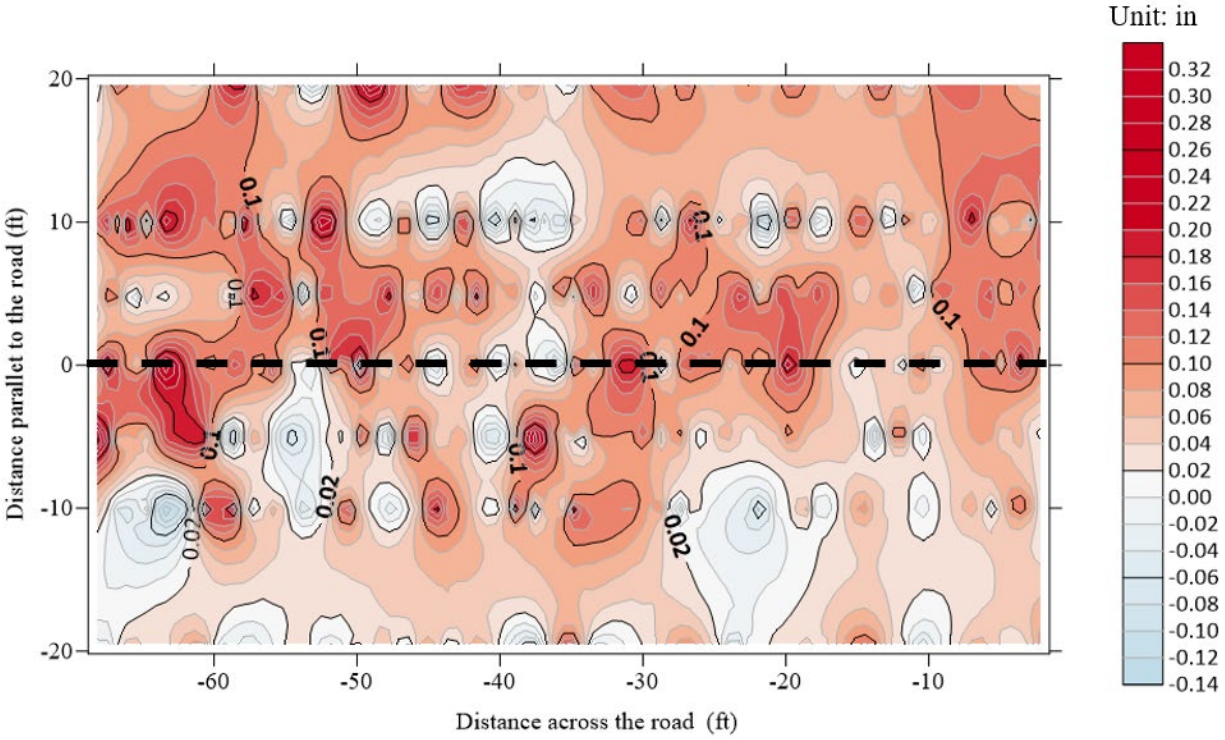


Figure 247. Graph. Surface deformation after pilot drilling. Dashed lines mark the boring alignment. Positive is heave.

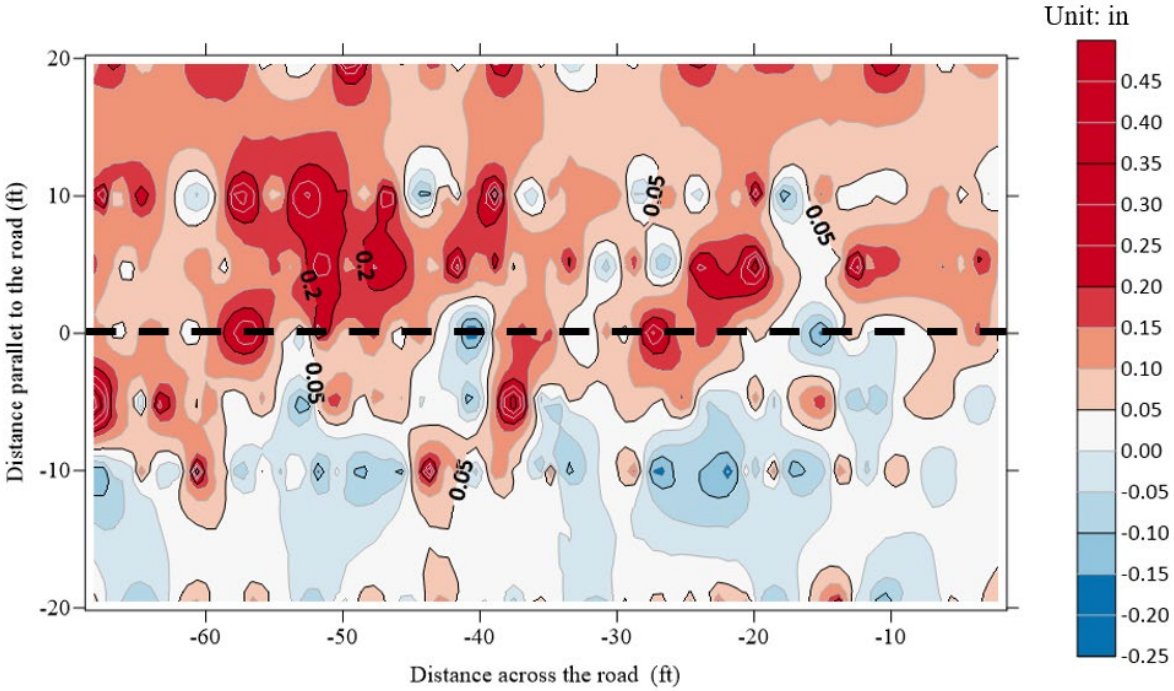


Figure 248. Graph. Surface deformation after the end of construction. Dashed lines mark the boring alignment. Positive is heave.

G.4.8.2 Long-Term Measurements

Around two years after the end of construction on December 29, 2020, another set of measurements was taken. The surface deformations are plotted and presented in Figure 249. The plots show deformations less than 0.4 in. (1 cm) from the long-term measurement. Because of the random patterns of deformation, it is very likely that those measured deformations are measurement errors rather than real deformations.

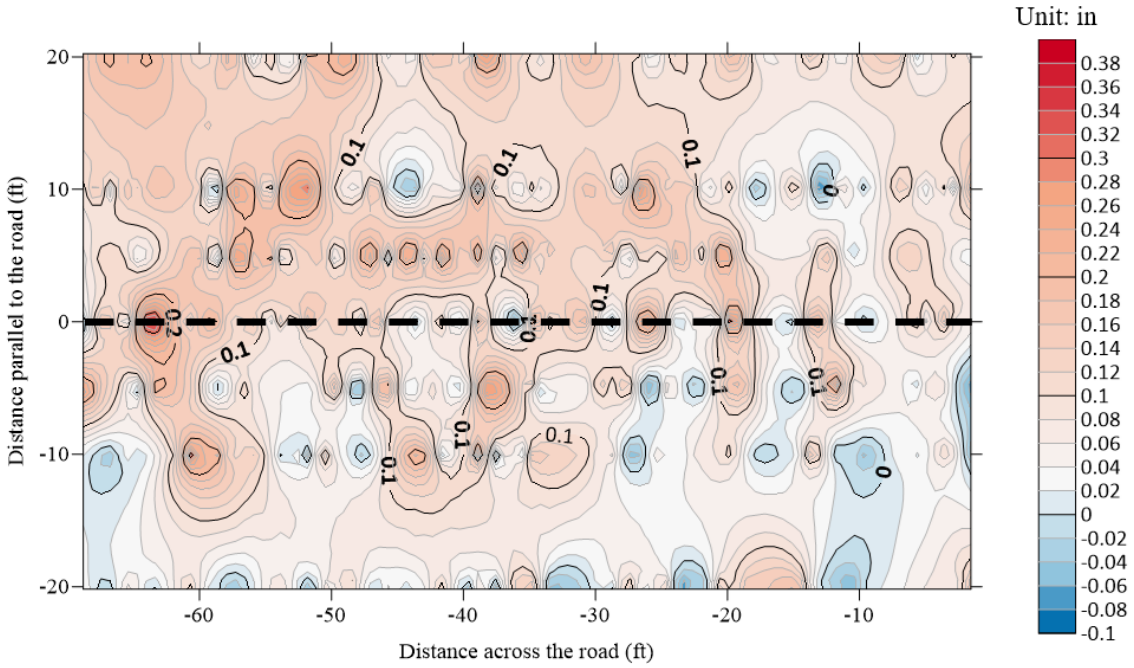


Figure 249. Graph. Surface deformation around two years after the end of construction. Dashed lines mark the boring alignment. Positive is heave.

G.4.8.3 Pipe Performance

The initial inspection of the coating of the pipe was done by J. D. Hair & Associates engineers. For gas lines, pipes are usually tested under pressure after they are installed to determine any possible leakage indicative of defects in the pipe or damage resulting from the installation.

G.4.8.4 Pipe Profile

The actual profile of the pilot bore and its deviations from the planned profile were presented in Figure 236 through Figure 238. The maximum deviations were less than the tolerances determined as vertically: 3 ft (0.9 m) above or 20 ft (6.1 m) below the planned profile and horizontally: 10 ft (3 m) right or left of the planned profile. The maximum horizontal deviations were about 4 ft (1.2 m), while the maximum vertical deviation slightly exceeded 10 ft (3 m) downward of the planned profile.

G.4.8.5 Fluid Pressures

The fluid pressures measured and presented in Figure 239 were comparable with the estimated pressures for most of the profile. On the southern half of the profile, the measured pressures were

typically 20% to 30% (up to 44%) higher than the estimated pressures. The measured pressures were, however, well below the calculated failure pressures for most of the profile. An exception to this might be the inadvertent return that was observed on the first 200 ft (61 m) of the northern side where the cover is relatively thin.

G.4.8.6 Schedule

The HDD installation was completed on April 17, around two months before the estimated completion date. The total number of days needed was 73 days for this 6336 ft long (1931 m long) boring.

G.4.9 Lessons Learned

The main lessons learned from Elsah case histories include the following:

- Long large-diameter installations can be performed using the HDD method.
- Contractor's experience with such projects and his/her capability of handling issues swiftly is essential for the success of such high-complexity projects.
- The use of advanced methods and equipment such as the tracking system (gyro-system), drilling method (the intersect method), and the conductor casings helped in the successful completion of this project.
- Making the proper downhole pressure calculations is a very good practice that should be adopted and generalized.
- The use of a fluid recycling system can save the contractor a lot of expenses and would save natural resources such as water.
- The detailed daily report was very valuable in documenting this case study and its progress and issues. Similar reports should be prepared for other projects.
- Monitoring the continuity of the fluid return and its volume is a very good practice that would allow the contractor to detect problematic zones and would enable him/her to adjust his/her procedure accordingly.
- Despite the pressure calculations, inadvertent returns have occurred near the ends of the installation. This is a risk that is always associated with the HDD construction method, and the owners and departments of transportations should be aware of it.

G.4.10 References

Denny, F Brett, and Joseph A Devera. 2008. "Bedrock Geology of Elsah Quadrangle, Jersey and Madison Counties, Illinois." IGQ Elsah-BG. Champaign, IL. http://hdl.handle.net/2142/77920

Revised
9/27/2018

Illinois Department of Transportation

Utility Permit

Public Improvement ☐ Yes ☒ No
IDOT Permit No. 8-30703
Utility Reference No. _____

I (We) Spire STL Pipeline LLC (Name of Applicant), 700 Market St. (Mailing Address)
St. Louis (City), MO 63101 (State & Zip), hereinafter termed the Permittee,
request permission and authority to occupy, and to do certain work herein described on, the right-of-way of the State highway
known as FAP 304 (IL 100), Section (401,402)RS-1,
at 619+70± in Jersey County.
The work is described in detail below and/or on the attached sketch or plans.

Install one 24 inch welded steel, coated and cathodically protected Natural Gas Pipeline by the method shown (HDD) on the permit drawing (STLP-RD-045) under State Highway100. Install temporary driveway(s) to access pipeline ROW during construction. This pipeline and crossing is designed and to be constructed in accordance with Title 49, Code of Federal Regulations, Part 192. Contractor shall verify exact location and elevation of any/all utilities in the area of work prior to construction and call Illinois One Call System (Julie)at 811 or 1-800-892-0123 at least two (2) working days (48 hours) prior to construction. NO PAVEMENT OR DRAINAGE TO BE DISTURBED.

This permit covers the operation and presence of specified equipment, material or facility on the right-of-way that may be related to the authorized work. A copy of this permit must be present when crews or equipment occupy highway right-of way. Failure to comply may result in the cessation of all construction.

This permit is subject to conditions and restrictions of Part 530 of Title 92 of the Illinois Administrative Code, Accommodation of Utilities on Right-of-Way of the Illinois State Highway System. The removal, relocation or modification of facilities permitted to occupy the right-of-way is governed by Section 9-113 of the Illinois Highway Code, as amended by Public Act 92-0470. The Permittee agrees to comply with the requirements of these laws and with all terms and conditions established by this permit. This permit is subject to revocation by the Department on violation of the terms and conditions governing its use.

If you're directional boring please install the service line 4' below the lowest point of the crossing. If the lowest point is the ditch line make sure you're using the design flow line of the ditch as it could be silted in.

Signature of Agent for Permittee — Date: 6/21/18

Spire STL Pipeline LLC
Name of Permittee (Print or Type)

700 Market St
Mailing Address

St. Louis — MO — 63101
City — State — Zip

The work authorized by this permit shall be completed by _____ or within 180 days after the date of approval by the Department, otherwise the permit will be considered null and void.

Public Improvement Projects only: The anticipated letting date is _____

This permit allowing occupancy and work on state right-of-way is approved. The Utility Coordination Council established by the Department in the area covered by this permit is District 8 Collinsville UCC

Department of Transportation — Date: AUGUST 9, 2018

Figure 250. Document. Utility permit.

DISTRICT 8 UTILITY PERMIT SHEET
APPLICABLE TO
PERMIT NO. 8-30703

Attached is a copy of TYPICAL APPLICATION OF TRAFFIC CONTROL DEVICES HIGHWAY CONSTRUCTION AND MAINTENANCE Standard No. (s) 701101 & 701106. These Standards are being attached to aid you in selecting the correct Application of Traffic Control to meet the conditions of your construction and does not relieve you of your responsibility of having the correct Traffic Control Devices if the above Standards do not fit your situation. If you have any questions concerning Traffic Control, please contact IDOT's Traffic Control Technician, Phone No. 618-346-3287, or the Department Representative.

The STATE OF ILLINOIS, DIVISION OF HIGHWAYS, shall in no way be held liable for any accidental breakage or damage to any installations that are installed within the State's right-of-way due to any maintenance work or operations of the DIVISION.

The applicant will be responsible for determining location of and protecting all State-owned facilities including buried facilities (such as Culverts, Storm Sewer Drainage, Traffic Signal Conduits, Lighting Conduits) and will be responsible for the cost of repair or replacement of any such facilities damaged as a result of the work covered herein.

Clean-up of the State's right-of-way shall immediately follow construction operations as the job progresses and shall not be left until all construction is completed. Maintenance of trenches, filling of settlement, cleaning out eroded dirt from highway ditches and drainage structures shall be a continuous operation. Upon completion of the work covered by this permit, final grading, seeding or sodding, or any other requirements to restore the right-of-way to a condition equivalent to that which existed prior to the commencement of work shall be completed.

The gas pipeline installation under conventional highways shall be installed by means of boring at a minimum depth of 48" below the elevation of the bottom of roadway pavement and/or flow lines of ditches. The length of bore shall extend a minimum distance of 10' beyond the outer edges of the highway pavement or as otherwise specified by IDOT's Utility Permit Technician.

Work shall be carried on in such a manner that traffic shall have full and unobstructed use of the pavement since actual construction work does not involve work in the traffic lanes.

Immediately following the described work, all excavation within the limits of the highway right-of-way shall be completely backfilled. The backfill shall be placed in layers of not over 6" each layer to be firmly tamped into place.

The Department is not a member of JULIE and does not locate its own facilities (such as underground conduit and/or cable for traffic signals or highway lighting). The applicant, at his/her own expense, must obtain the services of a qualified electrical contractor to locate such state-owned facilities.

Underground utility crossings without encasement will preclude future maintenance or repair in the area under the roadway and/or between ditch lines or toes of slopes.

All work shall comply with CFR 49 Part 192, RULES FOR THE CONSTRUCTION AND OPERATION OF GAS TRANSMISSION AND DISTRIBUTION PIPING SYSTEMS, by the Illinois Commerce Commission and any revisions thereof.

The issuance of this utility permit by the Department does not excuse the permittee from obtaining the necessary approvals from the Corps of Engineers, Division of Waterway, Department of Public Health, IDNR, and any other property owner, municipality, or agency that may be involved or have concerns with this procedure.

The work area must be left in a safe and presentable condition at the end of each workday.

Figure 251. Document. Utility Permit Sheet.

G.5 HIGHLAND CASE HISTORY

G.5.1 Project's Goal

In this project, a 12.75 in. (32.4 cm) uncased steel wall half-inch-thick natural gas transmission line was to be installed under road IL-143 (Figure 252) parallel to US-40 using HDD. This segment is part of a long gas line installed by Ameren between Troy and Highland in Madison County. The HDD crossing also targets bypassing two parking lots east and west of the road, hence bringing the total length to about 1100 ft (335.3 m).



Figure 252. Photo. Road IL-143 (photo looking West).

G.5.2 Location and Surroundings

The project is located in Highland, Illinois (Figure 253–Figure 255), and its GPS coordinates are 38°44'55.6"N 89°40'51.9"W.

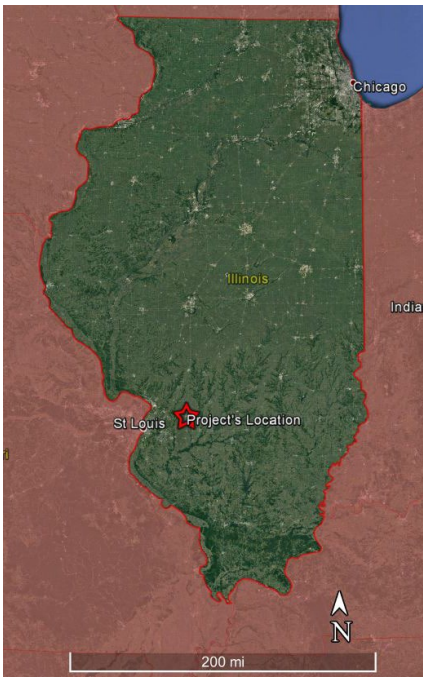


Figure 253. Photo. Google Maps capture showing Highland project on state levels.

Source: Google Maps

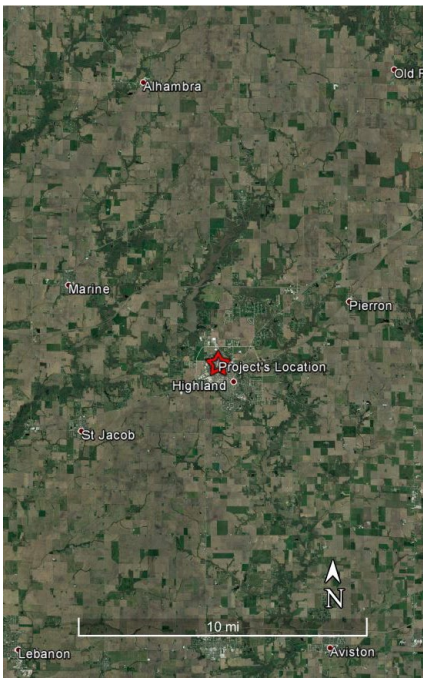


Figure 254. Photo. Google Maps capture showing Highland project on county levels.

Source: Google Maps

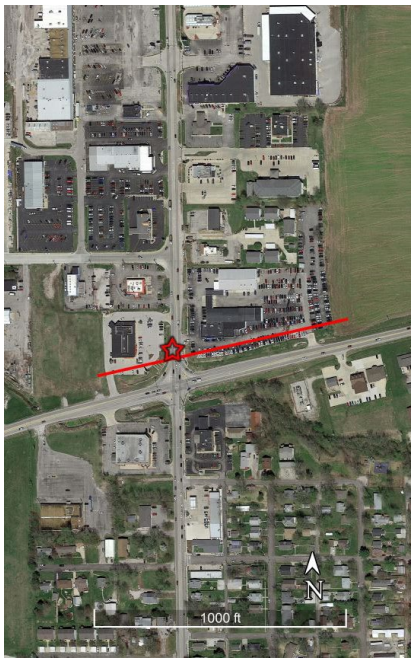


Figure 255. Photo. Google Maps capture showing Highland project on neighborhood levels.

Source: Google Maps

The proposed alignment passes below the parking lot of a pharmacy (West of IL-143), IL-143, and the parking lot of a car dealer (East of IL-143). The buildings of the pharmacy and the dealer are about 50 ft (15 m) north of the alignment, and US-40 is about 50 ft (15 m) south of it.

The alignment passes below and next to many utilities including fiber optic cables, a water line, and a sewer line. Prior to the commencement of the drilling, those utilities were accurately located using pit holes, then surrounded with a small plastic fence, and the depth of cover available for each utility was marked on a wooden lathe (Figure 256–Figure 258).



Figure 256. Photo. Many fenced pit holes dug to locate the existing fiber cables.



Figure 257. Photo. A wooden lathe showing that 112 in. (284.5 cm) of cover is available for the sewer line.



Figure 258. Photo. A manhole next to the parking lot east of IL-143.

G.5.3 Site Conditions

G.5.3.1 Soil Conditions

A geotechnical investigation was done by SKS Engineers, LLC. For the whole project (extending from Troy to Highland), forty-seven borings were drilled. One boring (B-43), however, is adjacent to the segment of the line documented in this report and is drilled using a hollow steam auger next to the eastern end of the installation. SPT blow counts were recorded, and soil samples were taken to the lab to determine the in situ water content and the unconfined compressive strength. B-43 was drilled 31 ft (9.45 m) deep. Water was encountered at around 8 ft (2.4 m) below the ground surface. The topography of the area, per the soil report, is generally flat to rolling, resulting from the glaciation and later weathering.

The boring shows that the site is composed of stiff lean clay and sandy lean clay of different colors and thicknesses varying between 2.5 and more than 11 ft (0.76 and more than 3.35 m). Figure 259 presents the stratigraphy of the site, the SPT blow count, the unconfined compressive strength, and the water content of the layers.

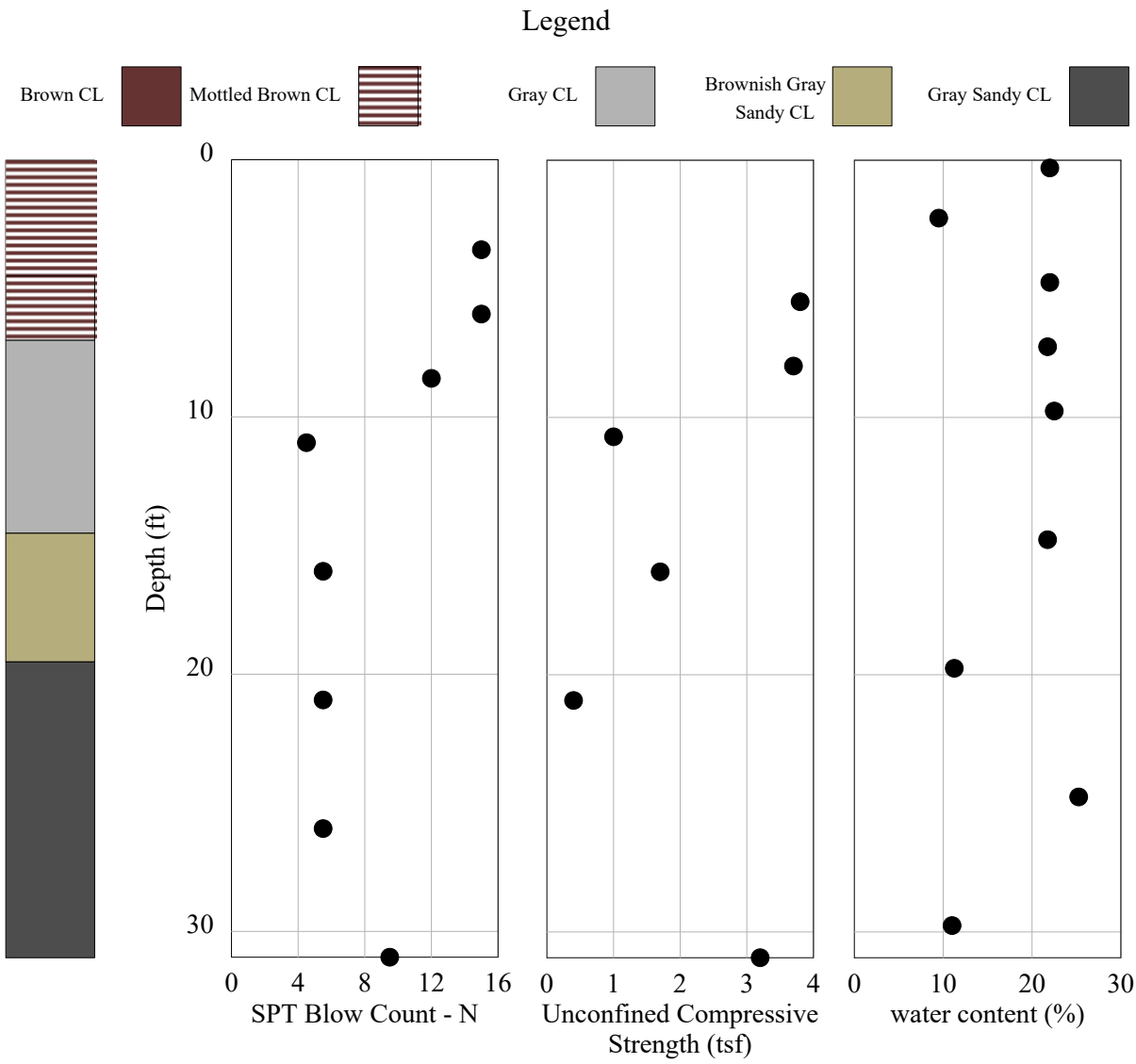


Figure 259. Chart. Stratigraphy and soil properties obtained from the boring performed.

G.5.3.2 Geology (modified from [Phillips 2005])

The geology of the area is described by Phillips (2005) and is summarized here:

> *The Highland quadrangle is located about 15 miles (24.14 km) east of bluffs that overlook the Mississippi River valley, and near the margins of the Illinois and pre-Illinois Episode glaciations. The landscape is comprised of three geomorphic regions: river valleys, low relief uplands and valley slopes, and ridged or hummocky uplands. River valleys, including some terraces and small fans on valley sidewalls, are mainly comprised of waterlaid sediments… Uplands are composed of glacial, stream, lake, and windblown sediment (loess). Prominent ridges and isolated mounds mainly west and south of Highland break the otherwise subdued topography of the upland surface. These features are part of a regional train of ridges that trend northeast-southwest…*

The Quaternary sediment overlying bedrock was deposited during at least three episodes of glaciation that were separated by relatively warm, interglacial episodes, including the present-day postglacial episode. Before the earliest Quaternary glaciation, erosion had exposed much of the land surface to bedrock… During the pre-Illinois and the Illinois glacial episodes, glaciers flowed over the region from the northeast to the southwest, extending across the Mississippi Valley to the St. Louis area. The glaciers sculpted the pre-existing landscape and left deposits of diamicton (a poorly sorted mixture of rocks, sand, silt, and clay) as till at the base of the glacier or as sediment piles sloughed off of glacier margins or into crevasses. Sorted silt, sand, and gravel were deposited from meltwater streams. During the last (Wisconsin Episode) glaciation, ice only advanced into the northeastern quadrant of Illinois, about 80 miles (128.75 km) to the northeast of Highland. The main influence of the glacier in this area was to discharge large volumes of sediment into the Mississippi River valley, where extensive plains of meltwater sediment were deposited. During glaciation, silt was eroded by westerly winds off the unvegetated sandy floodplains in the Mississippi Valley, and then deposited across the upland landscape as blankets of loess. Between glaciations, streams continued to erode some sediment out of their valleys, and soils developed on the fresh land surface. (Phillips 2005, 2)

The surficial geology presented in Figure 260 is taken from Phillips (2005). The map suggests that the surficial layers would be silty loams part of the Cahokia Formation or the Peoria and Roxana Silts Formation. The Cahokia Formation is described in (Phillips 2005) as "*Silty clay to silt loam with loam to sandy loam, local sand and gravel lenses; massive to well stratified; gray to brown; leached, very soft to moderately stiff; typically moist to very moist but seasonally variable; up to 25 feet (7.62 m) thick*" (2), while the Peoria and Roxana Silts Formation is described in (Phillips 2005) as "*massive to weakly stratified; dark yellow brown to gray, may have pink hue; noncalcareous; friable; contains modern soil solum in upper 2 to 5 feet (0.61 to 1.52 m) (commonly weathered to silty clay loam); typically 10 feet (3.05 m) on flat uplands but up to 15 feet (4.57 m) thick*" (2). The description of the geologic units is consistent with the boring shown in section G.5.3.1.

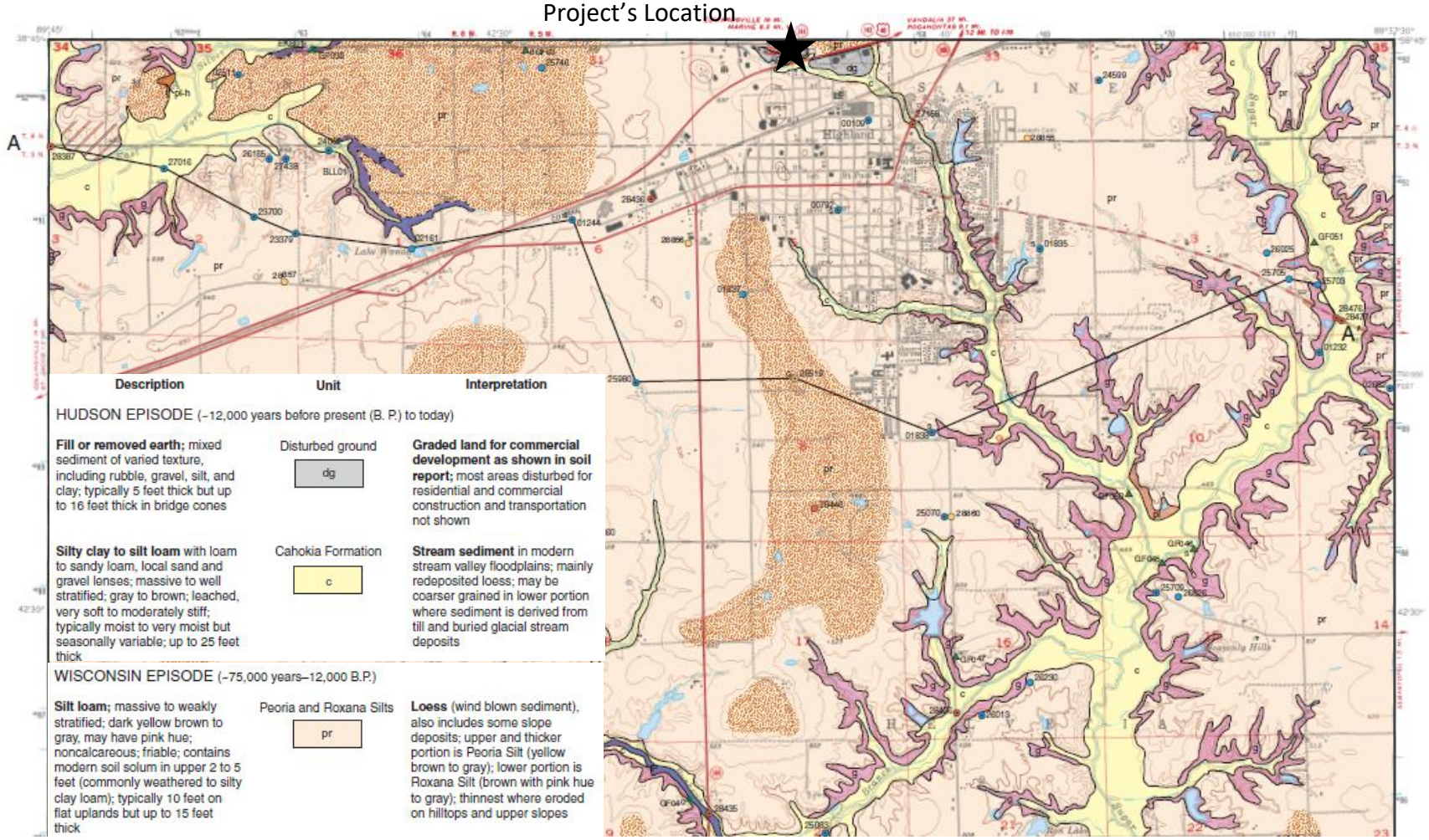


Figure 260. Graph. Geologic map showing surficial geology of the area of Highland. The project location is shown on the northern part of the map.

Source: (Phillips 2005)

G.5.4 Design

HDD was selected to install the gas line below the road and the two parking lots. The planned profile is presented in Figure 261. The installation starts at station 947+15.51 and extends to station 957+82.77, with a total projected length of around 1067 ft (325 m). The planned profile passes around 15 ft (4.6 m) below the highway. The depths of the cover of the fiber optic cables are 73, 56, 58, 10, 49, 31, 23, 19 in. (185, 142, 147, 25.4, 124.5, 78.7, 58.4, 48.3 cm), respectively (from west to east), and the depth of cover of sewer is 112 in. (284.5 cm). The planned HDD entry and exit angles are 10°.

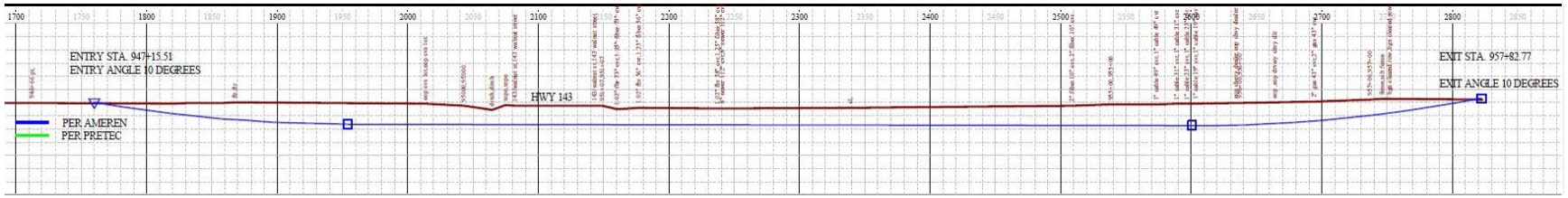


Figure 261. Graph. Planned profile of the natural gas line to be installed using HDD.

G.5.5 Features and Foreseen Challenges

The following list contains some of the interesting features and challenges of this project:

- The profile is long, and the depth of cover provided seems thin. This might cause inadvertent returns, especially if high pressures are required to transport the cuttings to the entry or exit pits.
- Pressure relief holes, which would decrease the risk of inadvertent returns, were not included in the design.
- The utilities are close to the profile, and if inadvertent returns occur, they might be at threat of being displaced. This might be most relevant to the sewer line.
- The soil expected to be encountered is clay loam or sandy clay loam. The boring might ravel in this type of soil, and the drilling fluid should be adjusted to avoid that.

G.5.6 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- PRETEC Directional Drilling (https://pretecdd.com/), which is the HDD contractor.
- Ameren (https://www.ameren.com/), which is the owner of the gas line.
- SKS Engineers, LLC (http://www.sksengineers.com/), which carried out the soil investigation and prepared the soil report for Ameren.
- Millenia Professional Services (https://www.millennia.pro/), which is the utility inspector recruited by IDOT.

The main point of contact during this project was IDOT's Project Support Engineer and TRP member Rebecca Tharp (email: Rebecca.tharp@illinois.gov; phone: 618-346-3197), and Matthew Tebbe, the Permits and Agreements Technician in District 8 (email: matthew.tebbe@illinois.gov; phone: 618-346-3200)

On July 7, 2019, Cody Mason (email: CMason@ameren.com) from Ameren arranged a preconstruction meeting with IDOT representatives, PRETEC representatives, and the UIUC team. Cody and the PRETEC team shared with the attendees' technical details of the project and answered many questions about the design, schedule, and procedure. After the project started, Brandon Lumpkins, which is Ameren's on-site inspector, wrote daily reports and sent them to Cody who kindly shared them with the UIUC team. On site, the UIUC representative met Brandon Lumpkins, PRETEC's foreman Brandon Cole, Jason Kraner from Millenia Professional Services, and Matthew Tebbe from IDOT, who all shared information about the progress and issues faced in the project.

G.5.7 Execution

G.5.7.1 Settings

Preparations for installing the HDPE pipe via HDD started on July 3, 2019, and by July 10, 2019, 2:30 p.m., the pipe pulling was finished. Temperature in Highland varied between 80 and 87°F (26.7 and 30.6°C) on average over this period (Figure 262). Some precipitation was recorded in the first three days.

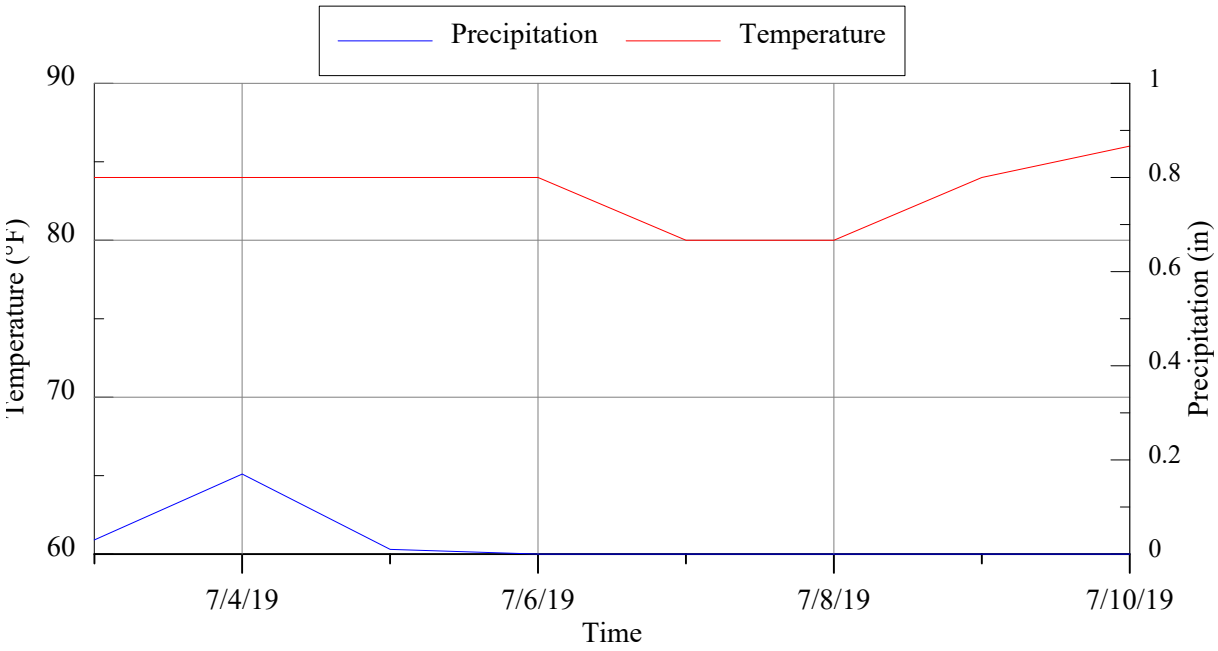


Figure 262. Chart. Temperature and precipitation in Highland, IL.

Source: ***https://www.wunderground.com/***

G.5.7.2 Machinery, Equipment and Materials

Machinery used in this project included the following (Photos presented in Figure 263–Figure 267):

- Excavator: 4 CAT excavators (3 used in pipe handling, including one which was used to assist the drilling and reaming operations, and 1 used to load and unload the rig with drilling rods).
- Rig: American Augers DD-110 D80x100. The rig uses 20 ft (6 m) long, 3.5 in. (9 cm) diameter drilling rods and is characterized by a torque capacity of 15 kip-ft (20.3 kN-m) and a max pumping capacity of 200 gpm (757 L/min).
- Fluid Pump: pumps returned fluid from the entry pit, through a sieve with inch-sized openings, to the fluid recycling system.
- Fluid Recycling System: mixes water with drilling additives (SandMaster in this case) and recycles the used fluid by sieving it to remove cuttings.

- Vacuum Excavator: used to empty the exit pit (which didn't have the fluid pump connected to it), and to clean locations where inadvertent returns occurred.

Equipment used in this project included is as follows (Photos shown in Figure 268–Figure 271):

- Drill bit.
- Reamers: 1 roller cone reamer of 18 in. (45.7 cm) in diameter.
- Pipe pull head.
- Swivel.
- Walkover tracking system.
- Wood Benching: used to support the heavy machinery on the entry and exit ends while moving over the weak topsoil layers.

Materials used in this project included the following (Photos shown in Figure 272–Figure 274):

- Pipe: steel pipe 12.75 in. (32.4 cm) in diameter and 0.5 in. (1.27 cm) in thickness.
- Bentonite: AMC Gel.
- Drill Fluid Additive: SandMaster (composed of Xanthan Gum).



Figure 263. Photo. Machinery used: 4 excavators.



Figure 264. Photo. Machinery used: rig.



Figure 265. Photo. Machinery used: fluid pump.



Figure 266. Photo. Machinery used: fluid recycling system.



Figure 267. Photo. Machinery used: vacuum excavator.



Figure 268. Photo. Photo for the 18” (45.7 cm) roller cone reamer.



Figure 269. Photo. The pull head.



Figure 270. Photo. The swivel.



Figure 271. Photo. Wood crane mats.



Figure 272. Photo. Bentonite (AMC Gel).



Figure 273. Photo. The additive (SandMaster).



Figure 274. Photo. Steel product pipe 12.75 in. (32.4 cm) in diameter and 0.5 in. (1.27 cm) in thickness.

G.5.7.3 Execution Metrics

Pipe Welding and Layout:

Before the drilling starts, the steel pipe, in excess of 1000 ft (304.8 m) in length, was welded and laid next to the eastern end of the profile, as presented in Figure 275–Figure 276. The pipe was rested on small wooden stands. Later, on July 9, 2019, the joints were wrapped with TRENTON's anticorrosion and protective wraps (Figure 277–Figure 278).



Figure 275. Photo. Pipe laid next to the eastern end of the profile, photo looking west (the far end of the photo is next to the exit pit).



Figure 276. Photo. Pipe laid next to the eastern end of the profile, photo looking east.



Figure 277. Photo. Wrap used to protect the joints of the steel pipe; sealed TRENTON anticorrosive wraps.



Figure 278. Photo. Wrap used to protect the joints of the steel pipe; the steel pipe joints wrapped with the anticorrosive wraps.

Pilot Drilling:

This section was written by referring to Ameren's daily reports and the drilling contractor's rod-by-rod report containing timings and rig operation metrics (fluid pumping rate, torque, etc.)

On July 3, 2019, the crew of the drilling subcontractor (PRETEC) finished mobilizing to the site and dug the entry pit, preparing for drilling. Then, they were stopped by Ameren's inspector due to an issue with one of the easements.

On July 5, 2019, the pilot drilling started at 8:30 a.m. from the entry pit located west of the planned profile. Inadvertent returns occurred, close to the drill bit (where the highest pressure is), at many locations: at STA 947+58 at 10:30 a.m., STA 949+27 at 11:41 a.m., 950+00 at 12:20 p.m., and STA 951+50 at 2:10 p.m. At 2:15 p.m., lightning started, so the drilling team halted drilling for two hours. After resuming work, two additional inadvertent returns occurred, within 15 ft (4.6 m) of the drill bit, at STA 952+50 at 4:00 p.m. and at STA 954+55 at 6:36p.m. The vacuum truck was used to clean the inadvertently returning fluid, and, when the vacuum truck had to leave, the drilling was stopped to avoid spreading this fluid. The total length drilled this day was 800 ft (244 m), with 274 ft (83.5 m) left.

On July 6, 2019, the crew started with cleaning the inadvertently returning fluid at STA 954+55 then resumed drilling. An incident of inadvertent return occurred at STA 956+00 at 11:00 a.m. The drilling reached the exit pit at 11:46 a.m.

Based on the drilling contractor's rod-by-rod report, during pilot drilling, the time required to add a new 20 ft (6.1 m) long joint averaged 5 mins, and the drilling fluid pumping rate averaged 20 gpm (75.7 L/min).

The as-built profile shared by Ameren showed an excellent match of the actual and planned profile horizontally and vertically.

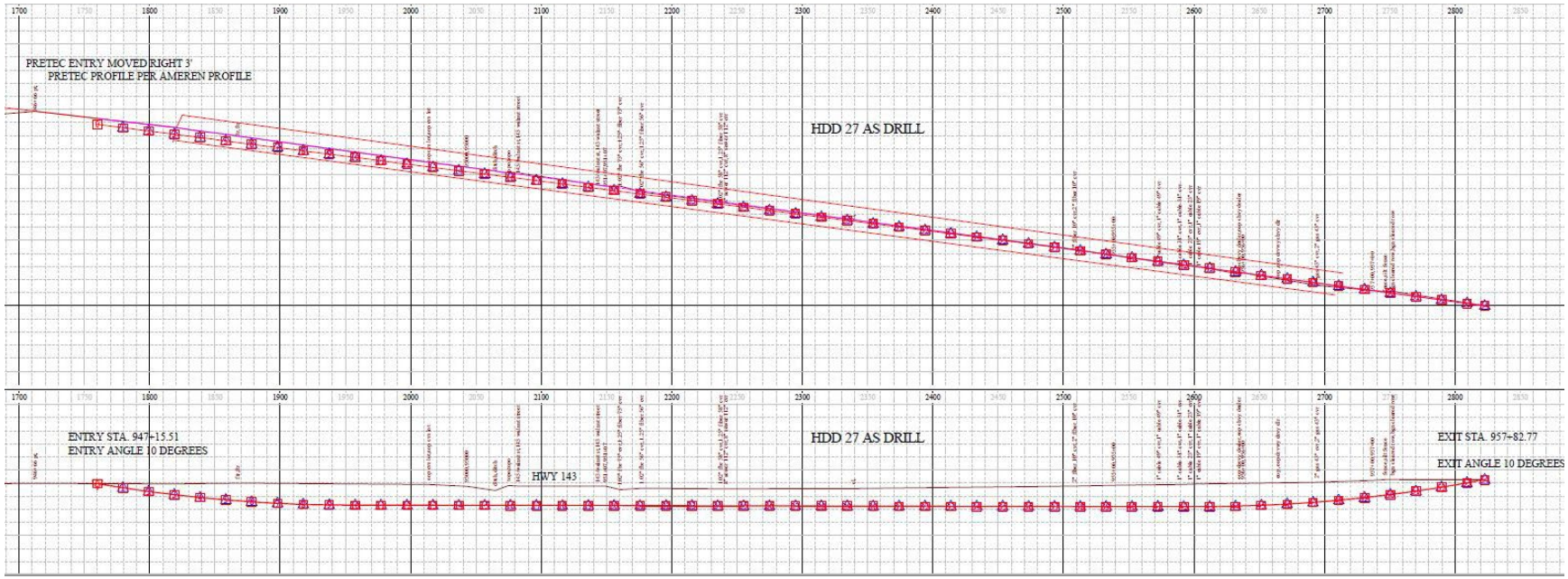


Figure 279. Chart. As built profile shared by Ameren, showing an excellent match of the actual and planned profile horizontally and vertically.

Reaming:

On July 6, 2019, after finishing pilot drilling, the drilling crew installed the 18 in. (45.7 cm) reamer to the rig at the entry pit and started forward reaming at 2:20 p.m. and reamed 220 ft (67 m) then decided to trip back to clean out the hole.

On July 7, 2019, the total reamed distance increased to 840 ft (256 m).

Information about inadvertent returns that may have occurred while reaming was not reported in Ameren's daily reports.

On July 9, 2019, (the day of arrival of the UIUC team), Jason Kraner pointed out some of the locations where inadvertent returns occurred over the past days, which are presented in Figure 280–Figure 281. During that time, the forward reaming operations were proceeding with the assistance of an excavator on the exit pit, which was providing a pulling force, as presented in Figure 282–Figure 283. An inadvertent return was occurring at the eastern end of the car dealer's parking lot, as presented in Figure 284–Figure 285, through one of the pit holes that were dug before drilling to expose the locations of utilities. The reamer reached the exit pit at around 9:45 a.m.

Based on the drilling contractor's rod-by-rod report, during reaming, the time required to add a new 20 ft (6.1 m) long joint averaged 5 to 7 min, and the drilling fluid pumping rate averaged 20 gpm (75.7 L/min), except for the first 10 joints, which averaged 10 min per joint and for which the drilling fluid pumping rate averaged 30 gpm (113.5 L/min).



Figure 280. Photo. Some of the locations where inadvertent returns occurred (and were cleaned); photo (looking west) of the remains of the inadvertent return that occurred next to the road curb.



Figure 281. Photo. Some of the locations where inadvertent returns occurred (and were cleaned); photo (looking right) of the remains of the inadvertent return that occurred in the ditch of the road.



Figure 282. Photo. The reaming operation; photo of the reamed hole taken at the entry pit.



Figure 283. Photo. The reaming operation; photo of the drill pipe being pulled by the excavator next to the exit pit.



Figure 284. Photo. An inadvertent return that occurred during reaming; photo of the fluid before cleaning.



Figure 285. Photo. An inadvertent return that occurred during reaming; photo of the fluid after cleaning, exposing that the inadvertent return was occurring through one of the pit holes that were dug to expose the location and depth of the utilities.



Figure 286. Photo. The end of the reaming operation; the ground heaving next to the exit pit just before the reamer arrives at the exit pit.



Figure 287. Photo. The end of the reaming operation; the reamer arriving at the exit pit (notice the orientation of the reamer used in forward reaming).

Swabbing:

On July 9, 2019, after finishing the reaming, the reamer was uninstalled then installed with the opposite orientation to be used in back reaming. Since the hole is already reamed, this reaming pass targets cleaning the hole rather than enlarging it and hence is called swabbing. A swivel was installed at the end of the drill pipe's string to allow the reamer to rotate while the excavator was lifting the drill pipe as presented in Figure 288–Figure 290. After swabbing around 300 ft (91.4 m), an inadvertent return occurred, and no vacuum truck was available to clean the drilling fluid, so the swabbing operations stopped at 1:30 p.m. till 4:30 p.m. when a vacuum truck arrived and cleaned the inadvertent return (Figure 291–Figure 292). An additional 200 to 300 ft (61 to 91.4 m) were swabbed till the end of the day. Before the end of the day, some cracks in the pavement of the car dealer's parking lot were observed, and the driller claimed that they were caused by the heavy vacuum trucks. On the morning of the following day, an inadvertent return occurred through those same cracks as presented in Figure 293–Figure 294.

On July 10, 2019, the swabbing continued and finished around 9:30 a.m. (Figure 295).

Based on the drilling contractor's rod-by-rod report, during swabbing, the time required to add a new 20 ft (6.1 m) long joint averaged 5 min (due to the 3-hour stop) for the first 30 joints and 2 min for the rest of the joints, and the drilling fluid pumping rate averaged 20 gpm (75.7 L/min).



Figure 288. Photo. The swabbing operation; photo showing the reamer's orientation after being flipped.



Figure 289. Photo. The swabbing operation; the swivel carried by the excavator before being attached to the end of the drill pipes string.



Figure 290. Photo. The swabbing operation; the excavator assisting the rig with the swabbing.



Figure 291. Photo. An inadvertent return that occurred during swabbing; the fluid emerging at the ground surface.



Figure 292. Photo. An inadvertent return that occurred during swabbing; the vacuum truck cleaning the fluid.



Figure 293. Photo. Cracks in the pavement of the car dealer's parking lot; the cracks observed on July 9.



Figure 294. Photo. Cracks in the pavement of the car dealer's parking lot; inadvertent returns coming out of the same cracks.



Figure 295. Photo. The reamer arriving at the entry pit after completing the swabbing pass.

Pipe Pulling:

After the swabbing pass ended, the reamer was removed from the entry pit and transported to the exit pit, where it was attached to the end of the drill pipe string, then a swivel was attached to the back of the reamer. The pull head was welded to the end of the steel pipe (Figure 296–Figure 297), and then the steel pipe was moved by three excavators until its end was close to the swivel attached to the reamer (Figure 298–Figure 299).

Pipe pulling then started at around 11:00 a.m. on July 10, 2019. As the pipe was being pulled, a device for measuring the thickness of the cathodic coating was used (Figure 300). Inadvertent returns occurred at multiple locations as the pipe was being pulled, generally occurring close to the location of the pull head. Some of those locations were the same locations where inadvertent returns had already occurred, and some were new. Some returns occurred through the utility pit holes, and some occurred through the parking lot pavement, grass, and gravel (Figure 301–Figure 307). The pipe pull head arrived at the entry pit at around 2:00 p.m. (Figure 308–Figure 309).

Based on the drilling contractor's rod-by-rod report, during pipe pulling, the time required to remove a 20 ft (6.1 m) long joint averaged 1 min, and the drilling fluid pumping rate averaged 20 gpm (75.7 L/min).

The push/pull and the torque were reported without units but are reported here for comparison between the different stages of this process. During pilot drilling, the push reported is 6000 for the first 41 joints and 4000 for the rest, while the torque reported is 1200. During reaming, the push reported is 3000 for the first 11 joints and 5000 for the rest, while the torque reported is 3000 for the first 11 joints, 3600 for the next 30 joints, and 2500 for the last 13 joints. During swabbing, the pull reported is 4500 to 5000, while the torque reported is 4500 for the first 30 joints and 1200 for the rest. During pipe pulling, the pull reported is 14000, while the torque reported is 12000.



**Figure 296. Photo. Preparations for the pipe pulling;
photo of the reamer and swivel attached to the drill pipe string.**



Figure 297. Photo. Preparations for the pipe pulling; the pull head welded to the steel pipe.



Figure 298. Photo. The steel pipe being moved to reach the drill pipe; pipe being lifted by the three excavators.



Figure 299. Photo. The steel pipe being moved to reach the drill pipe; the pipe's end reaching the swivel attached to the reamer, which is attached to the drill pipe.



Figure 300. Photo. Measurement of the thickness of the cathodic coating as the pipe is being pulled.



Figure 301. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (1)



Figure 302. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (2)



Figure 303. Photo. Some inadvertent returns that occurred in and next to the car dealer's parking lot. (3)



Figure 304. Photo. Some inadvertent returns that occurred in important locations; next to the manhole of the sewer line.



Figure 305. Photo. Some inadvertent returns that occurred in important locations; next to the western curb of the road.



Figure 306. Photo. Some inadvertent returns that occurred in important locations; through the ditch on the western side of the road.



Figure 307. Photo. An inadvertent return as it is happening. The fluid is squirting through the ground surface.



Figure 308. Photo. The steel pipe after finishing the pipe pulling; photo of the pull head at the entry pit.



Figure 309. Photo. The steel pipe after finishing the pipe pulling; photo of the end of the pipe at the exit pit.

G.5.8 Performance Metrics

G.5.8.1 Surface Deformation

A surveying crew from IDOT District 8 took an initial survey of the surface of IL-143 on July 3, 2019, before the beginning of construction. This set of measurements is taken as the baseline. After pilot drilling (on July 10, 2019), another set of measurements was taken. On the next day, after the end of reaming and pipe pulling, another set of measurements was taken. The surface deformations are plotted and presented in Figure 310. After pilot drilling, it seems that no significant deformation was caused, and it is likely that the measured deformations are measurement errors rather than real deformations. However, after reaming and pipe pulling, it seems that there is one area, on the western side of the road and close to the center of the pipe alignment, where a significant heave up to 1 in. (2.54 cm) was induced. It is worth noting that this area is close to the edge of the road, where small inadvertent returns have occurred.

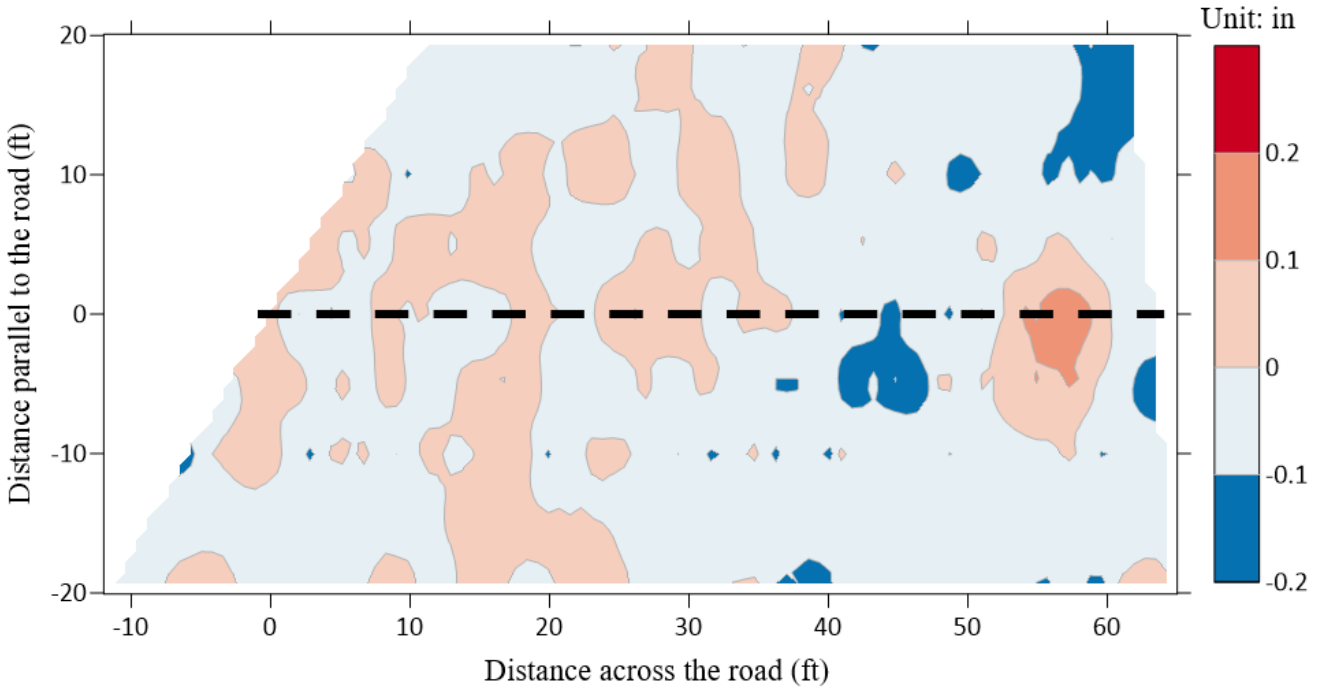


Figure 310. Graph. Surface deformations after pilot drilling. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East.

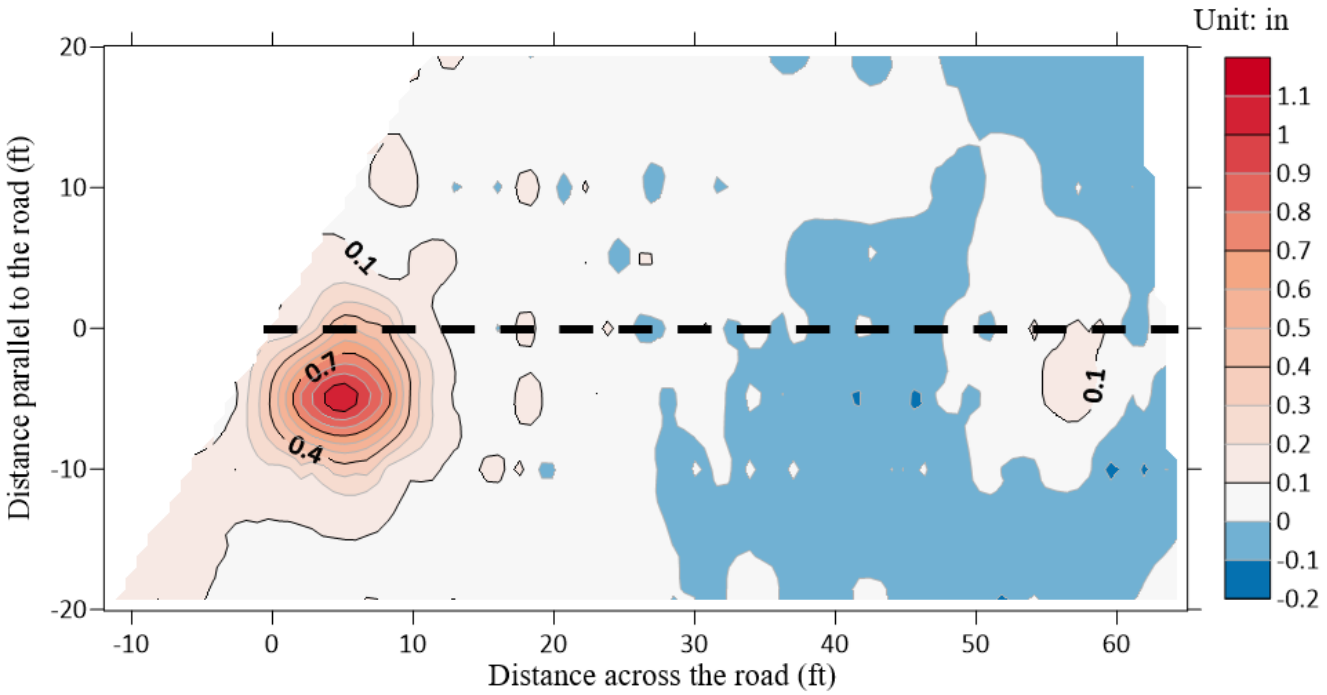


Figure 311. Graph. Surface deformations after reaming and pipe pulling. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East.

G.5.8.2 Long-Term Measurements

Around one and half years after the end of construction, another set of measurements was taken. The surface deformations are plotted and presented in Figure 312. It seems that no significant deformation was caused, and it is likely that the measured deformations are measurement errors rather than real deformations.

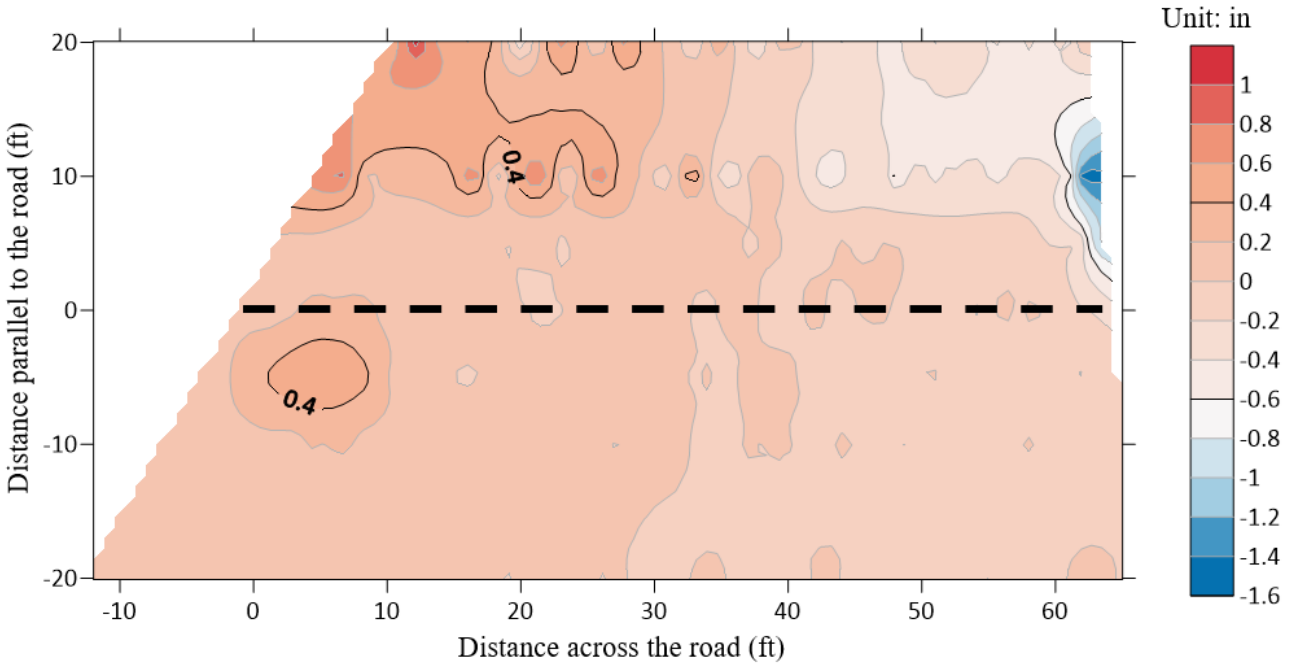


Figure 312. Graph. Surface deformations around one and half years after the end of construction. Dashed lines mark the boring alignment. Positive is heave. Positive distances are North and East.

G.5.9 Important Remarks and Conclusions

G.5.9.1 Contractor's Experience

The foreman of the drilling contractor was asked many questions about the design and execution of the HDD. The following was summarized from the conversation:

- Although the downhole pressure is measured during pilot drilling and received by the walkover system, the drilling fluid pumping rate is usually adjusted based on the ease of drilling and advancing. If the drilling is going smoothly, the fluid pumping rate is maintained constantly and may be decreased, but if it is getting harder, the pumping rate is usually increased to clean the cuttings.
- The driller usually tries to maintain a uniform pumping rate if possible.
- Contractors benefit from a phone app called M-I SWACO, which does some necessary calculations for HDD execution.

G.5.10 Lessons Learned

The main lessons learned from Highland case history include the following:

- Using HDD for long, shallow installations comes with a great risk of inadvertent returns that may undermine overlying structures and utilities. This should be avoided by using a greater depth of embedment or other means of protection.

- Movement of heavy equipment on pavement may impact the pavement by cracking it, allowing for inadvertent returns to pass through it, which magnifies this problem.

- The pit holes that were drilled to identify the location and depth of utilities worked as pressure relief holes in this case. Although this reduced the pressure inside the hole, it is not ideal as the fluid flow occurred next to the utilities. However, this points to the importance of pressure relief holes in reducing downhole pressure in pre-defined locations far away from utilities or critical points of the profile.

- The occurrence of inadvertent returns in early stages of the drilling in certain locations may suggest a good chance of inadvertent returns happening again in the same or nearby locations during later stages of construction.

G.5.11 References

Phillips, Andrew C. 2005. "Surficial geology of Highland Quadrangle, Madison, St. Clair, and Clinton Counties, Illinois." IPGM Highland-SG, Illinois State Geological Survey. Champaign, IL. http://hdl.handle.net/2142/77826.

G.6 JACKSONVILLE CASE HISTORY

G.6.1 Project's Goal

In this project, a 10 in. (25.4 cm) steel casing is to be installed under road IL-104 and the adjacent BNSF Railway (Figure 313–Figure 314). A 4 in. PVC water main will be installed inside the casing.



Figure 313. Photo. Road IL-104 (photo looking east).



Figure 314. Photo. The railroad to the north of the road (photo looking south).

G.6.2 Location and Surroundings

The project is located southeast of Jacksonville, Illinois (Figure 315–Figure 317), northwest of the intersection of IL-104 with Ginder road. Its GPS coordinates are 39°41'32.94"N 90° 9'20.37"W.

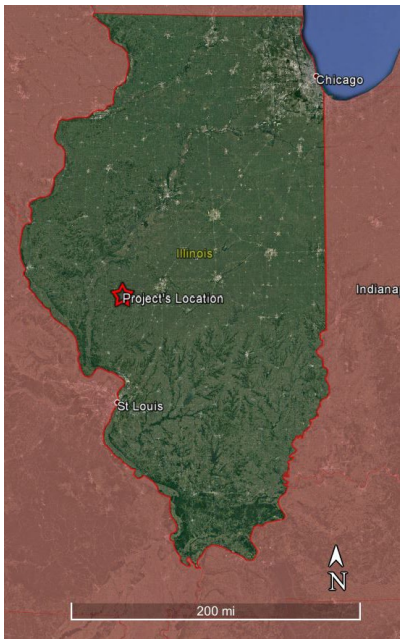


Figure 315. Photo. Google Maps captures showing Jacksonville project on state levels.

Source: Google Maps

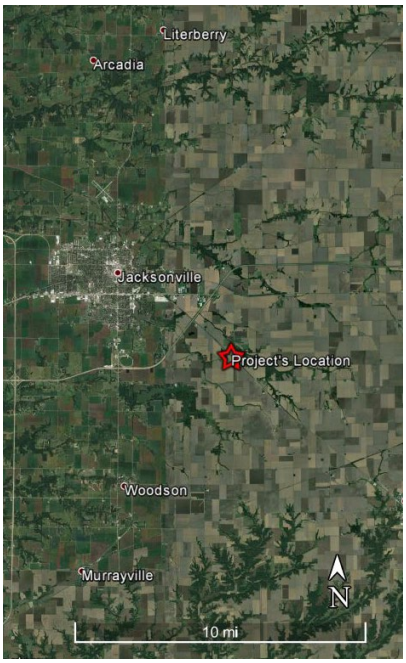


Figure 316. Photo. Google Maps capture showing Jacksonville project on county levels.

Source: Google Maps

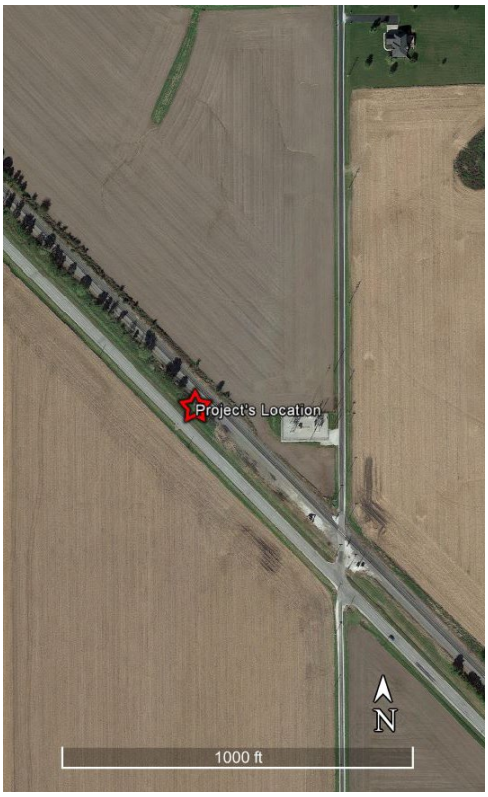


Figure 317. Photo. Google Maps capture showing Jacksonville project on neighborhood levels.

Source: Google Maps

The nearest structures (small homes) are more than 1000 ft (304.8 m) away from the proposed alignment. Hence the road and railroad are the only structures that might be impacted because of the HDD. The section of the road above the proposed alignment showed many minor cracks, as presented in Figure 318. Fiberoptic cables were located at a depth of 4 ft (1.2 m) below ground surface via pits dug using vacuum trucks. After confirming their locations, the pits were filled with soil (Figure 319). A water main parallel to the road is located around 20 ft (6.1 m) south of the road at an approximate depth of 7 ft (2.1 m). The pipe was exposed during the entry trench digging located on the southern side of the road (Figure 320).



Figure 318. Photo. Minor pavement cracks that appeared before the installation of the pipe.



Figure 319. Photo. One of the pits that were dug to locate the fiberoptic cables after being filled with soil.



Figure 320. Photo. The white water main exposed while digging the entry trench.

G.6.3 Site Conditions

G.6.3.1 Soil Conditions

No borings were performed prior to the commencement of the project. However, the contractor said that he had performed many HDDs in the vicinity of this area. With two trenches dug on the entry and exit sides of the road, visual inspection and manual field tests were possible. The soil seemed to be composed of 3 ft (0.9 m) of black silty clay topsoil (or organic clay) underlaid with 3 ft (0.9 m) of stiff brown silty clay with trace sand, which was underlaid by stiff silty clay (Figure 321).



Figure 321. Photo. The soil layers in the northern trench.

G.6.4 Design

The HDD profile was designed to pass at least 5 ft (1.5 m) below the lowest ground elevation (which corresponds to the ditches) and at least 10 ft (3 m) below the railroad. The planned profile spans around 200 ft (61 m) and has no slope. To install the casing and the pipe in this straight bore, a trench is to be dug at each end of the bore with an approximate depth of 8 ft (2.4 m). The plan and cross-section of the planned profile are presented in Figure 322.

G.6.5 Features and Foreseen Challenges

The following list contains some of the interesting features and challenges of this project:

- The existence of the water main at a depth close to the depth of the planned profile might call for an adjustment of the profile.
- The railroad imposes strict deformation limits. If the deformation were to exceed the limits, the railroad personnel would stop the construction activities.

G.6.6 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- Scott-Morgan-Greene Water Cooperative, which is the owner.

- Benton and Associates (http://www.bentonassociates.com/), which is the consultant.
- Great Plains Contractors, LLC, which is the subcontractor responsible for horizontal directional drilling.

The main points of contact during this project were IDOT's District 6 Permit Technician and TRP member Joseph Angeli (email: Joseph.Angeli@illinois.gov; phone: 217-782-7744) and Chris Harris, the subcontractor from Great Plains Contractors, LLC (phone: 660-216-0304).

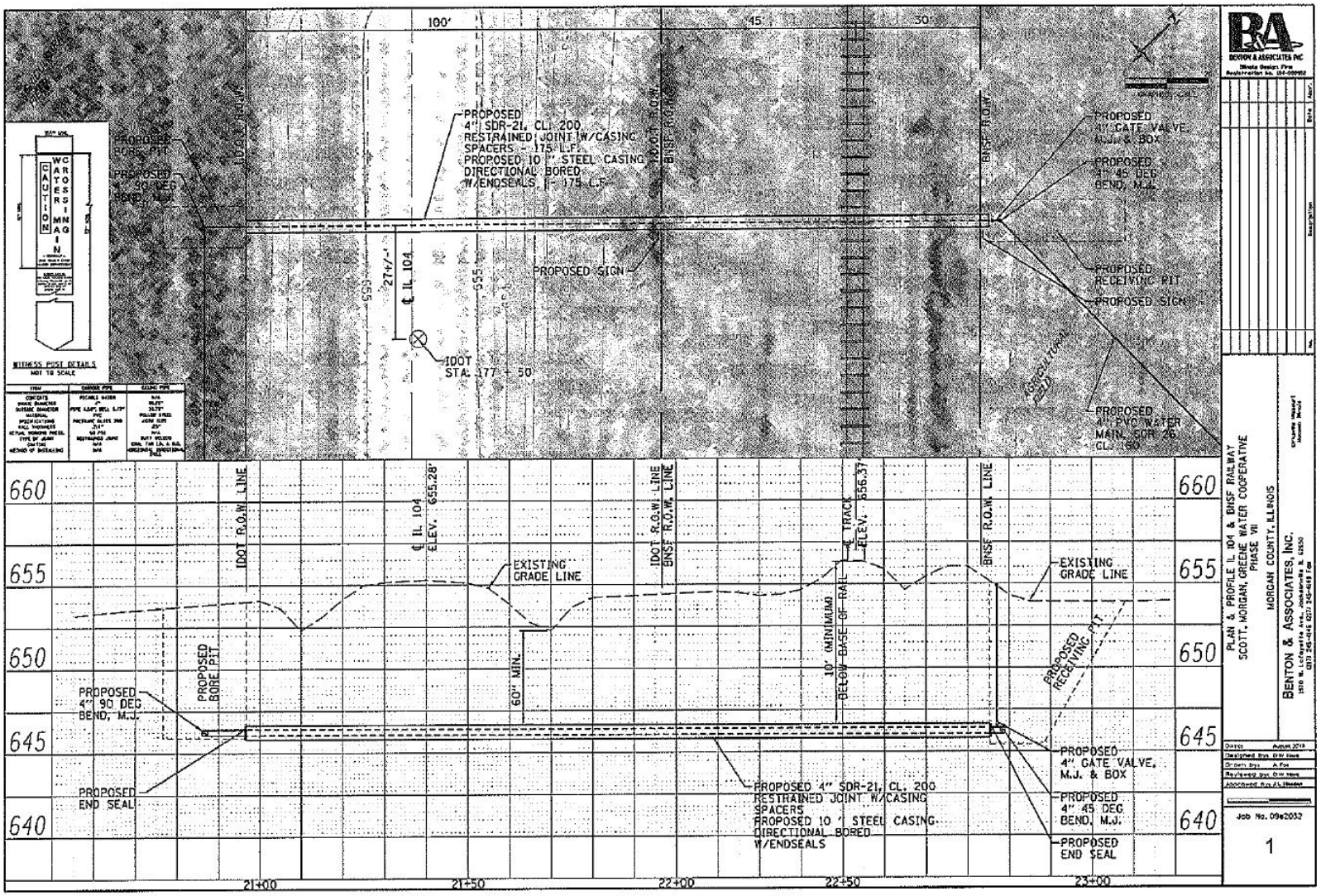


Figure 322. Graph. Plan and cross-section of the planned profile.

G.6.7 Execution

G.6.7.1 Settings

The HDD boring, reaming, and pipe pulling were all performed on September 24, 2019. No precipitation was recorded on that day, and temperatures varied between around 55 and 80°F (12.7°C and 26.7°C), as presented in Figure 323.

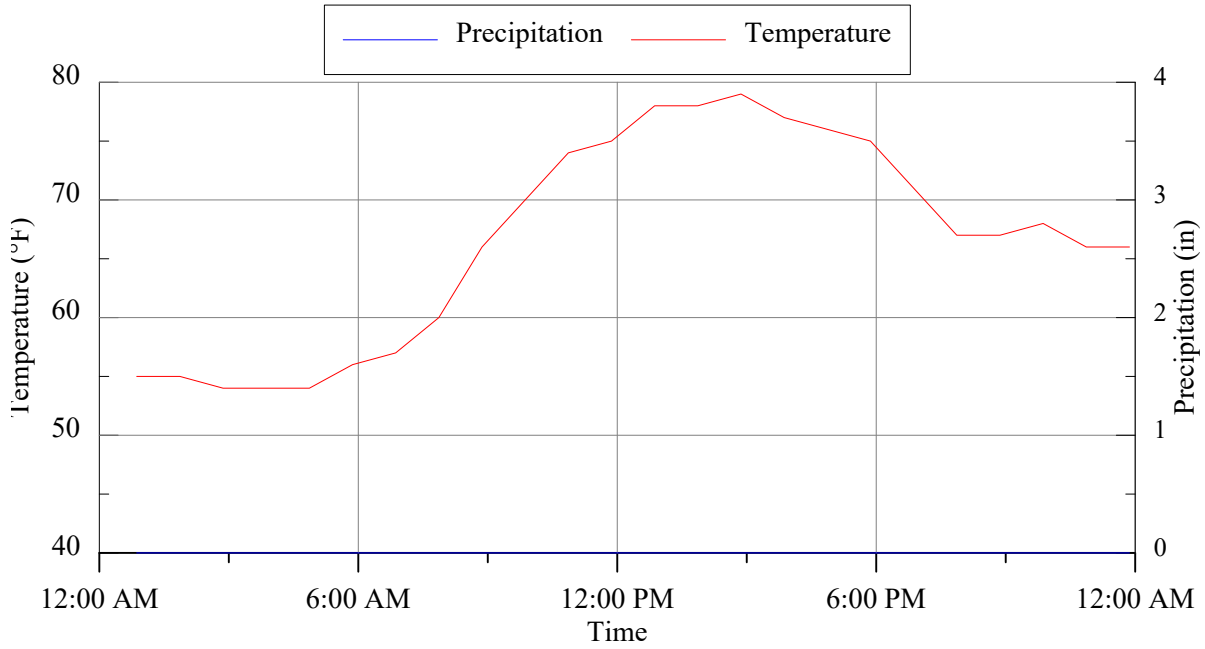


Figure 323. Chart. Temperature and precipitation in Jacksonville, Illinois.

Source: ***https://www.wunderground.com/***

G.6.7.2 Machinery, Equipment and Materials

Machinery used in this project included the following (photos presented in Figure 324–Figure 327):

- Excavators: CASE CX160 excavator and DAEWOO 55v mini-excavator.
- Bulldozer: CASE bulldozer.
- Rig: Vermeer Navigator which uses 15 ft (4.6 m) long, 3.5 in. (9 cm) thick drilling rods.
- Fluid Tank and Mixer: Vermeer fluid tank characterized by a capacity of 1000 gallons (3785 L).



Figure 324. Photo. Machinery used: rig.



Figure 325. Photo. Machinery used: CASE CX160 excavator.



Figure 326. Photo. Machinery used: CASE CX160 excavator.



Figure 327. Photo. Machinery used: fluid tank and mixer.

Equipment used in this project included the following (photos presented in Figure 328–Figure 331):

- Drill bit: slanted bit.
- Reamers: a 15 in. (38 cm) mixer-cutter reamer.
- Pipe pull head.
- Swivel.
- Walkover tracking system.



Figure 328. Photo. Equipment used: slanted drill bit.



Figure 329. Photo. Equipment used: cutter-mixer reamer.



Figure 330. Photo. Equipment used: pull head.



Figure 331. Photo. Equipment used: swivel.

Materials used in this project included the following (photos presented in Figure 332–Figure 335):

- Steel Casing: 10 in. (25.4 cm) steel casing, 200 ft (61 m) in length.
- PVC pipe: 4 in. (10 cm) diameter.
- ProAction drilling fluid agents: ClayLock, ProDrill, and ProDyne.



Figure 332. Photo. Materials used: 10 in. (25.4 cm) steel casing.



Figure 333. Photo. Materials used: restrained joint 4 in. (10 cm) PVC pipe.



Figure 334. Photo. Materials used: pipe lube.



Figure 335. Photo. Materials used: ProAction drilling fluid agents (ClayLock, ProDrill, and ProDyne).

G.6.7.3 Execution Metrics

Work Area Preparation:

The preparation for the drilling was performed before the start of the drilling. It included clearing a work area in the cornfield north of the road (and railroad) and the soy-bean field south of the road and laying the steel casing on the northern end. A trench was dug on each end of the planned profile around 20 ft (6.1m) away from the railroad (on the northern end) and 20 ft (6.1 m) away from the road (on the southern end). The trenches were used as both bore entry and receiving pits and were around 10 ft (3 m) deep.

Steel Casing Welding:

The 40 ft (12 m) segments of the steel casing were welded together into one 160 ft (48.8 m) long casing (Figure 336). This length was thought to be enough. Later, once the 160 ft (48.8 m) pipe was pulled, and the steel casing end did not show up, an additional 40 ft (12 m) segment was welded to the casing in place, bringing the total length of the casing to 200 ft (61 m).



Figure 336. Photo. Photo of the welding connection of two casing segments.

Pilot Drilling:

The rig was placed around 50 ft (15 m) to the southern side of the road. After the trench (the drill entrance pit) exposed the water main, the driller had to ensure that the drilling path is deep enough to avoid damaging the water main. The drilling started at around 8:20 a.m. and finished by 9:20 a.m.

(Figure 337). A walkover system was utilized to navigate the path of the bore. The boring passed around 3 ft (0.9 m) below the water main. The drill bit was then removed in preparation to install the reamer.



Figure 337. Photo. The northern trench, a receiving pit, after the end of the pilot drilling. The drill bit was removed in preparation to install the reamer.

Reaming:

A cutter-mixer reamer was installed to the end of the drill string, and, before pulling it back, some drilling fluid was ejected from the nozzles of the reamer to ensure that most of the nozzles were not obstructed, and hence can deliver the drilling fluid necessary for reaming (Figure 338–Figure 339). The reaming started around 9:45 a.m. and ended around 11:30 a.m. The rig operator was swabbing the hole after reaming each rod-length: he would pull a rod while reaming, and, once this rod was fully pulled, he would push it back to clean the hole before pulling it back again then detaching it from the drill string to pull the next rod. This process consumes more time than just pulling, but the drilling subcontractor explained that, by cleaning the hole in this way, the chances for obstructing the path of drilling fluid, which might cause building up of pressure and possibly fracking, greatly decrease. Throughout the reaming stage, a good flow of cuttings was observed especially while swabbing (Figure 339).

The reaming was interrupted many times by passing trains. The railroad inspector signaled to the drilling team to stop operations before the arrival of any train and signaled again after the train passed the drilling site (Figure 341). This stoppage happened three times and varied in time according

to the length of the passing train. Some pauses were also needed to wait for the fluid tank to go to fill water.

After the hole was fully reamed, and the reamer appeared at the southern trench, the reamer was pushed back to the northern trench (Figure 340).



Figure 338. Photo. The cutter-mixer reamer being tested before starting the reaming.



Figure 339. Photo. Good flow observed at the northern trench, the receiving pit.



Figure 340. Photo. The drill entrance pit after the end of the reaming. The reamer appears in the bottom left of the photo. Some of the drilling fluid appears in the bottom right of the photo.



Figure 341. Photo. A passing train. Reaming operations were paused before the arrival of the train and resumed after its departure.

Pipe Handling:

The excavator dug a narrow trench that can contain the steel casing while it is being pulled. The excavator then incrementally pulled the steel casing down the narrow trench using a steel chain (Figure 342–Figure 343).



Figure 342. Photo. The narrow trench the excavator dug to contain the steel casing while it is being pulled.



Figure 343. Photo. The pipe after it was pulled down into the narrow trench.

Pipe Pulling:

The pull head was attached to the steel casing. A swivel was used to connect the reamer with the pull head as presented in Figure 344–Figure 345. The pulling started at around 1 p.m., and continued till around 2:30 p.m., when most of the pipe was pulled and the pull head did not show up on the southern end, indicating that the length of the steel casing was not enough. Realizing this issue, the last 40 ft (12 m) steel casing segment had to be welded in place, so the narrow trench was deepened to allow a good alignment of the segment with the steel casing. While doing that, a clay drainage tile was encountered and broken, then replaced by a PVC segment.



Figure 344. Photo. The pull head attached to the steel casing.



Figure 345. Photo. The steel casing, attached to the pull head, swivel, and reamer before pipe pulling starts.

Meanwhile, the 10 ft (3 m) segments of the restrained joint PVC pipe to be installed inside the steel casing were assembled and lined parallel to the narrow trench on the northern side, as presented in Figure 346–Figure 347.



Figure 346. Photo. The assembly of the PVC pipe, before pushing it into the steel casing. (1)



Figure 347. Photo. The assembly of the PVC pipe, before pushing it into the steel casing. (2)

After welding the 40 ft (12 m) steel segment, the pulling resumed at around 4:00 p.m. and was done just before 4:30 p.m. The steel casing appeared at both ends of the boring as presented in Figure 348–Figure 349.



Figure 348. Photo. The steel casing after it was pulled into the bore.
Photo of the steel casing end at the northern trench (the receiving pit).



Figure 349. Photo. The steel casing after it was pulled into the bore.
Photo of the steel casing end at the southern trench (drill entrance pit).

Cuttings Disposal and Site Restoration:

The cuttings were being removed by the excavator and dumped next to the side of the northern trench (Figure 350–Figure 351). Towards the end of the pipe pulling, the excavator and the bulldozer worked on filling the narrow trench and part of the main northern trench (receiving pit). The cuttings were mixed with the cut soils and were used for fill.



Figure 350. Photo. The excavator removing the cuttings from the northern trench (receiving pit created for pulling the pipe) before dumping them on the side of the trench.



Figure 351. Photo. The excavator and bulldozer working on filling the trenches.

G.6.8 Performance Metrics

There were no incidents (frack-out, inadvertent return, sink holes, etc.) observed during the installation.

G.6.8.1 Surface Deformation

A surveying crew from IDOT District 6 took an initial survey of the surface of the road on July 24, 2019, before the beginning of construction. This set of measurements is taken as the baseline. After the end of construction (on October 7, 2019), another set of measurements was taken. The comparison of the elevations before and after the construction is presented in Figure 352. The comparison shows that the elevation of the road changed very little. The noticeable differences are because fewer points were taken before construction (reflected by the straight black line between -12 ft (-3.7 m) and -25 ft (-7.6 m) in the center and bottom figures) and because the points of measurement before and after construction are not the same location. The pavement elevations [between -12 ft (-3.7 m) and 12 ft (3.7 m)] before and after construction are almost identical.

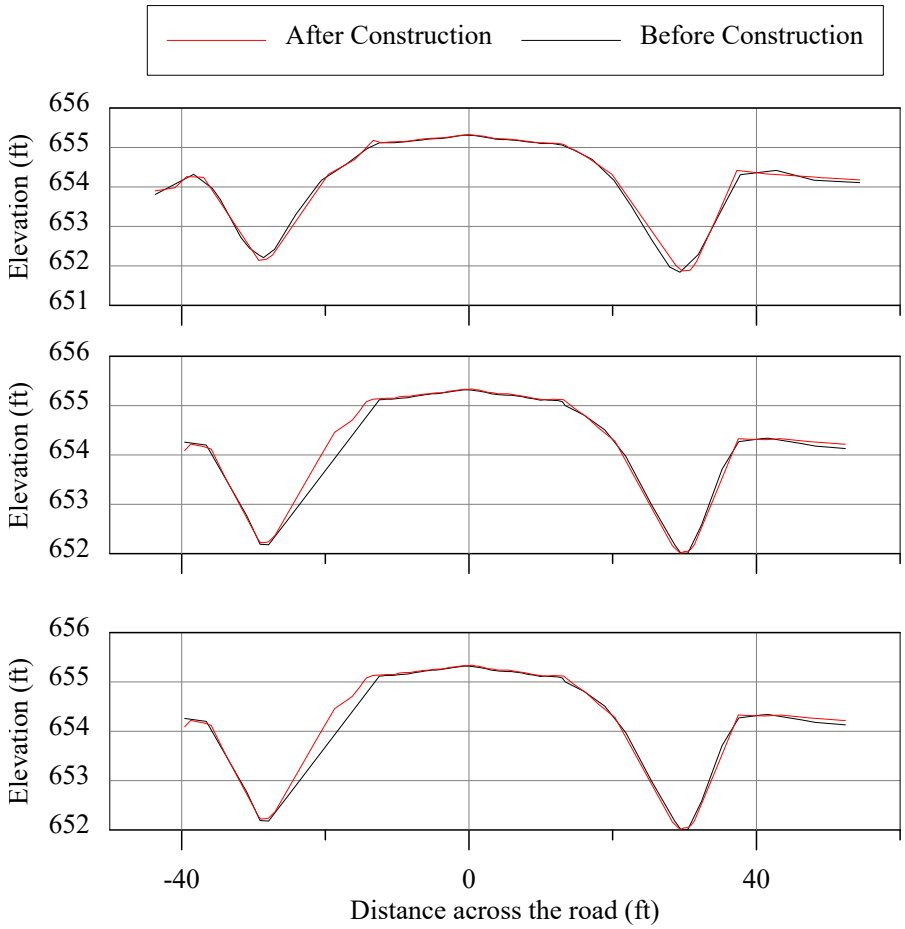


Figure 352. Graph. Comparison of road elevation before and after construction. Top: 30 ft (9.14 m) left of the alignment. Center: Along the alignment. Bottom: 30 ft (9.14 m) Right of the alignment.

G.6.8.2 Long-Term Measurements

Not available.

G.6.9 Important Remarks and Conclusions

G.6.9.1 Contractor's Experience

The drilling subcontractor was very helpful and shared some of his experience. The points he made are summarized below:

- On the ProAction agents used in the drill fluid mix: "Claylock prevents the clay from swelling. Prodrill is a thick viscous lubricant that can suspend cuttings." The contractor demonstrated the role of the ProAction agent ProDyne by mixing a small quantity of the agent with a cup of water. The mix was not typical, as the quantity of the agent relative to the quantity of water was very high. After mixing thoroughly, the mix became very thick with a consistency and smell close to that of wood glue (Figure 353). The mix was capable of suspending soil particles that the subcontractor threw into it. However, the actual mix was much thinner and might behave differently.



Figure 353. Photo. A very thick mix of the drilling fluid, which the contractor prepared to demonstrate the properties of the ProAction Fluids agents that he is using.

- On Swabbing: "Reaming then swabbing for every rod helps avoid fracturing of the ground and damaging the road. This method enabled him to drill a 1000 ft (304.8 m) boring at 5 ft (1.5 m) depth without needing pressure relief holes. Swabbing also prevents the hydro-locking of the pipe due to elevated pressures."

- On PVC casings (not pipes): "Although not used in this case, PVC casings are cheaper, more flexible and easier to handle. It was usually thought that the main role of the casing is to

support the ground around the pipe, but now it is realized that the main purpose of the casing is to prevent erosion of the surrounding materials in case the water main was damaged. This protection against erosion is provided by the PVC."

- On Reamers: "Compaction reamers compact the soil in the hole. If the soil has no way to go, it might result in fracking of the ground. In sand those reamers might work, but in clay they don't. In cobles, they might be preferable."

- On overcut size: "Actual over-ream size of reamer depends on the reamer type."

- On installing fiberoptic lines: "Sometimes a special kind of weak swivels are used instead of steel swivels to protect installed fiberoptic lines from being over tensioned. Those swivels will break once the tension exceeds a certain threshold. They hence act like fuses."

- On detecting the potential for hydro-lock and hydro-fracture onsite: "Once the pulling pressure (measured by the rig) quickly spikes while reaming or pulling the pipe, you know you are experiencing a hydro-lock and the chances for hydro fracture increases."

- On general equipment information: A useful website to check the types of HDD equipment is www.MelfredBorzall.com.

G.6.10 Lessons Learned

The main lessons learned from Jacksonville case history include the following:

- Some fluid mixes that are not bentonite-based are being used in the industry and seem to work well in some ground conditions.

- Selecting an adequate reamer type is essential in avoiding build-up of pressure inside the hole. The contractor recommends avoiding compaction reamers for fine-grained soils that cannot consolidate quickly as reaming is happening (in contrast with coarse-grained soils that can be compacted by those reamers).

- Railways impose different special restrictions on HDD construction (frequent stops as trains pass) and design (deeper embedment depth) that have to be considered when planning for HDD projects.

- The needed length of the casing should be properly estimated before the construction to avoid the need of attaching extra casing sections while pulling the pipe, as this causes delays and would require the extra sections to be attached to the casing while the casing is bent inside the boring.

- Trench support should be provided for deep trenches to protect laborers that have to go into the trenches, if this is needed (for example, to change the drilling bit, attach reamer, fix the pipe, etc.).

G.7 FARMER CITY CASE HISTORY

G.7.1 Project's Goal

In this project, a 12 in. (30.5 cm) HDPE casing will be installed beneath the interstate highway I-74 (Figure 354), and then an 8 in. (20.3 cm) HDPE water main will be installed inside the casing. The total length of the boring is 400 ft (1219 m), approximately. This new line will be installed next to three other lines, which were installed shortly before the installation of this line.



Figure 354. Photo. Interstate highway I-74.

G.7.2 Location and Surroundings

The project is located northwest of the I-74 and IL-54 interchange (Figure 355–Figure 357) northeast of Farmer City of Dewitt County, Illinois. Its GPS coordinates are 40°15' 12"N 88°37'40"W.

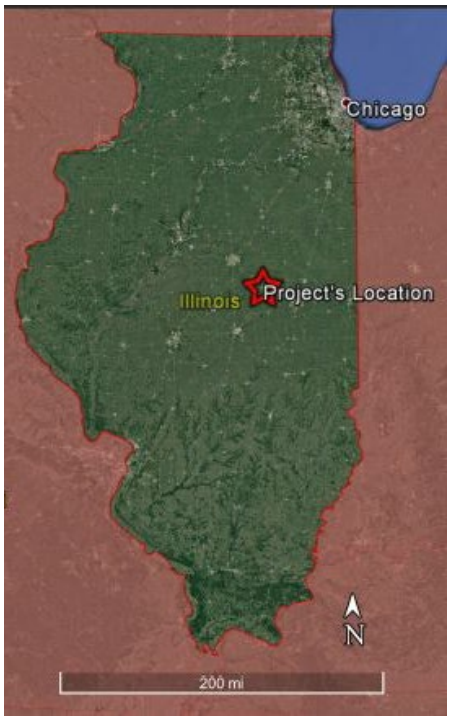


Figure 355. Photo. Google Maps captures showing Farmer City project on state levels.

Source: Google Maps

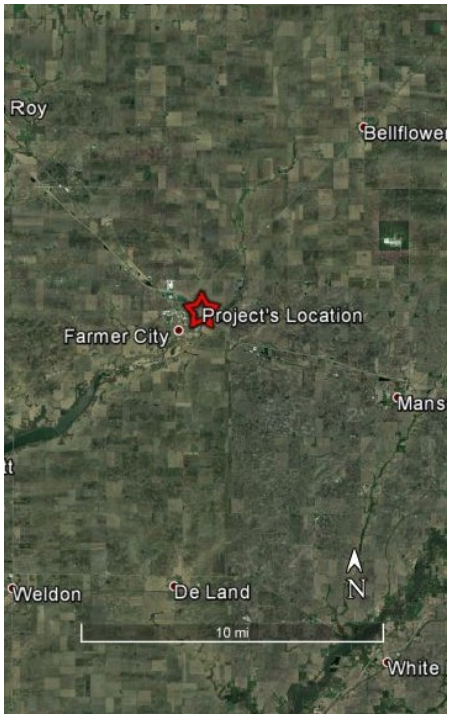


Figure 356. Photo. Google Maps captures showing Farmer City project on county levels.

Source: Google Maps



Figure 357. Photo. Google Maps captures showing Farmer City project on neighborhood levels.
Source: Google Maps

The job site is surrounded by a corn field on the northern side and a soybean field on the southern side (Figure 358–Figure 359). The closest structure is more than 500 ft (152 m) away from the proposed alignment. Hence, the road is the only structure that might be impacted because of the HDD. The closest utilities are the three lines of utilities previously installed by the same contractor using HDD.



Figure 358. Photo. Northern side of the site.



Figure 359. Photo. Southern side of the site.

G.7.3 Description of the Previous HDD Borings

As mentioned above, the boring documented in this report was preceded by three adjacent borings. The horizontal spacing between borings is around 10 ft (3 m). The profiles of those three borings are very similar to the fourth boring (documented in this report), which will be described in section G.7.5. The construction of those three lines was not observed by the UIUC team but was described by the contractor.

The first two borings were completed without any issues. However, while boring the third boring, fracking occurred and damaged the pavement in the southern lane of I-74. The construction was ceased, and the pavement was repaired, as presented in Figure 360.



Figure 360. Photo. Pavement which was repaired after the occurrence of fracking.

The contractor thinks that this fracking happened because no pressure relief holes were used and because the entry point is significantly higher than the road, which resulted in a significant fluid head.

G.7.4 Site Conditions

G.7.4.1 Geology

The geology of the area including Farmer City and its surroundings was studied by Soller et al. (1999), who showed that the shallow quaternary deposits are mostly tills of different formations as presented in Figure 361.

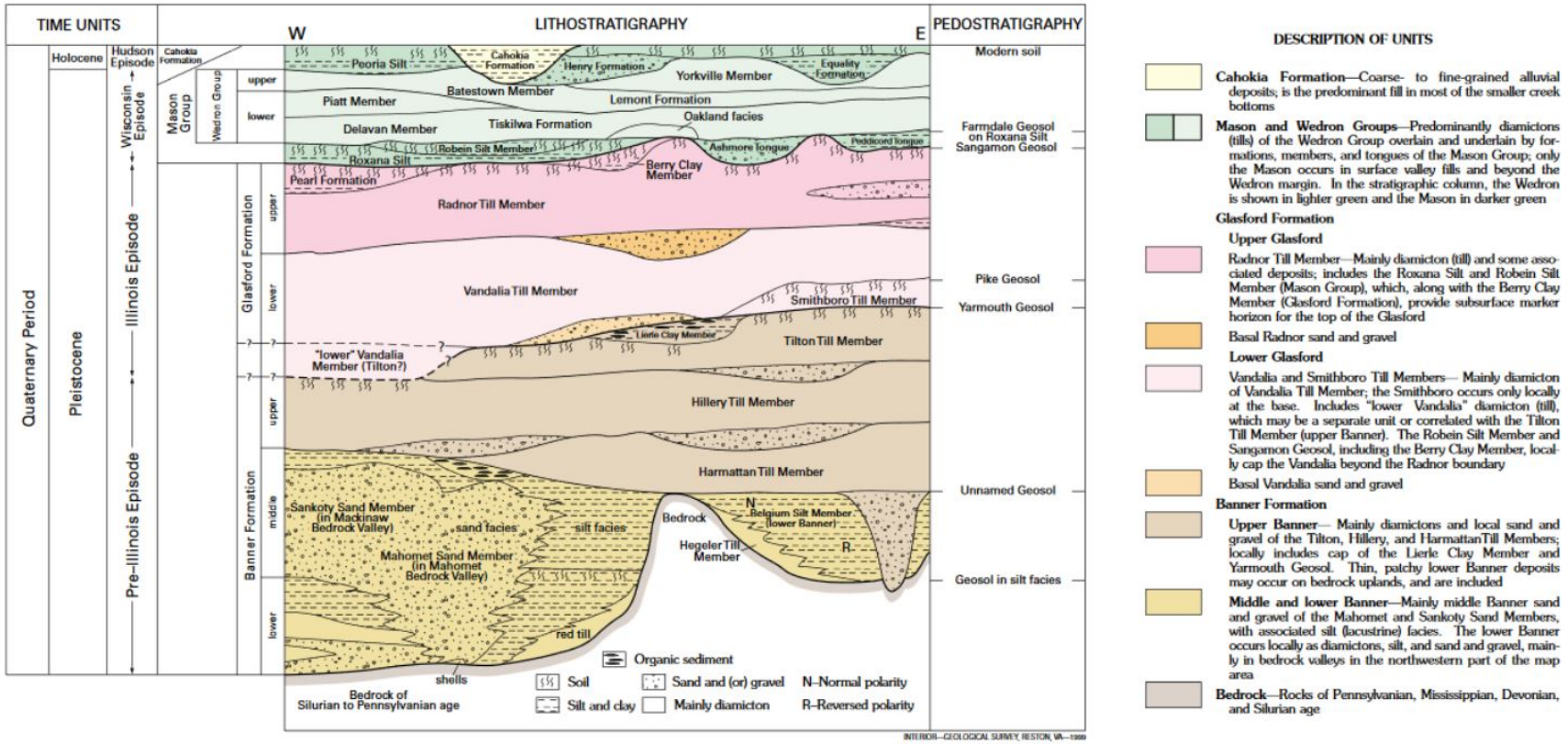


Figure 361. Graph. Diagrammatic stratigraphic column of glaciogenic sediments in east-central Illinois.

Source: Soller et al. (1999)

G.7.4.2 Soil Conditions

Three 25 ft (7.6 m) deep soil borings were bored prior to the commencement of the HDD boring documented in this report and after the occurrence of the fracking described above. The borings were performed by Ramsey Geotechnical Engineering. The borings were performed at the two edges of the interstate highway and in the median as presented in Figure 362. The soil boring logs are presented in Figure 363.

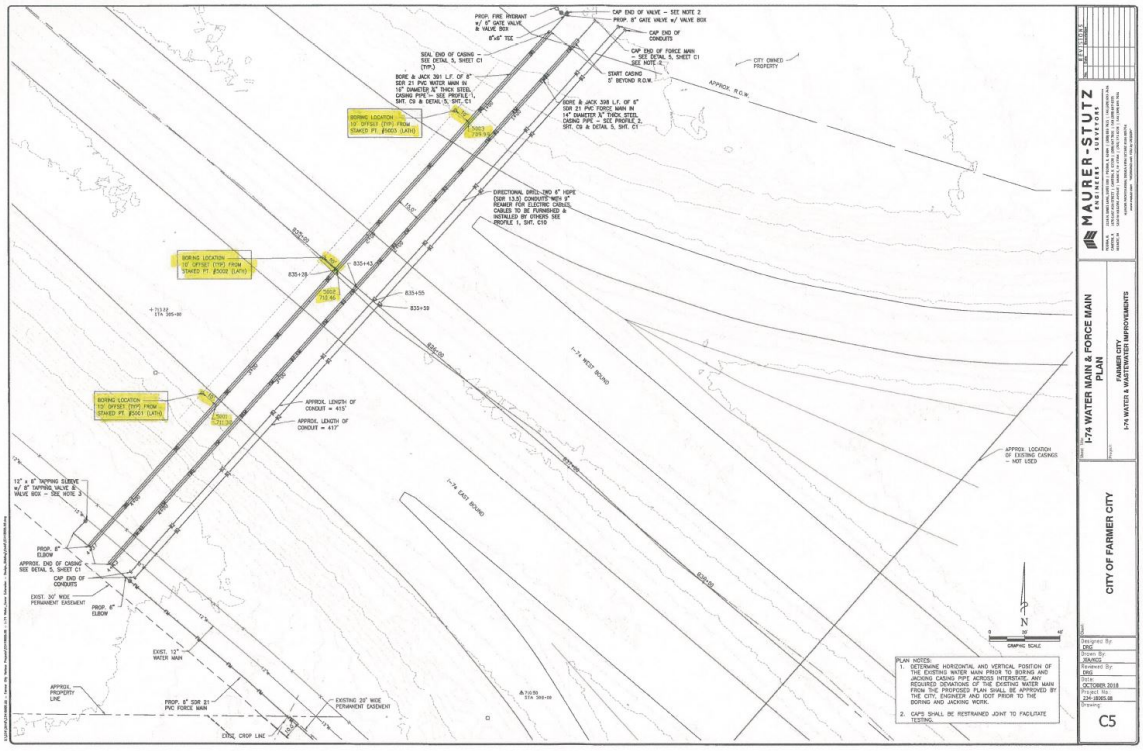


Figure 362. Graph. Locations of the soil borings relative to the interchange.

Source: Ramsey Geotechnical Engineering geotechnical investigation report

The geotechnical report by Ramsey Geotechnical Engineering, based on those three borings, describes the soil conditions at the site, and the findings from the report are summarized next: With the exception of a layer of sand in the upper 2 ft (0.6 m) at the northern boring, the soils for the entire depth of the borings consist of glacial till clay loam that contains approximately 75% to 80% silt and clay-sized particles with the remainder consisting of sand and gravel. Upper layers of the clay loam are characterized by a high stiffness with unconfined compressive strength values ranging from 2.0 up to around 8.0 tsf (191 to 796 kPa). The moisture content in these soils is generally below 15%. Groundwater was not encountered while drilling even after the completion of the borings.

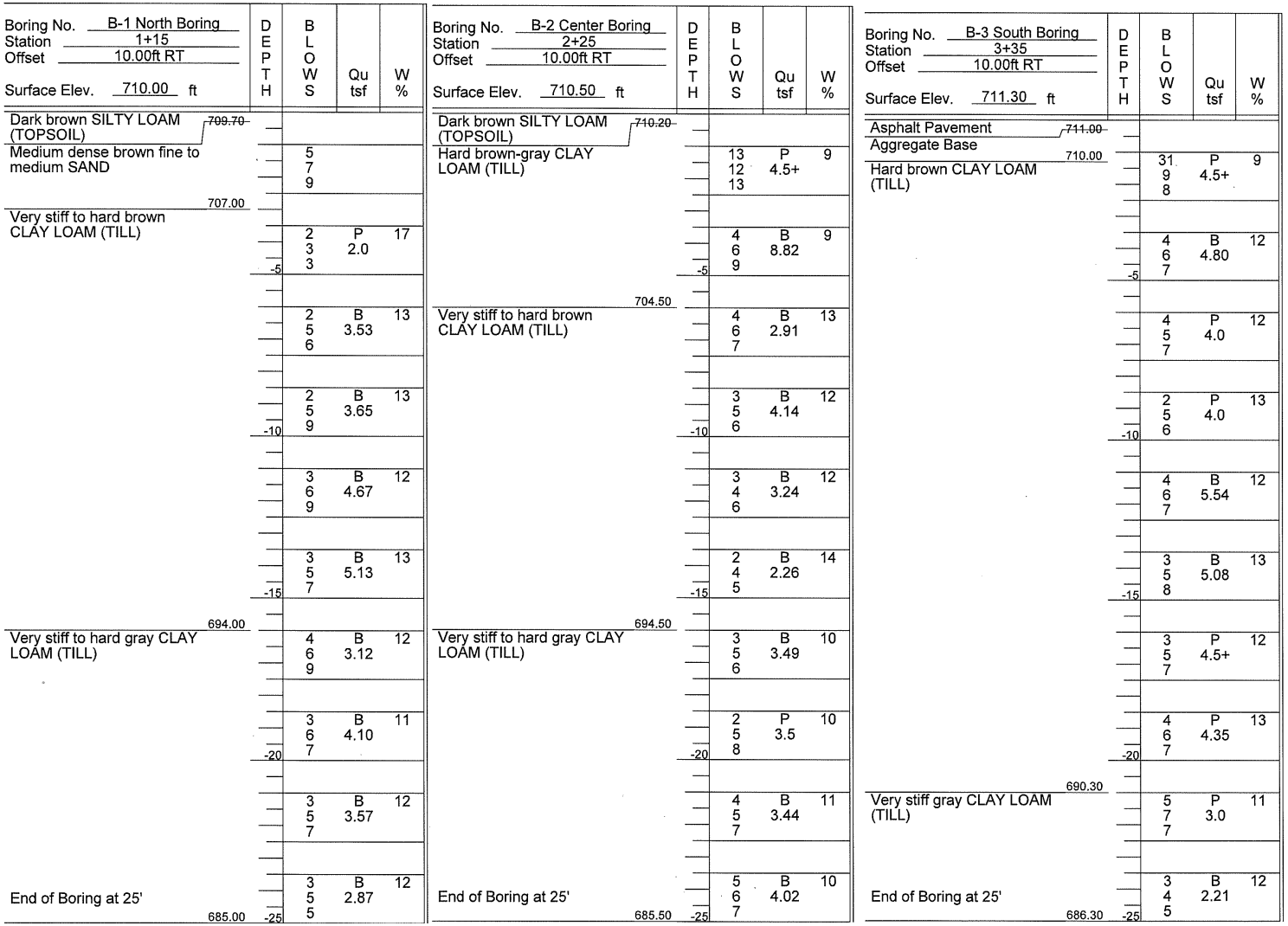


Figure 363. Chart. Soil boring logs at the north, median, and south of the interstate highway.

Source: Ramsey Geotechnical Engineering geotechnical investigation report

G.7.5 Design

The initially planned profile for the fourth boring is presented in Figure 364. The design requires a minimum cover of 5 ft (1.5 m). The elevation difference between the entry point and the lowest points of the boring which are beneath the interstate highway exceeds 10 ft.

After the fracking during the third boring occurred, and the soil investigation was performed, the design was modified as follows:

- The minimum depth of cover was increased to 8 ft (2.4 m).
- Three pressure relief holes were added at the northern and southern sides of the highway at the ditches and at the median.

There is no available information about any pressure calculations that may or may not have been done to check the possibility of fracking. The contractor, when asked, said that he is not aware that such calculations were done.

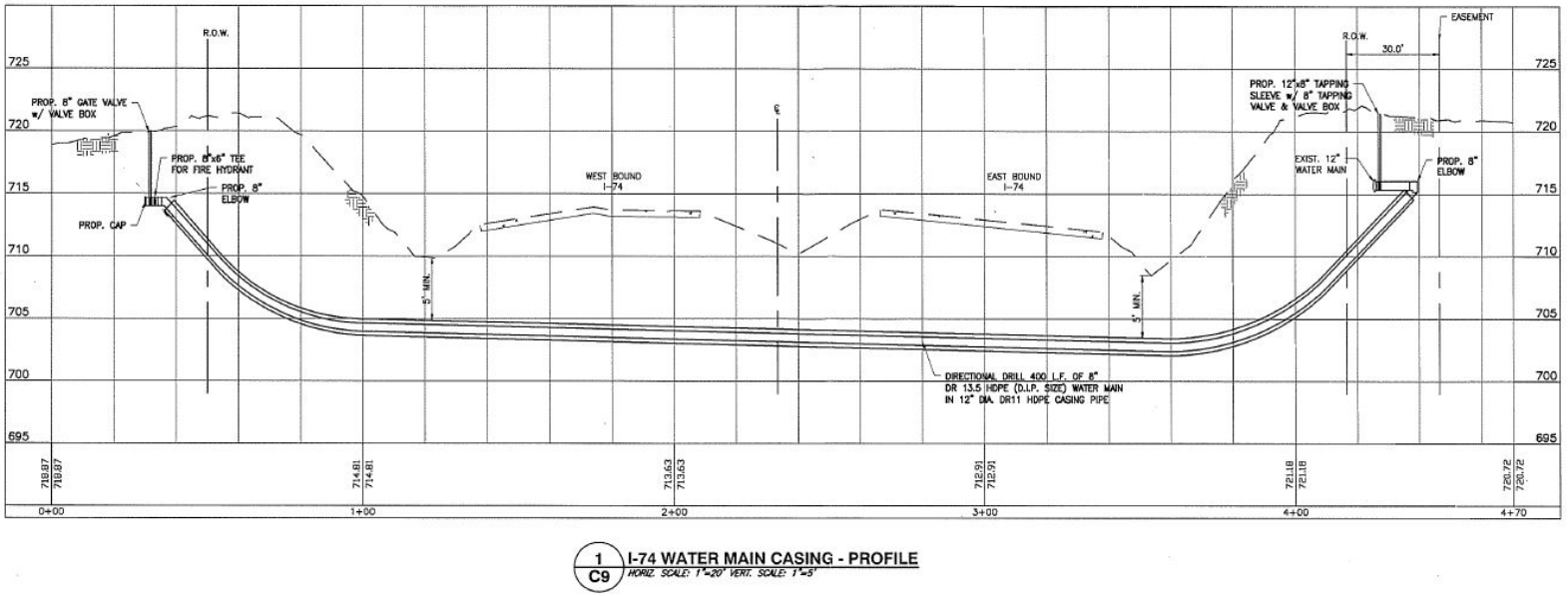


Figure 364. Graph. Original planned alignment of the water main.

G.7.6 Entities and People Engaged

In addition to IDOT, the other company engaged in this project was B&T Drainage (http://www.btdrainage.com), which is the horizontal drilling contractor.

The main points of contact during this project were IDOT's Central Office Geotechnical Engineer Heather Shoup, District 5 Geotechnical Engineer Rustin Keys, and District 5 Permit Technician Joshua Lowry in addition to the contractor from B&T Drainage.

G.7.7 Execution

G.7.7.1 Settings

The HDD boring, reaming and casing, and pipe pulling were all performed on October 3, 2019. No precipitation occurred during the construction activities, and temperatures varied between around 52 and 71°F (11 and 22°C).

G.7.7.2 Machinery, Equipment and Materials

Machinery used in this project included the following (photos presented in Figure 365–Figure 369):

- Rig: Vermeer D60x90 which uses 15 ft (1.5 m) long 3.5 in. (9 cm) diameter drilling rods.
- Fluid Tank and Mixer: Vermeer MX240 fluid tank and mixer characterized by a capacity of 1000 gallons.
- Excavators: Case 580 series 2 backhoe loader and John Deere 60G excavators.
- Pipe Fusor: McELROY fusor.

Equipment used in this project included the following (photos presented in Figure 370–Figure 372):

- Drill bit: slanted bit.
- Reamers: a helical reamer.
- Pipe pull head.
- Swivel.
- Walkover tracking system.

Materials used in this project included the following (photos shown in Figure 373–Figure 374):

- Steel Casing: 12 in. (30.5 cm) casing, approximately 200 ft (61 m) in length.
- HDPE pipe: 8 in. (20.3 cm) in diameter.

- Mi SWACO drilling fluid agents: PLATINUM ROD EASE and POLY-PLUS.
- Bentonite.



Figure 365. Photo. Machinery used: rig.



Figure 366. Photo. Machinery used: fluid tank and mixer.



Figure 367. Photo. Machinery used: John Deere 60G excavator.



Figure 368. Photo. Machinery used: Case 580 series 2 backhoe loader.



Figure 369. Photo. Machinery used: pipe fusor.



Figure 370. Photo. Some of the equipment used: slanted drill bit.



Figure 371. Photo. Some of the equipment used: cutter-mixer reamer.



Figure 372. Photo. Some of the equipment used: pull head.

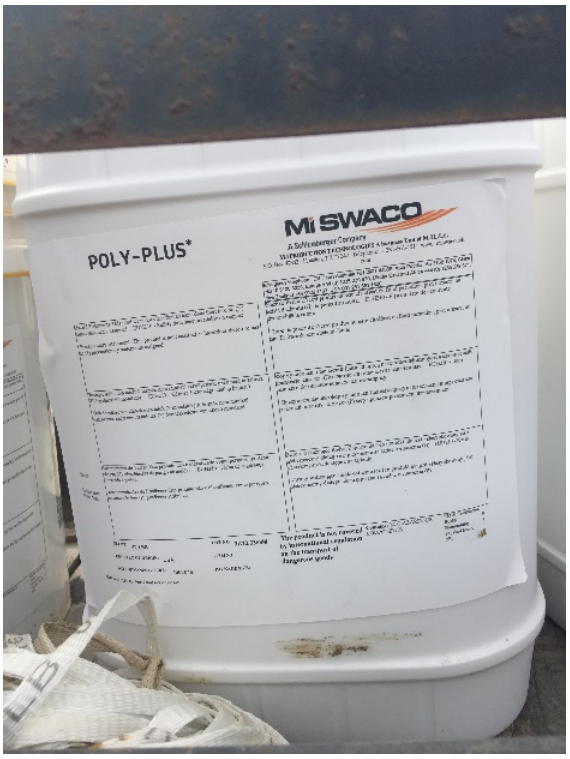


Figure 373. Photo. Some of the materials used: Mi SWACO drilling fluid agents POLY-PLUS.



Figure 374. Photo. Some of the materials used: PLATINUM ROD EASE.

G.7.7.3 Execution Metrics

The drilling for the fourth boring started on the morning of October 3, 2019. The drilling and casing pulling were observed by IDOT's Permit Technician Joshua Lowry, and he reported no issues. The construction was very fast; the casing pulling was completed around 3 p.m.—the time at which the UIUC team arrived at the field. The UIUC team observed the product pipe handling and pulling and interviewed the contractor. The information on previous stages comes mostly from what the contractor reported to the UIUC team.

The pilot drilling was performed using a slanted drill bit, which is tracked by a walkover system. POLY-PLUS and PLATINUM ROD EASE drilling fluid agents are added to the bentonite-based drilling fluid. The pilot drilling was started at the entry (northern) side where the rig was staged.

After the pilot drilling was completed, the drilling bit was removed, and the helical reamer was attached to the drill string and used to ream the boring.

The UIUC team asked the contractor if the hole was swabbed during reaming, and the contractor replied that swabbing was not used. This might explain the speed at which the boring was completed.

After the reaming was completed, the pull head was attached to the HDPE casing, and the casing was pulled throughout the boring as presented in Figure 375 and Figure 376. The pull head was then removed, and the extra length of the casing was cut using an automatic saw (Figure 377–Figure 379). Upon realizing that the elevation of the casing at the exit side was high, the excavator was used to push the casing downward, then the soil was dumped on the top of it to lock it in place at the proper elevation.



Figure 375. Photo. The casing pulling. The pull head at the exit (southern) side, before pulling started.



Figure 376. Photo. The casing pulling. Photo of the pull head appearing at the entry (northern) side.



Figure 377. Photo. The casing. Photo at the entry (northern) side.



Figure 378. Photo. The casing at the exit (southern) side before the extra length of casing was cut.



Figure 379. Photo. The casing after its extra length was cut, and its elevation was lowered, forcing it down using the excavator then dumping soil on the top of it to lock it in place.

During the reaming and casing pulling, the drilling fluid was flowing out of the pressure relief holes, as presented in Figure 380–Figure 382.



Figure 380. Photo. Drilling fluid appearing at the northern pressure relief holes.



Figure 381. Photo. Drilling fluid appearing at the southern pressure relief holes.



Figure 382. Photo. Drilling fluid appearing at the median pressure relief holes.

After the casing was in place, the slanted drill bit was attached again to the drill string at the rig and pushed all the way through the casing from the entry side till it showed at the exit side as presented in Figure 383.



Figure 383. Photo. The slanted drill bit at the exit side after it was pushed through the casing.

The 8 in. (20.32 cm) HDPE product pipe then had to be placed next to the exit (southern) side before being pulled. The pipe was at the fusing machine location, hundreds of feet away from the exit pit. The excavator's arm was chained to the pull head fused to the pipe, and then the excavator dragged the pipe over the ground without any rollers, until it reached the exit side of the boring as presented in Figure 384–Figure 385.



Figure 384. Photo. The product pipe at the fusing machine being chained to the excavator arm before being pulled to the exit side of the boring.



Figure 385. Photo. The product pipe being dragged on the ground. The red arrow shows the location of the fusing machine.

After arriving at the exit side, the pipe had to be rotated to align with the casing. The two excavators were used to orient the pipe horizontally and vertically before the pipe was pulled through the casing by chaining the drill bit to the pull head, as presented in Figure 386–Figure 388. A tracing wire was pulled with the product pipe.



Figure 386. Photo. The excavator orienting the pipe in the horizontal plane.



Figure 387. Photo. The second excavator orienting the pipe in the vertical place.



Figure 388. Photo. The pipe being pulled through the casing.

G.7.8 Performance Metrics

G.7.8.1 Surface Deformation

Hydro-fracturing occurred during the installation of the third line. The damaged pavement was required to be repaired before the HDD installation of the fourth line could begin. Road surface settlement and uplift were introduced by hydro-fracturing, as presented in Figure 389–Figure 391.



Figure 389. Photo. Road deformation due to hydro-fracturing during the HDD construction. (1)



Figure 390. Photo. Road deformation due to hydro-fracturing during the HDD construction. (2)



Figure 391. Photo. Road deformation due to hydro-fracturing during the HDD construction. (3)

G.7.8.2 Long-Term Measurements

Long-term surface deformation is limited to visual observation. There was no issue found at the time of the observation till December 2020. There was no pipe testing performed for this construction.

G.7.9 Lessons Learned

Many lessons can be learned from this case history:

- Pressure calculations are essential in checking the possibility of fracking, and important design modifications might be made such as using pressure relief holes or increasing the depth of cover.

- Pressure relief holes and increased depth of cover were effective in reducing the risk of fracking. While fracking happened in the third boring, it didn't happen in the fourth boring after those measures were taken.

- Despite the high strength of the clay deposits, they were still susceptible to fracking, especially at shallow depths.

- Swabbing might help in cleaning the boring and preventing its blockage which might lead to accumulation of pressure and possibly to fracking.

- The importance of proper handling of the product pipe: a product pipe—and even a casing—might be damaged if subjected to high stresses because of dragging on the ground or being excessively bent. A plan should be prepared for handling the pipe, and the bent angles must be calculated and kept within safe limits to protect the pipe.

- HDD installations where the pavement is below the level of the entry and exit points are characterized by extra vulnerability to frac-outs since the elevation difference adds to the rig's pumping pressure. The bigger the elevation difference, the bigger the role of this component.

- Extra caution should be given to critical highways like the interstates because damaging them would result in significant traffic disruption and large repair costs.

- Handling the pipe or casing should be planned and executed properly. Sharp angles might damage the pipe or shorten its service life.

- Installing multiple lines in an area might give contractors extra confidence, and may encourage them to quickly execute similar lines, which might result in problems. The drilling, reaming, and fluid pumping rates should always be monitored and kept below acceptable limits.

- The presence of inspectors is necessary throughout the whole HDD process, including the casing and product pipe pulling.

- The alignment of the casing should be tested during and after the pilot drilling stage, and corrections should be made then, rather than waiting until after reaming or pipe pulling at which adjustments might be impossible or not feasible.

- It is important to closely monitor and adjust the profile elevation during the drilling and reaming process.

G.7.10 References

Soller, David R, Susan D Price, John P Kempton, and Richard C Berg. 1999. *Three-dimensional geologic maps of Quaternary sediments in east-central Illinois.* US Geological Survey.

G.8 LITCHFIELD CASE HISTORY

G.8.1 Project's Goal

In this project, a 16 in. (40.6 cm) restrained joint (RJ) PVC forced sewer main is to be installed under the interstate highway I-55 (Figure 392). The PVC pipe will be installed inside a 24 in. (61 cm) HDPE casing. The casing spans 330 ft (100.6 m) in length and is to extend at least from the edge of right-of-way to the edge of the right-of-way of the interstate highway and at least 10 ft beyond the edge of the pavement. This line is one of 4 water or sewer lines, 3 of which cross I-55, and one crosses IL-16, which the city of Litchfield intends to install.



Figure 392. Photo. Road I-55 (photo looking south).

G.8.2 Location and Surroundings

The project is located on the western edge of Litchfield, Illinois (Figure 393–Figure 395), just before the interchange of I-55 with IL-16. The GPS coordinates of the project site are 39°10'52"N 89°40'35"W.



Figure 393. Photo. Google Maps captures showing Litchfield project on state levels.

Source: Google Maps

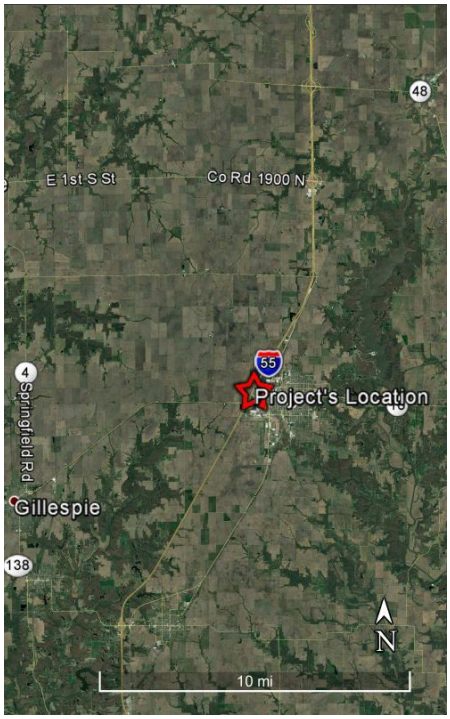


Figure 394. Photo. Google Maps captures showing Litchfield project on county levels.

Source: Google Maps

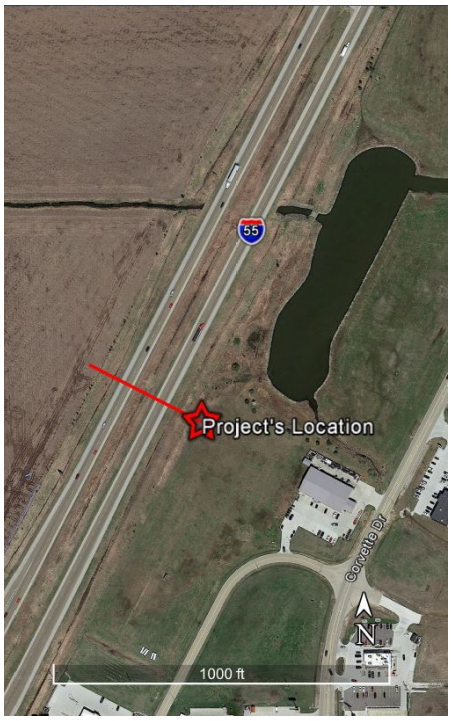


Figure 395. Photo. Google Maps captures showing Litchfield project on neighborhood levels.
Source: Google Maps

The proposed alignment is more than 200 ft (61 m) away from the nearest structure, a small building to the east of the alignment. A storm sewer line was close to the alignment, and precisely locating it on the first day delayed the start of the drilling.

G.8.3 Site Conditions

G.8.3.1 Soil Conditions

No borings were performed prior to the commencement of the project. However, the contractor said that he has performed many HDDs in the vicinity of this area and that he expects to encounter clay deposits. After digging the first trench (Figure 396) on the entry (eastern) side, visual inspection and manual field tests were possible. The top 5 ft (1.5 m) of soil seemed to be composed of desiccated black silty clay topsoil. The soil below the bottom of the trench was not exposed and hence could not be identified.



Figure 396. Photo. The entry (eastern) bore pit.

G.8.4 Design

The initial design of this line dictated the use of a jack and bore to install the casing (Figure 397). It also dictated the use of a steel casing; however, the design was modified later, changing the construction to horizontal drilling (Figure 398) and the casing material to restrained joint PVC. Apparently, the casing material was later changed to HDPE, as an HDPE pipe was used as a casing.

The HDD design shows a minimum depth of cover to the median of 5 ft (1.5 m) while the depth of cover to the pavement exceeds 10 ft (3 m). The profile is horizontal, extending between the entry and exit pits. The permit given for this project states that back-reaming is required and that multiple passes of reaming should be employed. It also states that the boring should be 25% to 50% greater in diameter compared to the casing.

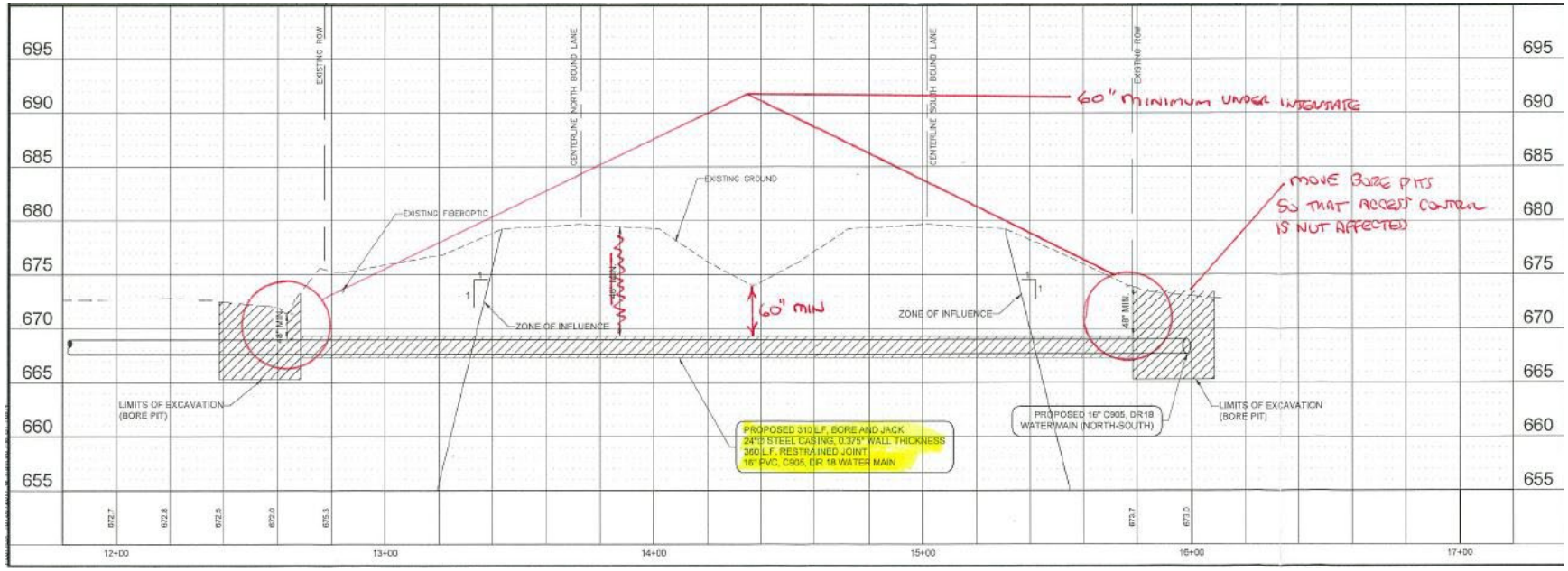


Figure 397. Graph. Cross section view of the initial design using the jack and bore construction method.

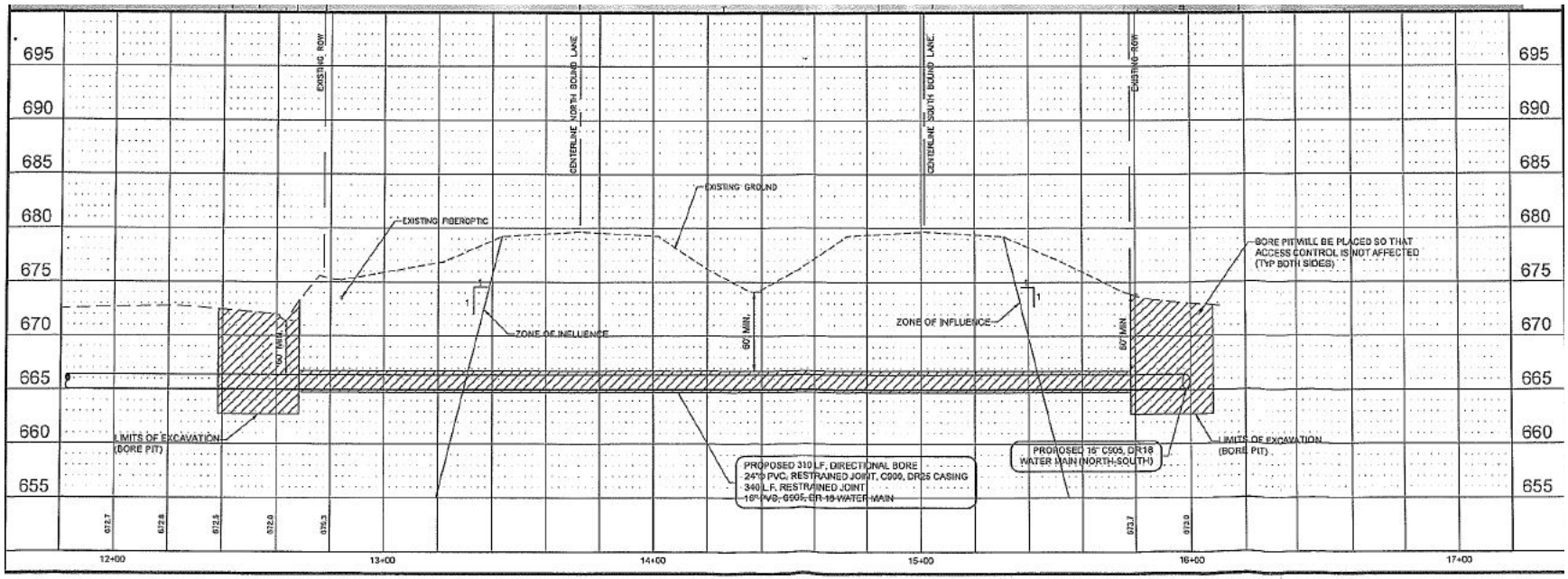


Figure 398. Graph. Cross section view of the new design using the horizontal directional drilling construction method.

G.8.5 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- The City of Litchfield, which is the owner of the utility.
- Ray's Construction Company, which is the horizontal drilling subcontractor.
- Heneghan and Associates (https://haengr.com/), which is the main contractor and also prepared the design for the line.

The main points of contact during this project were IDOT's District 6 Permit Technician and TRP member Joseph Angeli (email: Joseph.Angeli@illinois.gov; phone: 217-782-7744), Clinton Ray (email: info@t-rayconstruction.com; phone: 573-754-2590) from Ray's Construction Company, and Craig Thurston (email: Crthurston@heneghanassoc.com; phone: 618-946-2106) from Heneghan and Associates.

G.8.6 Execution

G.8.6.1 Settings

The execution of this project started on the morning of December 2, 2019, and by December 6, 2019, the HDPE casing pulling was finished. The temperature in Litchfield varied between 31 and 36°F (-0.56 and 2.22°C) on average over this period (Figure 399). Some precipitation was recorded in the first two days.

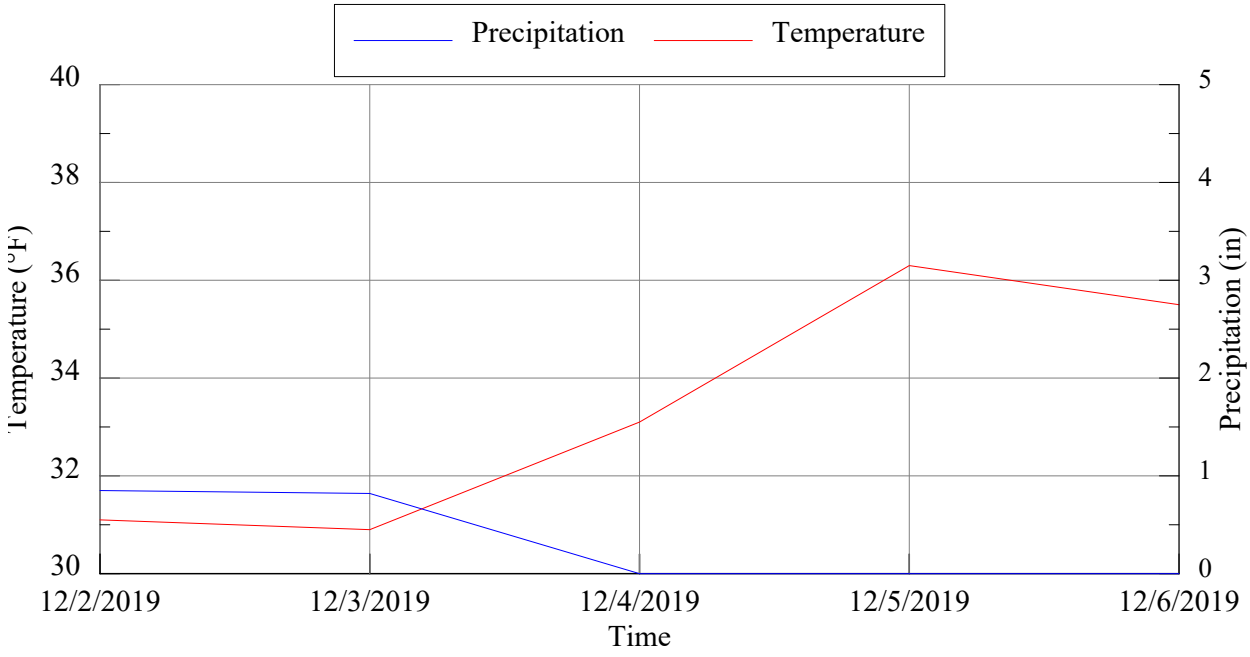


Figure 399. Chart. Temperature and precipitation in Litchfield, Illinois.

***Source:* https://www.wunderground.com/**

G.8.6.2 Machinery, Equipment and Materials

Machinery used in this project included the following (photos presented in Figure 400–Figure 403):

- Excavators: John Deere 310E backhoe loader and 2 Komatsu 200 LC excavators.
- Rig: Vermeer D36x50 rig. The rig uses 10 ft (3-m) long 2.625 in. (6.7 cm) diameter drilling rods and is characterized by a torque capacity of 5.5 kip-ft (7.5 kN/m), and a max pumping capacity of 70 gpm (265 L/min).
- Fluid Tank and Mixer: Vermeer MX240 fluid tank and mixer.

Equipment used in this project included the following (photos presented in Figure 404–Figure 405):

- Walkover tracking system.
- Slanted drill bit.

Materials used in this project included the following (photos presented in Figure 406–Figure 408):

- 24 in. (61 cm) HDPE casing.
- 16 in. (40.6 cm) RJPVC pipe.
- Drill Fluid Additive: DET CON 1 (by RightTurnSupply.com).



Figure 400. Photo. Machinery used: rig.



Figure 401. Photo. Machinery used: fluid tank and mixer.



Figure 402. Photo. Machinery used: John Deere 310E backhoe loader.



Figure 403. Photo. Machinery used: Komatsu 200 LC excavators.



Figure 404. Photo. Some of the equipment used: walkover system.



Figure 405. Photo. Some of the equipment used: slanted drill bit.



Figure 406. Photo. Some of the materials used: HDPE casing.



Figure 407. Photo. Some of the materials used: RJPVC pipe.



Figure 408. Photo. Some of the materials used: DET CON 1 drilling fluid agent.

G.8.6.3 Execution Metrics

The UIUC team observed the construction activities on December 2, 2019. Construction activities for the consecutive days were observed by Heneghan and Associates inspector Craig Thurston who shared his notes and photos with IDOT and the UIUC team. IDOT's Permit Technician, Joseph Angeli, also visited the site multiple times and shared his observations with the UIUC team. The description of the construction activities after December 2, 2019, is based on Craig's and Joseph's notes and photos.

Pilot drilling started on the eastern side of the interstate on December 2, 2019, around 1:30 p.m. (Figure 409–Figure 410). The drilling was delayed because the existing sewer line was not located early in the morning. Pilot drilling finished around 3:30 p.m. While drilling beneath the road, the police, based on a request from the contractor, assisted in slowing up and constraining the traffic to allow for the person with the walkover system to track the drill bit, which is necessary for steering the drill bit along the planned profile (Figure 411). Water for the drill rig was obtained from the hydrant, which was located 300 ft (91.4 m) away from the drill rig, as presented in Figure 412.

On December 3, 2019, the drill bit was removed, and a 16 in. (40.6 cm) fly cut reamer (Figure 413) was attached to the drill string. Some welding for the downhole assembly was needed, which delayed the start of the reaming. At 1:00 p.m., the back-reaming started and continued till it reached the entry pit. On December 4, 2019, the same 16 in. (40.6 cm) reamer was used to swab the hole. The HDPE casing was fused then welded to the pull head as presented in Figure 415–Figure 416. The HDPE casing was then dragged to the edge of the exit pit, as presented in Figure 417.

On December 5, 2019, the hole was reamed, this time using a 30 in. (76.2 cm) reamer (Figure 414). On December 6, 2019, the HDPE casing pulling started at 8:00 a.m. and finished at 12:30 p.m. (Figure 418–Figure 419).



Figure 409. Photo. Pilot drilling. (1)



Figure 410. Photo. Pilot drilling. (2)



Figure 411. Photo. Police assisting with the traffic control.



Figure 412. Photo. The water line feeding into the rig, connected to the hydrant.



Figure 413. Photo. The 16 in. (40.6 cm) fly cutter reamers.



Figure 414. Photo. The 30 in. (76.2 cm) fly cutter reamers.



Figure 415. Photo. The HDPE casing fusing.



Figure 416. Photo. The HDPE casing welding to the pull head.



Figure 417. Photo. The HDPE casing being dragged to the edge of the exit pit.



Figure 418. Photo. The HDPE casing being pulled into the hole at the exit pit. (1)



Figure 419. Photo. The HDPE casing being pulled into the hole at the exit pit. (2)

G.8.7 Performance Metrics

There were no incidents (frack-out, inadvertent return, sink holes, etc.) observed during the installation.

G.8.7.1 Surface Deformation

Not available.

G.8.7.2 Long-Term Measurements

Not available.

G.8.8 Important Remarks and Conclusions

G.8.8.1 Contractor's Experience

The drilling subcontractor Clinton Ray shared with the UIUC team some of his experience in HDD:

- The reamer type is very important for the success of drilling and the safety of structures above it. A compaction reamer may be used in sands and gravels. It would work by compacting the cut sand and gravel into the periphery of the hole. Using a compaction reamer in clay would not work because clay is not as compressible in short durations. The clay would squeeze around the reamer or stick to it. A fly cutter reamer is preferable for clay.

- Polymers are used in clays to prevent them from expanding. Bentonite is used to create a filter cake in sands and gravels to stabilize the soil.

- A rule of thumb, commonly used by the subcontractor, for calculating the fluid pumping (or drilling) rate is:

$$Drilling\ rate \cong \frac{D^2}{25} gallon\ per\ foot$$

Figure 420. Equation. An equation to calculate the fluid pumping (or drilling) rate.

  Where D is the diameter of the hole in inches.

- So, if the drilling rate is 1 ft/min (0.3 m/min), the fluid to be pumped is 36 gpm (136 L/min) for a 36 in. (91.4 cm) diameter hole.

- The subcontractor mentioned a project in which rainwater flooded an HDD boring. They grouted the whole boring to avoid any damage to superstructures due to caving.

- Open casing pull head is sometimes used to reduce the risk of pressure build-up. The pull head will have a cavity to which the drilling fluid can enter the casing, to release extra pressure while pulling. The fluid in the casing is then displaced when pulling the product pipe.

G.8.9 Lessons Learned

The following are lessons learned from this project:

- Contractor experience is necessary for critical projects, including those with crossings beneath interstate highways.
- Coordination between the contractor and the local authorities (city council, police department, etc.) might save all parties a lot of time and cost.

G.9 ROCHELLE CASE HISTORY

G.9.1 Project's Goal

In this project, two parallel steel casings, 20 in. (50.8 cm) and 12 in. (30.5 cm) in diameter, are to be installed under interstate I-39, north of the interchange with IL-38. The 20 in. casing is to house a water main while the 12 in. (30.5 cm) is to house a sewer main. Those crossings are part of a project, planned by the city of Rochelle and Pilot Travel Centers, that aims at extending the sewer and water services to the northeast corner of IL-38 and I-39 in the city of Rochelle, which includes the proposed Pilot Travel Center. The total length of the section to be installed by HDD is about 440 ft (134 m), out of the total length of the line extension of around 5000 ft (1524 m).



Figure 421. Photo. Road I-39 (looking south).

Source: Google Maps

G.9.2 Location and Surroundings

The project is located in Rochelle, Illinois (Figure 422–Figure 424), and its GPS coordinates are 41°56'16.6"N 89°01'26.9"W.

The nearest structures to the proposed alignment are more than 800 ft (244 m) away from the proposed alignment. Hence, the only structure that can be impacted by the construction is I-39 and its interchange with IL-38.



Figure 422. Photo. Google Maps captures showing Rochelle project on state levels.

Source: Google Maps

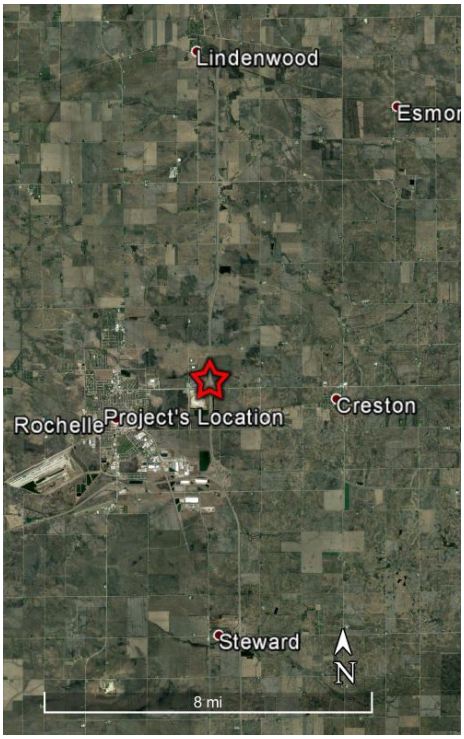


Figure 423. Photo. Google Maps captures showing Rochelle project on county levels.

Source: Google Maps

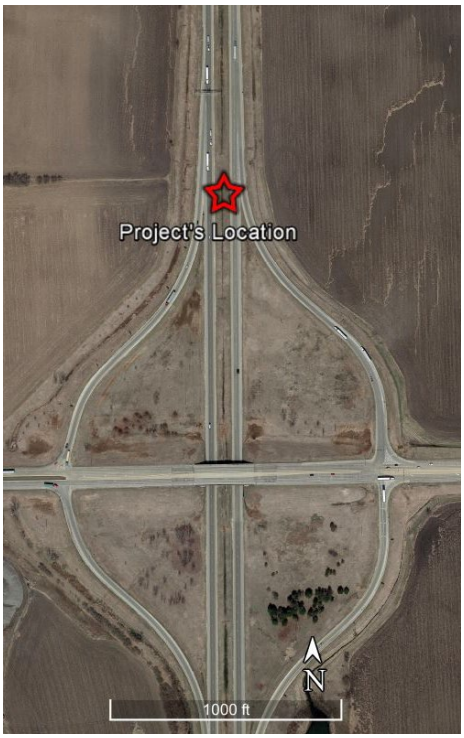


Figure 424. Photo. Google Maps captures showing Rochelle project on neighborhood levels.

Source: Google Maps

G.9.3 Site Conditions

G.9.3.1 Soil Conditions

Two geotechnical borings were drilled previously at the area of the project, for the sign truss structure 0.3 miles (483 m) north of the I-39 interchange with IL-38. Those boreholes, named in this report preliminary borings PB-1 and PB-2, are located around 400 ft (122 m) north of the proposed alignment and were advanced to the depth of auger refusal. PB-1, advanced 19 ft (5.8 m), shows medium, stiff to very stiff silty clay deposits in the top 8 ft (2.4 m), underlain by around 8 ft (2.4 m) of soft to medium sandy loam, underlain by 3 ft (0.9 m) of very dense weathered limestone. The groundwater table is shown at a depth of 7 ft (2.1 m). PB-2, advanced 14 ft (4.3 m), shows stiff clay loam in the top 4 ft (1.2 m), underlain by 4 ft (1.2 m) of stiff silty clay, then 3 ft (0.9 m) of stiff sandy loam. Dense weathered limestone is shown below 11 ft (3.4 m).

Sixteen borings were drilled for this project to depths ranging from 5.5 ft to 26.9 ft (1.7 m to 8.2 m), by ATC Group Services LLC, at locations decided by Pilot Travel Centers and Manhard Consulting, along the profile of those lines' extensions. Two of those borings, B-4 and B-5, were drilled next to the edges of I-39 and will be discussed in this report. The locations of those two borings and the preliminary borings are presented in Figure 425.

The B-4 boring reached refusal at just 5.5 ft (1.7 m) depth, at which limestone was encountered. The top 5 ft (1.5 m) were composed of 3 ft (0.9 m) of topsoil and fill, underlain by 1 ft (0.3 m) of medium

dense silty sand. The B-5 boring extended to a depth of 21.2 ft (6.5 m) at which fractured limestone was encountered. The soil column consisted of 1 ft (0.3 m) of topsoil, underlain by 2.5 ft (0.76 m) of medium stiff sandy silt then 2.5 ft (0.76 m) of soft silty clay, then 1 ft (0.3 m) of medium dense silty sand, then 7 ft (2.1 m) of stiff to very stiff silty clay, then 2 ft (0.6 m) of medium stiff silty clay, then 1 ft (0.3 m) of stiff sandy clay. The boring logs of all 4 borings are presented in Figure 426, Figure 427, Figure 428, and Figure 429.



Figure 425. Photo. Planned alignment of the pipe's installation. Boreholes locations are shown in blue.

Illinois Department of Transportation
Division of Highways
IDOT

SOIL BORING LOG

Page 1 of 1

Date 1/16/19

ROUTE FAI-39 DESCRIPTION P-92-OHS-19 - Sign Truss I-39 SB @ IL 38 LOGGED BY W. Garza

SECTION _____ LOCATION Denent - SE17, SEC. , TWP. 40N, RNG. 2E

COUNTY Ogle DRILLING METHOD Hollow Stem Auger HAMMER TYPE CME-45 Automatic

STRUCT. NO. 071-037
Station _____

Latitude 41° 56' 20.66" Northing 1,922,393.3791
Longitude -89° 01' 27.29" Easting 2,607,395.5118

BORING NO. B-1
Station 23' S of S Foundation
Offset 37.00ft E of CL SB
Ground Surface Elev. 96.63 ft

Surface Water Elev. _____ ft
Stream Bed Elev. _____ ft

Groundwater Elev.:
First Encounter 89.6 ft ▼
Upon Completion 79.6 ft ▽
After _____ Hrs. _____ ft

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)	Soil Description
		0.8 P	22.0	MEDIUM brown SILTY CLAY LOAM
94.63				
	8 6 6	2.5 P	23.0	VERY STIFF gray SILTY CLAY
93.13				
-5	2 2 5	1.3 P	24.0	STIFF gray SILTY CLAY
90.63				
▼	3 3 6	1.2 B	25.0	STIFF gray SILTY CLAY TILL
88.13				
-10	2 5 7	0.3 P	14.0	SOFT tan SANDY LOAM
85.63				
	2 4 9	0.8 P	15.0	MEDIUM gray SANDY LOAM
83.13				
-15	1 2 15	0.4 B	16.0	SOFT gray LOAM with WEATHERED LIMESTONE bottom 2"
80.63				
▽				
	100 for 3"			VERY DENSE tan WEATHERED LIMESTONE
				Auger Refusal @ 19.0'
77.63				
-20				End of Boring

Northing and Easting were calculated using the ILHP-WF coordinate system

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, from 137 (Rev. 8-99)

Figure 426. Chart. Boring log of the preliminary bore hole B-1.

Illinois Department of Transportation
Division of Highways
IDOT

SOIL BORING LOG

Page 1 of 1

Date 1/14/19

ROUTE FAI-39 DESCRIPTION P-92-OHS-19 - Sign Truss I-39 SB @ IL 38 LOGGED BY W. Garza

SECTION _____ LOCATION Denent - SE17, SEC. , TWP. 40N, RNG. 2E

COUNTY Ogle DRILLING METHOD Hollow Stem Auger HAMMER TYPE CME-45 Automatic

STRUCT. NO. 071-037
Station _____

Latitude 41° 56' 20.73" Northing 1,922,400.1449
Longitude -89° 01' 28.53" Easting 2,607,301.5412

BORING NO. B-2
Station 16' S of S Foundation
Offset 54.00ft W of CL SB
Ground Surface Elev. 95.60 ft

Surface Water Elev. _____ ft
Stream Bed Elev. _____ ft

Groundwater Elev.:
First Encounter None ft
Upon Completion Dry ft
After _____ Hrs. _____ ft

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)
STIFF brown SILTY CLAY LOAM		1.1 P	23.0
93.60			
STIFF brown SILTY CLAY LOAM	4 7 9	1.1 P	22.0
92.10			
-5 STIFF gray SILTY CLAY	5 4 7	1.3 P	26.0
89.60			
STIFF gray SILTY CLAY TILL	3 4 5	1.7 B	18.0
87.10			
-10 STIFF tan SANDY LOAM with SAND LENS	3 4 5	1.7 B	17.0
84.60			
VERY DENSE light gray WEATHERED LIMESTONE	59 41 for 1"		
Auger Refusal @ 14.0'			
81.60			
End of Boring			
-15			
-20			

Northing and Easting were calculated using the ILHP-WF coordinate system

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, from 137 (Rev. 8-99)

Figure 427. Chart. Boring log of the preliminary bore hole B-2.

7988 Centerpoint Drive, Suite 100
Indianapolis, IN 46256
(317) 849-4990
Fax (317) 849-4278

TEST BORING LOG

CLIENT: Pilot Travel Centers, LLC
PROJECT NAME: Sanitary Sewer and Water Main Installation
PROJECT LOCATION: Illinois Route 38 and Interstate 39, Rochelle, Illinois
BORING #: B-4
JOB #: PTROCHELC1

DRILLING and SAMPLING INFORMATION

Date Started	6/27/19	Hammer Wt.	140 lbs.
Date Completed	6/27/19	Hammer Drop	30 in.
Drill Foreman	Groff	Spoon Sampler OD	2.0 in.
Inspector	S. Rushfeldt	Rock Core Dia.	-- in.
Boring Method	HSA	Shelby Tube OD	-- in.

TEST DATA

SOIL CLASSIFICATION SURFACE ELEVATION 799	Stratum Elevation	Stratum Depth, ft	Depth Scale, ft	Sample No.	Sample Type	Sampler Graphics / Recovery Graphics	Groundwater	Standard Penetration Test, Blows per 6 in. Increments	Moisture Content, %	Pocket Penetrometer PP-tsf	Remarks
12 in. Topsoil	798.0	1.0									Ground surface elevation estimated from Google Earth.
Gray, very moist, silty clay with trace gravel and roots (FILL)				1	SS			2-2-2	26.8		
	795.5	3.5									
Brown and gray, wet, medium dense, SILTY SAND (SM)	795.0	4.0		2	SS			3-50/0.3			
Light brown, fractured, LIMESTONE	793.5	5.5	5								
Bottom of Test Boring at 5.5 ft											Auger refusal at 5.5 ft.

Sample Type
SS - Driven Split Spoon
ST - Pressed Shelby Tube
CA - Continuous Flight Auger
RC - Rock Core
CU - Cuttings
CT - Continuous Tube

Depth to Groundwater
Noted on Drilling Tools 3.5 ft.
At Completion 4.0 ft.
After -- hours -- ft.
Cave Depth -- ft.

Boring Method
HSA - Hollow Stem Augers
CFA - Continuous Flight Augers
CA - Casing Advancer
MD - Mud Drilling
HA - Hand Auger

Page 1 of 1

Figure 428. Chart. Boring log of the bore hole B-4.

ATC
7988 Centerpoint Drive, Suite 100
Indianapolis, IN 46256
(317) 849-4990
Fax (317) 849-4278

TEST BORING LOG

CLIENT: Pilot Travel Centers, LLC
BORING #: B-5
PROJECT NAME: Sanitary Sewer and Water Main Installation
JOB #: PTROCHELC1
PROJECT LOCATION: Illinois Route 38 and Interstate 39
Rochelle, Illinois

DRILLING and SAMPLING INFORMATION

Date Started	6/28/19	Hammer Wt.	140 lbs.
Date Completed	6/28/19	Hammer Drop	30 in.
Drill Foreman	Groff	Spoon Sampler OD	2.0 in.
Inspector	S. Rushfeldt	Rock Core Dia.	-- in.
Boring Method	HSA	Shelby Tube OD	-- in.

TEST DATA

SURFACE ELEVATION 799

SOIL CLASSIFICATION	Stratum Elevation	Stratum Depth, ft	Depth Scale, ft	Sample No.	Sample Type	Sampler Graphics / Recovery Graphics	Groundwater	Standard Penetration Test, Blows per 6 in. Increments	Moisture Content, %	Pocket Penetrometer PP-tsf	Remarks
12 in. Topsoil	798.0	1.0									Ground surface elevation estimated from Google Earth.
Dark gray, moist, medium stiff, SANDY SILTY CLAY (CL) with trace gravel				1	SS			2-3-3	29.4	1.75	
Gray, very moist, soft, SILTY CLAY (CL)	795.5	3.5		2	SS		●	2-2-2	24.9	0.25	
	793.0	6.0	5								
Brown, wet, medium dense, SILTY SAND (SM) with trace gravel	792.0	7.0		3	SS		▽	3-5-6			
Gray, very moist, stiff to very stiff, SILTY CLAY (CL)				4	SS			5-8-7			**Sample No. 4:** LL = 28, PL = 18, PI = 10
			10	5	SS			7-12-9			
Dark gray, very moist, medium stiff, SILTY CLAY (CL) with trace organics and marl	785.0	14.0		6	SS			3-3-3	21.1	<0.25	**Sample No. 6:** Organic content = 2.5% Ca/MgCO3 content = 3%
	783.0	16.0	15								
Brown, moist, medium stiff, SILTY CLAY (CL)				7	SS			3-3-4	25.5	1.5	
	780.5	18.5									
Gray, moist, stiff, SANDY CLAY (CL) with trace gravel	779.5	19.5		8	SS			3-5-9	17.2	0.75	
Light brown, fractured, LIMESTONE			20								
	777.8	21.2		9	SS			50/0.2			Auger refusal at 21.2 ft.
Bottom of Test Boring at 21.2 ft											

Sample Type
SS - Driven Split Spoon
ST - Pressed Shelby Tube
CA - Continuous Flight Auger
RC - Rock Core
CU - Cuttings
CT - Continuous Tube

Depth to Groundwater
● Noted on Drilling Tools 5.0 ft.
▽ At Completion 7.0 ft.
▼ After -- hours -- ft.
Cave Depth -- ft.

Boring Method
HSA - Hollow Stem Augers
CFA - Continuous Flight Augers
CA - Casing Advancer
MD - Mud Drilling
HA - Hand Auger

Page 1 of 1

Figure 429. Chart. Boring log of the bore hole B-5.

G.9.4 Design

The initial design of this crossing, presented in Figure 430, used jack and bore to install the pipe under the I-39. The initial length using this method was 350 ft (106.7 m). The design shows a minimum cover to the ditch level of 5 ft (1.5 m). The cover to the level of the pavement is around 15 ft (4.6 m). The design was later modified to use horizontal directional drilling with a total length of 440 ft (134 m). The decision-making process to switch from jack and bore to horizontal directional drilling is described by IDOT's District 2 Geotechnical Engineer and TRP member Jan Twardowski who performed on-site inspection observations and reporting of the HDD installation:

> *Initially, due to the variability in the bedrock in the push pit, Bull's Eye (the boring subcontractor) proposed to lower the north bore and raise the south one in order that the north bore would be entirely in bedrock, and the south bore would be entirely in soil. Bull's Eye then proposed to "sleeve" the north bore (center the 20" [50.8 cm] casing in a 36" [91.4 cm] casing) to be able to work within the casing. Upon completion of the bore, the void between the 20" (50.8 cm) casing and 36" (91.4 cm) sleeve would have to be grouted entirely to ensure the gap between the two was filled in its entirety at the point where the 20" (50.8 cm) casing extended past the 36" (91.4 cm) sleeve.*
>
> *Pilot Travel Center called to discuss the proposed jack and bore and to inquire if IDOT accept directional bores at this location. IDOT personnel Dan Long and Jan Twardowski agreed to this trenchless technique, provided the casing was steel, as required for interstate bores, and it was required that the casing should be installed in one continuous pull, with all sections pre-welded, and the casing be pulled directly after the last reaming pass (as opposed to 20' [6.1 m] sections welded on individually as the casing is pulled into position). Melcar Underground has been contracted to do these directional bores.* (Twardowski 2016, 2)

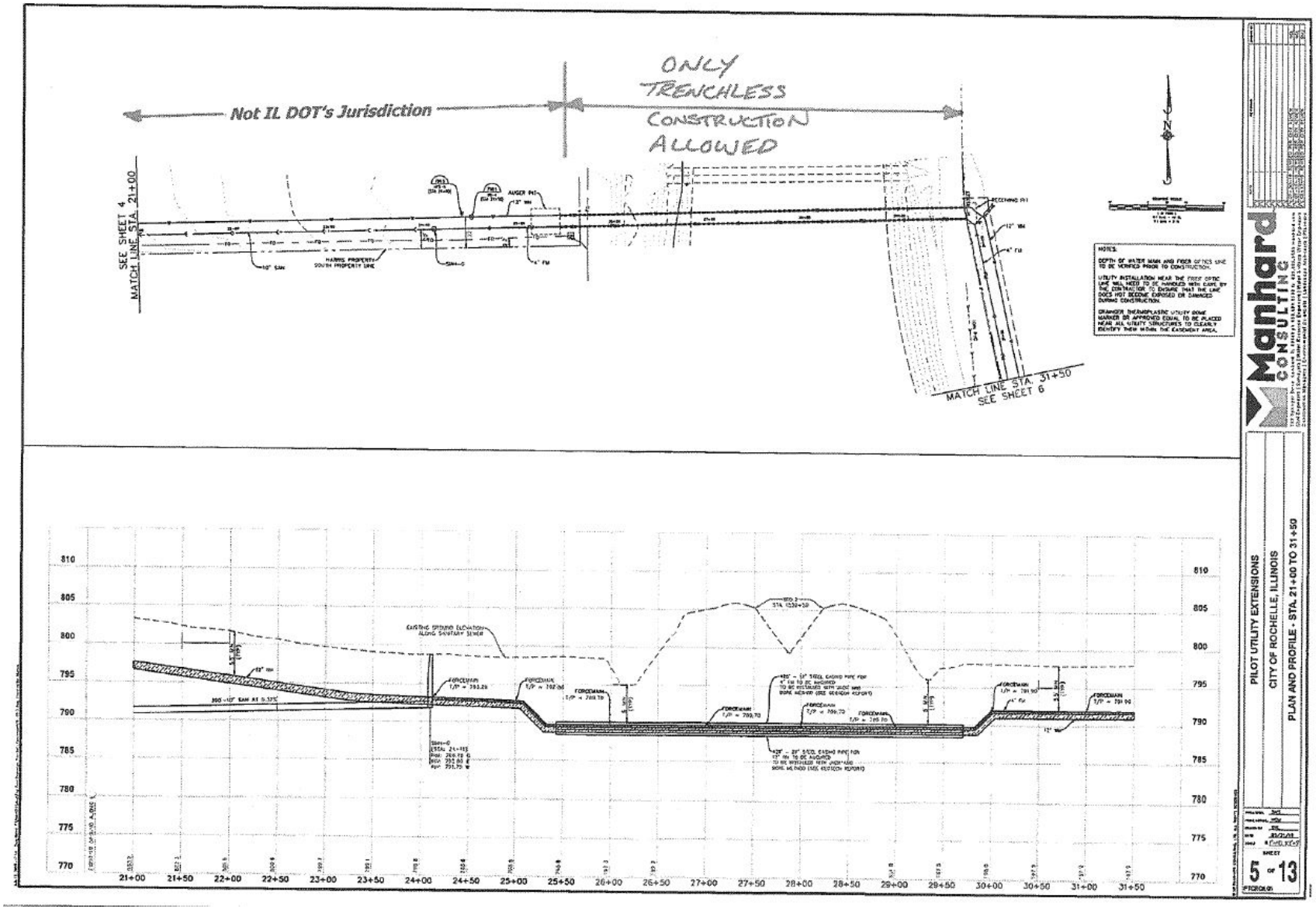


Figure 430. Graph. Initial design of the crossing under I-39, using jack and bore.

G.9.5 Entities and People Engaged

In addition to IDOT, the following companies were engaged in this project:

- The City of Rochelle, also known as Rochelle Municipal Utilities (R. M. U.), was the owner.
- Pilot Travel Center was the developer that requested the facilities be installed on their property.
- Manhard Consulting (https://www.manhard.com/) was the consultant on this project.
- Melcar Underground (https://www.melcarunderground.com/) was the horizontal drilling subcontractor.
- N-Trak Group (https://ntrakgroup.com/).

The main point of contact during this project was IDOT's Inspector: District Geotechnical Engineer Jan Twardowski (email: Jan.Twardowski@illinois.gov; phone: +1-815-284-5429).

G.9.6 Execution

G.9.6.1 Settings

Preparations for installing the steel casing started on December 4, 2019, then stopped for around two months (in which designs were adjusted). The construction activities resumed on February 24, 2020. The construction continued through March 21, 2020. Temperatures in Rochelle varied between 22 and 50°F (-5.6 and 10°C) over this period (Figure 431). The maximum daily precipitation recorded was around 1 in. (2.54 cm) on March 10, 2020.

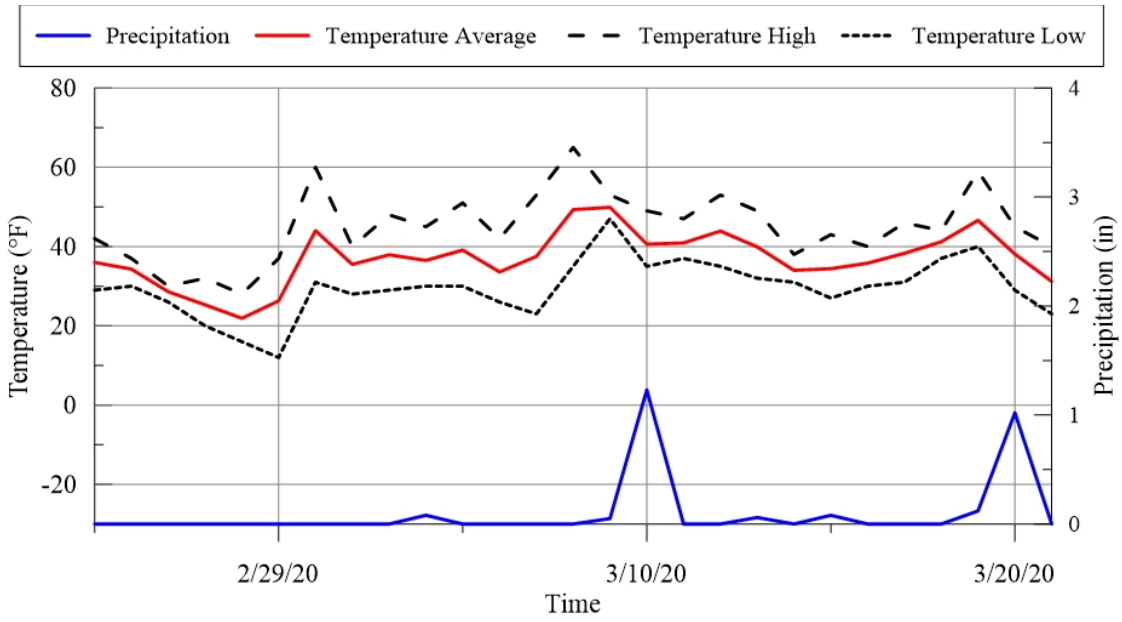


Figure 431. Chart. Temperature and precipitation in Rochelle, Illinois.

Source: ***https://www.wunderground.com/***

G.9.6.2 Execution Metrics

Construction activities for this project were observed by IDOT's Inspector Jan Twardowski, who shared their daily reports, notes, and photos with the UIUC team, which used those materials to prepare this report.

On December 4, 2019, N-Trak excavated the entry pit on the west side of I-39. The excavation was 24 ft (7.3 m) wide and 10 ft (3 m) deep. Limestone was encountered while excavating.

On December 5, 2019, N-Trak installed the 24 ft (7.3 m) wide trench boxes above the bedrock and continued to excavate the limestone with a Hydra hammer and rock bucket. With the variable conditions encountered in the entry pit, the design was revised as discussed before, and the horizontal directional drilling method was chosen to replace the jack and bore method.

On February 24, 2020, Melcar Underground mobilized its machinery. The company set a plan to a 12 in. (30.5 cm) bore for the 4 in. (10 cm) forced main sanitary sewer and a 20 in. (50.8 cm) bore for the 8 in. (20.3 cm) water main. The bores are to be completed in stages, first completing the rock portion to size, then completing the remainder in soil. There will always be rods in the bore as they over ream, and the steel casing will be welded entirely and pulled into place continuously.

On February 25, 2020, the sections of the casings were delivered: twelve 40 ft long, 20 in. diameter (12.2 m long, 50.8 cm diameter) sections and eleven 40 ft long, 12 in. diameter (12.2 m long, 30.5 cm diameter) sections. Melcar started preparing the sections for welding. N-Trak dewatered the original entry pit for jack and bore and pulled the trench box and backfilled the excavation for Melcar to proceed with horizontal drilling.

On February 28, 2020, Melcar installed a trench box at the rock face of the excavation and continued to pump out the water in the excavation.

After measuring elevations and considering the depth of the rock exposed in the bore pit, Melcar decided on the bore profile, which will be located approximately 8 ft (2.44 m) below the elevation of the ditch. During their preparation to start drilling, examining, and evaluating the existing utilities, they realized that the I-fiber sign truss and some high mast lights' electric services were not located, as they are IDOT facilities that are not covered by JULIE one call. Therefore, the preparations were to proceed, but the drilling would not start before those utilities were located.

On February 29, 2020, Melcar began the 6 in. (15.2 cm) pilot bore with the rock hammer for the forced main sewer casing (Figure 432–Figure 434). The rig was located 106 ft (32.3 m) west of the right-of-way fence and 82 ft (25 m) from the rock face of the entry pit. Therefore, four 20 ft (6.1 m) drill rods were attached before reaching the wall of the entry pit. After drilling 226 ft (69 m) (11 rods), soil was encountered with the beginning of the 12th rod, at a depth of 10.5 ft (3.2 m) below the western ditch. The rig operator realized the decrease in resistance on the drill string, and hence he reduced the water and air pressure to avoid disturbing the soil. The drilling fluid return did not indicate a loss of soil. The driller tripped the drill string out of the hole, replaced the rock drilling bit with a soil drilling bit, and replaced the drilling fluid with a bentonite drilling fluid. For tracking the drill bit, the walkover system was used and is presented in Figure 435–Figure 436.



Figure 432. Photo. Pilot boring. The drilling rig in action.



Figure 433. Photo. Pilot boring. The rock drilling bit.



Figure 434. Photo. Pilot boring. Pilot boring in action as seen from the entry pit.



Figure 435. Photo. The walkover system. Receiver.



Figure 436. Photo. The walkover system. Transmitter installed behind drill bit.

On March 2, 2020, Melcar finished the pilot bore, daylighting the bit on the east side of I-39, proceeding to push a total of 580 ft of rods. The drilling team then detached the drill string at the entry pit on the west side of I-39 and installed an 18 in. (45.7 cm) diameter roller reamer at the rock face (Figure 437–Figure 438). The drilling team started reaming the hole using the roller bit at 3:15 p.m. and proceeded 8 ft (2.44 m) before stopping at 5:30 p.m. The reaming rate was about 2.5 to 5 ft (0.76 to 1.5 m) per hour, and the reamer was operated at 22 RPM with 1600 ft-lb (2,17 kN-m) of torque and 10,000 lbs (4535 kg). of thrust. The drilling fluid was being pumped at a rate of 15 gallons (56.8 L) per minute, and the air compressor was set at 900 ft^3 (25.5 m^3) per minute at a pressure of 350 psi (2.4 MPa).



Figure 437. Photo. Reaming. The 18 in. tricone reamer.



Figure 438. Photo. Reaming in action as seen from the entry pit.

On March 3, 2020, the drilling team continued reaming the hole in the rock section, advancing the bit 72 ft (22 m) (about 4 rods) throughout the day.

On March 4, 2020, the drilling team continued reaming the hole in the rock section. Every 10 ft (3 m), the rig operator will swab 20 ft (6.1 m), and at the end of each rod (20 ft [6.1 m] length), the operator will swab the entire length of the bore (Figure 439). While advancing the fifth rod, a sand seam was encountered. This was evident from the cuttings and the drilling rate. Proceeding with the bore, bentonite was pumped for the remainder of this rock section, which terminated at 160 ft (48.8 m) from the rock face, located at 24 ft (7.3 m) west of the right-of-way fence. The rock-face interface is located beneath the south-bound exit ramp from I-39 to IL-38, at an approximate station of 1530+50. 6 ft (1.83 m) west of the east ramp line and 12 ft (3.7 m) east of the west ramp lane line.



Figure 439. Photo. Swabbing in action as seen from the entry pit.

The contractor tripped out of the hole at the end of the day, replacing the 18 in. (45.7 cm) roller bit with the 24 in. (61 cm) bit and 16 in. (40.6 cm) centralizer to oversize the rock bore to accommodate their 20 in. (50.8 cm) soil auger for the remainder of the bore. The 12 in. (30.5 cm) steel casing which was welded up over the weekend was measured at 464.5 ft (141.6 m) in length. There was a damaged portion located at 99 ft (30.2 m) from the pull head that the contractor was directed to remove and replace the damaged section.

On March 5, 2020, Melcar began the 24 in. (61 cm) over reaming of the 160 ft (48.8 m) rock section of the bore. The 24 in. (61 cm) roller bit had a 16 in. (40.6 cm) centralizer at the face to keep it centered in the 18 in. (45.7 cm) hole (Figure 440–Figure 442). The operator is running this bit at 18 to 22 RPM, at a thrust pressure of 7,500 lbs (3,400 kg). The operator continued to swab the hole every 10 ft (3 m) and entirely every time they added a rod (Figure 443). This reaming pass was advancing at approximately 10 ft (3 m) per hour. By the end of the day, they had reamed 100 ft (30.5 m) (added five rods), leaving three more rods to complete the rock portion of this bore. The contractor removed a 14 ft (4.3 m) section of the damaged 12 in. (30.5 cm) casing. The length of this casing now measures 450.5 ft (137.3 m).



Figure 440. Photo. Over-reaming. 24 in. (61 cm) reamer with 16 in. (40.6 cm) centralizer.



Figure 441. Photo. Over-reaming in action as seen from the entry pit.



Figure 442. Photo. Over-reaming. Interior of the 24 in. (61 cm) bore (behind the reamer).

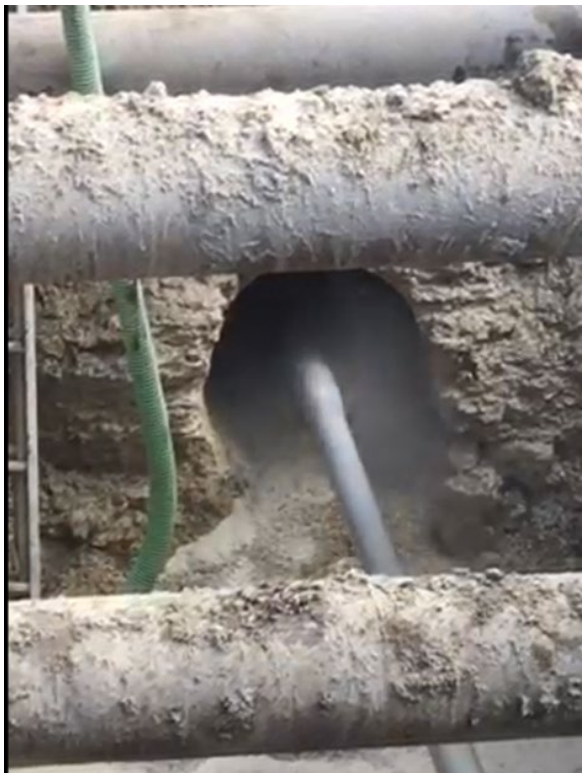


Figure 443. Photo. Swabbing with the 24 in. (61 cm) reamer.

On March 6, 2020, Melcar resumed the second pass of reaming while pumping bentonite drilling fluid for the first time in this pass to handle the suspected sand seam encountered in previous passes. The cuttings, however, showed just rock fragments just like the other sections.

On March 7, 2020, after finishing the second pass of reaming of the rock section of the boring, Melcar reamed the soil section of the bore with a 20 in. (50.8 cm) soil reamer. The bore in place measured 444 ft (135.3 m) from the rock face on the west side (entry pit), to the face of the plate on the trench box on the east side (receiving pit). The contractor was using a combination of "Drill-Terge" (drilling detergent/cutting agent) and "Insta-Vis Plus" (drilling fluid polymer) to keep the cuttings in suspension and maintain hole stability (Figure 444–Figure 445).



Figure 444. Photo. The drilling fluid agents that were used: Drill-Terge.



Figure 445. Photo. The drilling fluid agents that were used: Insta-Vis Plus.

Drilling fluid was returning to the east into the exit pit until the reamer was at 300 ft (91.4 m) into the bore from the east (past the east rock face under the ramp), then some drilling fluid flowed to the west. The drilling team pulled the 20 in. (50.8 cm) over reamer all the way to the drill rig, then removed the 20 in. (50.8 cm) reamer from the west end of the drill string and moved it to the east side of the road, ahead of the 12 in. (30.5 cm) casing to be pulled into the hole. Pulling was completed without any incident. Upon the request of IDOT's Jan Twardowski, the drilling team decided to flood the pit and backfill the face of the excavation. This was out of Jan's concern that the groundwater infiltration, which was flowing at an estimated rate of 4 gallons/minute (15 L/min), might wash out the cuttings that were filling the void between the casing and the oversized rock bored hole.



Figure 446. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The reamer before attaching the casing to it via the swivel.



Figure 447. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The casing being pulled into the hole.



Figure 448. Photo. The 12 in. (30.5 cm) casing while being pulled into the bore. The reamer entering the exit pit toward the entry pit.

On March 8, 2020, following the completion of the first 12 in. (30.5 cm) casing installation under I-39, the contractor pumped out the entry pit, removed the reamer from the casing, then backfilled the remainder of this excavation. They then excavated the entry pit for the adjacent 20 in. (50.8 cm) casing installation, installed the trench box, and prepared the site for this boring.

On March 9, 2020, Melcar was waiting for the delivery of a bigger track hoe in order to get their trench box at the required elevation. No other work was completed due to rain.

On March 10, 2020, N-Trak dug the tail ditch to improve drainage, then excavated and set an additional trench box behind the one they installed on March 8, 2020, as a longer, deeper, protected tail ditch is required for this 20 in. (50.8 cm) casing (Figure 449). Melcar set steel plates down to support the drill rig, as the one inch of rain received in Rochelle adversely affected the already challenging ground conditions.



Figure 449. Photo. The trench boxes being installed at the entry pit.

On March 11, 2020, Melcar continued struggling to get their trench boxes tight and dewatered. The site conditions were bad. By the end of the day, they had the boxes in and dewatered, the tail ditch dug, and rods with hammer advanced till the rock face. Several more plates were ordered and would have to be added to complete the shoring of this entry pit.

On March 12, 2020, Melcar began the 6 in. (15.24 cm) rock hammer pilot bore for the second casing installation on this project (Figure 450). This casing was to be installed 15 ft (4.6 m) north of the previously installed casing. The drilling bit passed 8.8 ft (2.7 m) below the western ditch. The drill bit encountered the rock-soil interface after drilling only 130 ft (39.6 m) (106 ft [32.3 m] from the fence), which is 30 ft (9.1 m) short where it encountered it in the first boring.



Figure 450. Photo. Pilot drilling for the second line.

The drilling team tripped out of the hole, then switched to the duck bill soil bit. After pushing 6 ft (1.8 m), the grade of the bit could not be held in an acceptable grade, as the bit was deflecting upwards. After "rocking" the bit for 2 hours to try to create a "cradle" to advance the bit at the proper grade, the team decided to mud the hole to hold it and trip back out of the hole, allowing the pit to fill with water to protect the hole from the groundwater that is flowing from the rock face at 5 gallons (19 L) per minute.

On March 13, 2020, Melcar resumed pilot drilling in the soil section of this bore with the “duck bill” bit. Working slowly and carefully, they were able to advance the bit, on grade, through approximately 20 ft (6.1 m) of suspected weathered limestone debris. They continued to complete the entire length of this pilot bore, with a total of 820 ft (250 m) of rods, from drill to daylight on the east side. Depth below ditch on the east side was recorded at 9 ft 3 in. (2.82 m).

Upon completion of the pilot bore, the drilling team removed the duck bill bit on the east side, then added the 18 in. (45.7 cm) rock reamer at the drill on the west side. They then began the 18 in. (45.7

cm) rock reaming, advancing the reamer 50 ft (15.24 m) into the rock. At the end of the day (at 6:00 p.m.), they swabbed out from the entry pit with the reamer and flooded the pit to reduce any flow.

On March 14, 2020, Melcar resumed the 18 in. (45.7 cm) rock reaming, beginning at 50 ft (15.24 m) into the rock face, with 80 ft of rock remaining to be bored to 18 in. (45.7 cm) diameter. In 5 hours, they completed this portion of the rock bore. They swabbed the hole every 6 to 8 ft (1.8 to 2.4 m). Cuttings included large limestone pieces and a high concentration of sand. The last 20 ft (6.1 m) of this rock ream was completed without air and with water only so as not to disturb the adjacent soil deposit. Upon completion of the 18 in. (45.7 cm) reaming pass, the drilling team tripped out of the hole and replaced the 18 in. (45.7 cm) rock reamer with a 24 in. (61 cm) rock roller reamer (Figure 451), with a 16 in. (40.6 cm) centralizer to keep the reamer centered in the existing hole.



Figure 451. Photo. The 24 in. (61cm) rock reamer.

On March 15, 2020, Melcar started the second pass of reaming, this time using the 24 in. (61 cm) reamer. The reaming rate averaged at 4 in. (10 cm) per minute, so one 20 ft (6.1 m) rod would take a little more than one hour to push. The last three rods averaged only 30 minutes per rod. Reaming the rock section of the boring (130 ft [39.6 m]) was completed in 5 hours. Upon completion of the 24 in. (61 cm) reaming pass, the drilling team tripped the reamer out of the hole and prepared to add the 30 in. (76.2 cm) rock reamer, which was en route from Kentucky, scheduled for delivery the next day (Figure 452–Figure 453).

On March 16, 2020, Melcar started reaming with the 30 in. (76.2 cm) reamer, with centralizers installed before and after it (22 in. [56 cm] and 28 in. [71 cm] respectively). After advancing the

reamer 5 ft (1.5 m), it was apparent that this large reamer was causing the rods to buckle; therefore, they added a swivel on the east end of the rods in the tail ditch and used an excavator to pull on the rod string from the east, while the drill rig pushed on the rods from the west. The operator swabbed to daylight upon completion of each 20 ft (6.1 m) rod. By the end of the day, the team has reamed 60 ft (18.3 m) of this 130 ft (39.6 m) rock bore in 5 hours.



Figure 452. Photo. The 30 in. (76.2 cm) reamer with the two centralizers. (1)



Figure 453. Photo. The 30 in. (76.2 cm) reamer with the two centralizers. (2)

On March 17, 2020, after Melcar resumed reaming with the 30 in. (76.2 cm) reamer, a sinkhole surfaced in the west slope (Figure 454), before the rods were even advanced. This sinkhole measured 17 ft (5.2 m) in length and 4 to 5 ft (1.2 to 1.5 m) in depth and was located above the alignment 104 ft to 121 ft (31.7 to 36.7 m) from the west rock face in the entry pit. A review of the rock boring logs indicates that this void developed within the interval of rods 6 and 7 during the boring operation, between 90 and 130 ft (27.4 and 39.6 m) from the west rock face. The 30 in. (76.2 cm) rock bit was advanced to just 60 ft when work was ceased the night before. Jan Twardowski thinks that this sinkhole was likely caused by the rock face dropping off gradually, therefore the bottom of the bit continuing to cut rock, while the top portion was encountering a sand seam, which was noted in a previous report. The reduced time of pilot drilling and reaming at the 5th, 6th, and 7th rod compared to the previous rods might support this hypothesis.



Figure 454. Photo. The first of the two sinkholes that appeared on the west side of I-39.



Figure 455. Photo. The second of the two sinkholes that appeared on the west side of I-39.

At 1:00 p.m., as the reaming reached 110 ft (end of the 6th rod), a second sinkhole (Figure 455) developed west of the previous one, at 84 to 94 ft (25.6 to 28.6 m) from the rock face (above the 5th interval). Sand seams were clearly visible in this sinkhole, as they were in the first one. The contractor filled both sinkholes with clay and drilling sediment from the site. After finishing the rock section of the bore, the drilling team retracted the 30 in. (76.2 cm) rock reamer back to the drill rig on the west side, removed the reamer, reconnected the rods, and then advanced all the rods they had to the east to attach the 16 in. (40.6 cm) soil reamer at the receiving pit.

On March 18, 2020, Melcar removed the trench box from the receiving pit at the first bore location, filled in the pit after pumping it out, then excavated for the new trench box, and installed it by the end of the day. They also started preparing the 463 ft (141 m) long, 20 in. (50.8 cm) casing for installation. They installed the 16 in. (40.6 cm) reamer 93 ft (28.3 m) east of the fence with 450 ft (137 m) of tail rods east of the reamer.

On March 19, 2020, Melcar began pulling the 16 in. (40.6 cm) reamer from the west side to the drill rig on the east side. By 12:30 p.m., they had pulled 400 ft (122 m) of the rods, and the reamer began encountering rock, approximately 120 ft (36.6 m) from the west rock face (at the west edge of the ramp shoulder). The drilling team then added more rods on the east side and continued to pull the rods to the drill, until the reamer was accessible. They removed the 16 in. (40.6 cm) reamer at the drill rig, then advanced all the rods to the east, then attached to them the 24 in. (61 cm) reamer.

On March 20, 2020, Melcar pulled the rods with the reamer back to the drill rig, generally taking 75 to 90 minutes to pull 9 rods. Inadvertent returns of drilling fluid from the original failure over the trench on the west ramp showed up while pulling beneath it (Figure 456). After pulling two more rods, they also had some swelling of soil above the second failure that had been backfilled. After pulling the reamer to the drill rig, they removed it from the west end and attached it to the end of the rods on the east side of the road with a swivel and pull plate for attachment to the 20 in. (50.8 cm) casing.



Figure 456. Photo. The inadvertent returns showing in the area of the sinkhole, which was previously back-filled.

On March 21, 2020, Melcar attached the 24 in. (61 cm) reamer and swivel to the casing on the east side of I-39. At 9:30 a.m. they began pulling the casing into the bore hole. At 10:30a.m., with 140 ft (42.7 m) of casing in the bore hole, they had an inadvertent return at the location of the first sinkhole, then the second sinkhole in the west foreslope/ditch. The detention basin at the area of the second sinkhole was enlarged, and a solid pump was mobilized into the basin. The receiving pit was excavated to provide an outlet for the cuttings being pushed ahead of the casing. The casing pulling was completed by 12:30 p.m. The drilling team removed the shackles from the swivel between the reamer and the pull head in the bore pit on the west side and retracted the rods and reamer to the drill, then spent the remainder of the day cleaning up the area.



Figure 457. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (1)



Figure 458. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (2)



Figure 459. Photo. Pulling the second 20 in. (50.8 cm) casing into the bore. (3)



Figure 460. Photo. Photo of the inadvertent return.

On March 23, 2020, a hand auger boring was completed at the bottom of the west foreslope, on the alignment of the first 12 in. (30.5 cm) casing which was installed. This hand auger extended to a depth of 5 ft (1.5 m), and no signs of instability were evident at this depth. In addition, saturated dense sand was encountered in the last 18 in. (45.7 cm) of this boring, making it unlikely that a void was present below this depth. Three hours after excavating, the hole filled to within a foot of the surface with water.

Melcar resumed their cleanup operation, grading out the sediment in the west ditch and properly backfilling the area of the inadvertent return which was quickly filled during the boring process. The moisture content of the soils on site made proper grading very difficult.

On March 24, 2020, the IDOT district crew completed three borings along the edge of the shoulder approximately 115 ft (35 m) from right-of-way (Figure 461). B-1 was performed above the 20 in. (50.8 cm) casing to a depth of 16 ft (4.9 m) (the casing is at a depth of 17 ft [5.2 m]). B-2 was performed above the 12 in. (30.5 cm) casing to a depth of 18.5 ft (5.64 m) (the casing is at a depth of 5.94 ft [1.81 m]). B-3 was performed 20 ft (6.1 m) south of B-2 to be used as a baseline boring; it was terminated at 18.5 ft (5.64 m) in limestone. Blow counts of the two borings above the casings (B-1, B-2) were compared to the baseline boring (B-3). There was not a significant difference between the densities, based on blow counts, of the casing borings and the baseline boring.

Blow counts of the two borings above the casings (B-1, B-2) were compared to the baseline boring (B-3). There was not a significant difference between the densities, based on blow counts, of the casing borings and the baseline boring. The three boring logs of the three borings are presented in Figure 465 through Figure 467.



Figure 461. Photo. The boring operation performed after the cases were pulled.

A week before April 3, 2020, N-Trak had excavated at the west end of the 20 in. (50.8 cm) casing, encountering a minor amount of seepage and no void present where the casing exited the rock face. On April 3, 2020, N-Trak excavated the 12 in. (30.5 cm) casing at the rock face, and a significant void was present around the top half of the casing (Figure 462). This void extended back 19 ft (5.8 m). However, the more concerning issue was the volume of groundwater flowing from this void and into the excavation. Jan Twardowski estimated it between 5 and 10 gallons/minute,as evident from the discharge from the pump, and this amount of flow carries a significant amount of fines with it. Jan alerted John from Melcar, Andrew from Pilot, and Troy from N-Trak that they had to grout this void to seal off the flow and prevent future subsidence from this erosion. They had been previously warned that this may be required, as noted in the March 27, 2020, memorandum.

On April 6, 2020, N-Trak resumed work at this 12 in. (30.5 cm) casing location. They pushed the force main carrier pipe with an additional duct and tracer wire. Upon completion of this work, they installed two 2 in. (5 cm) PVC pipes between the casing and the rock socket, at 10 and 2 o'clock along the casing. The north pipe was installed to refusal at 7 ft (2.1 m), and water ran from the pipe. The south pipe was installed to refusal at 15 ft (4.6 m). Elbows and riser pipes were installed on the ends so that the pit could be backfilled and the pipes could be grouted from the surface later in the week as presented in Figure 463 and Figure 464. By doing so, the pump can be pulled, and the water level will equalize, eliminating the flowing condition and subsequent erosion.



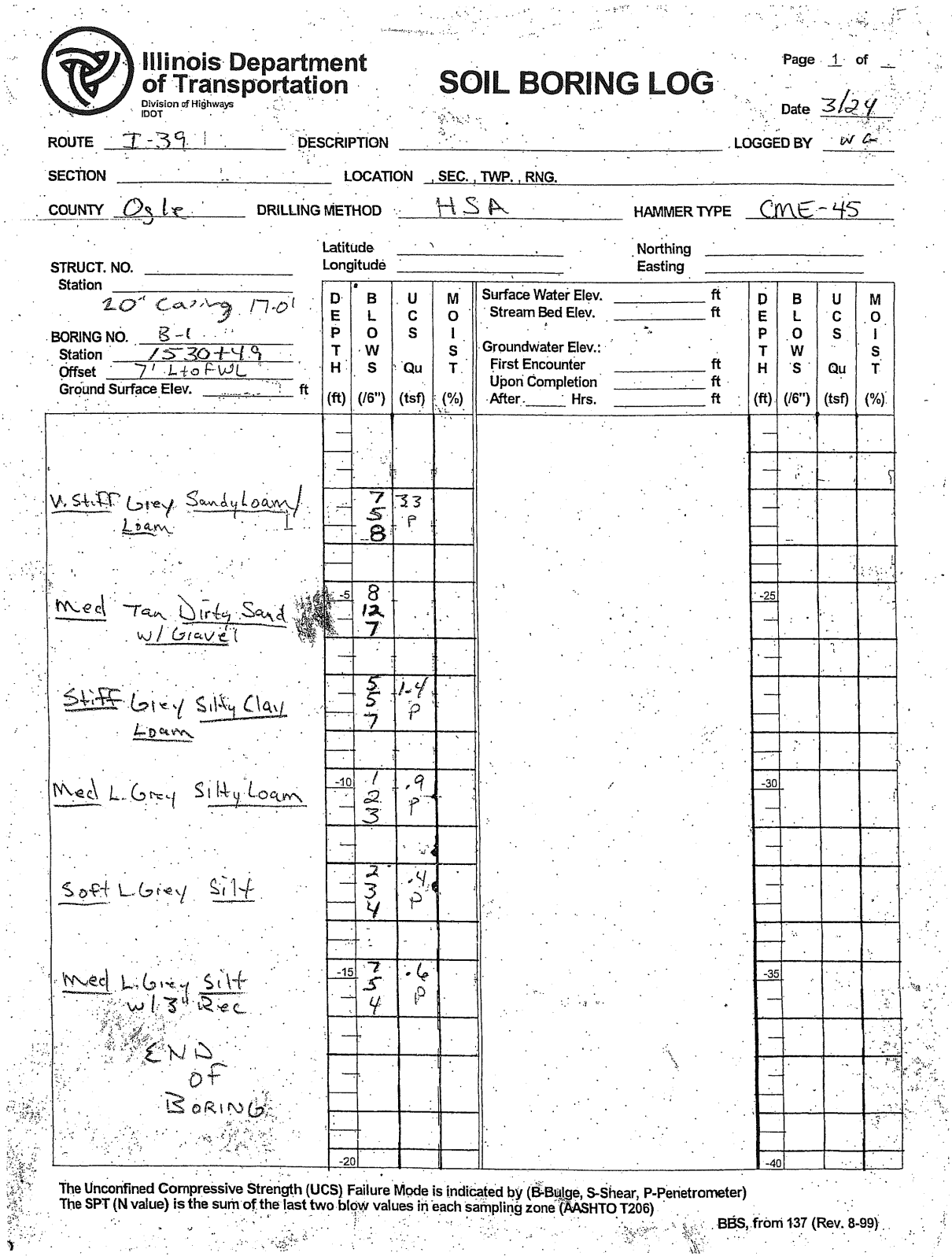
Figure 462. Photo. Void on the top of the installed casing.



Figure 463. Photo. One of the two PVC pipes installed on the top of the casing with water flowing out of it.



Figure 464. Photo. The two pipes with riser pipes attached to them to enable grouting.



Illinois Department of Transportation
Division of Highways
IDOT

SOIL BORING LOG

Page 1 of _

Date 3/24

ROUTE I-39 | DESCRIPTION | LOGGED BY WG

SECTION | LOCATION , SEC. , TWP. , RNG.

COUNTY Ogle | DRILLING METHOD HSA | HAMMER TYPE CME-45

STRUCT. NO.
Station
20" Casing 17.0'

BORING NO. B-1
Station 1530+49
Offset 7' Lt of WL
Ground Surface Elev. ft

Latitude
Longitude
Northing
Easting

Surface Water Elev. ft
Stream Bed Elev. ft
Groundwater Elev.:
First Encounter ft
Upon Completion ft
After Hrs. ft

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)
	7 5 8	33 P	
-5	8 12 7		
	5 5 7	1.4 P	
-10	1 2 3	.9 P	
	2 3 4	.4 P	
-15	7 5 4	.6 P	
-20			

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)
-25			
-30			
-35			
-40			

V. Stiff Grey Sandy Loam/ Loam

Med Tan Dirty Sand w/ Gravel

Stiff Grey Silty Clay Loam

Med L. Grey Silty Loam

Soft L. Grey Silt

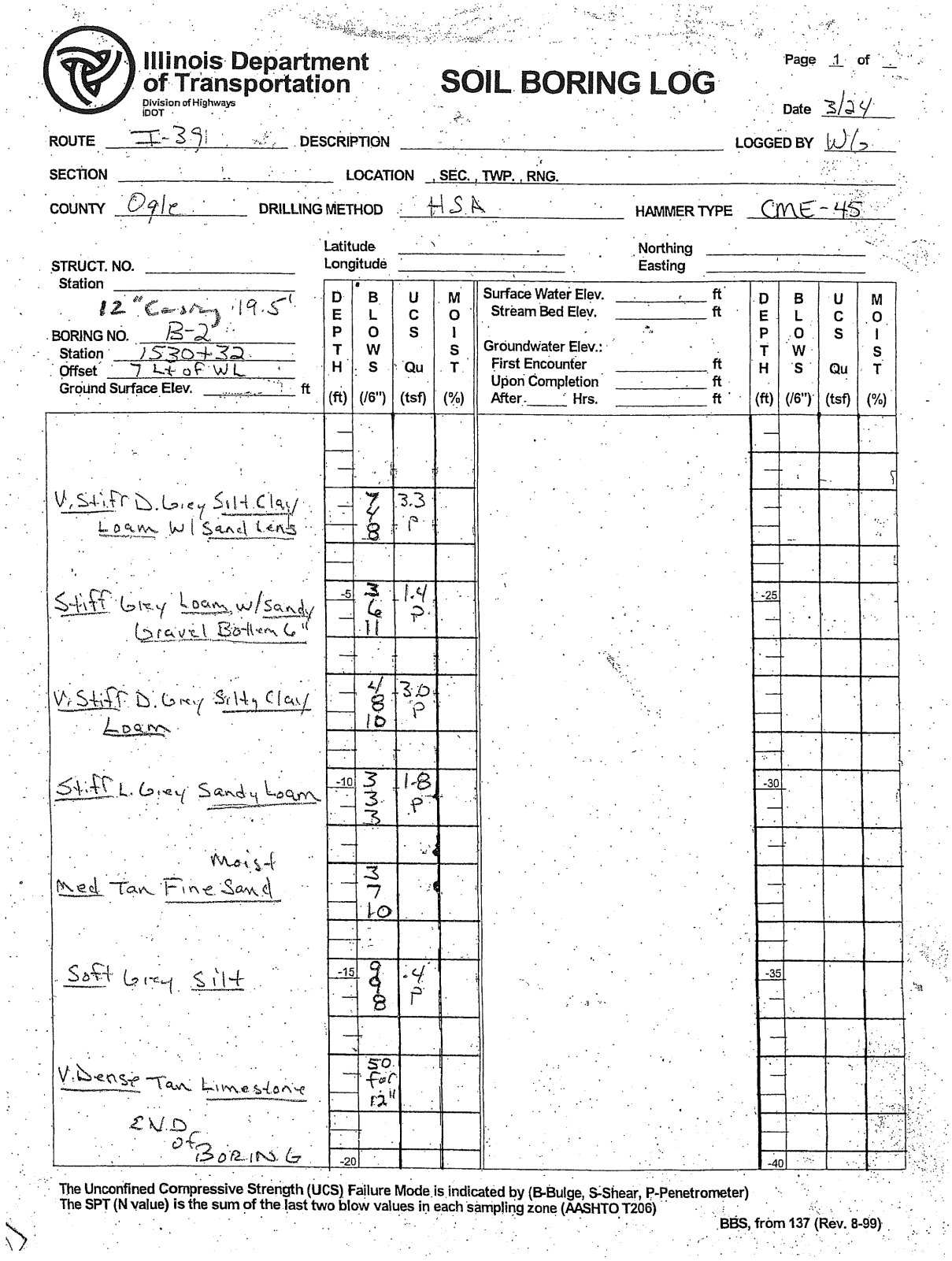
Med L. Grey Silt w/ 3" Rec

END OF BORING

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, from 137 (Rev. 8-99)

Figure 465. Chart. Boring log of the bore hole B-1.



Illinois Department of Transportation
Division of Highways
IDOT

SOIL BORING LOG

Page 1 of _

Date 3/24

ROUTE I-39 DESCRIPTION _____ LOGGED BY W/S

SECTION _____ LOCATION _____, SEC., TWP., RNG.

COUNTY Ogle DRILLING METHOD HSA HAMMER TYPE CME-45

STRUCT. NO. _____
Station _____
12" Casing 19.5'
BORING NO. B-2
Station 1530+32
Offset 7 Lt of WL
Ground Surface Elev. _____ ft

Latitude _____
Longitude _____
Northing _____
Easting _____

Surface Water Elev. _____ ft
Stream Bed Elev. _____ ft
Groundwater Elev.:
First Encounter _____ ft
Upon Completion _____ ft
After _____ Hrs. _____ ft

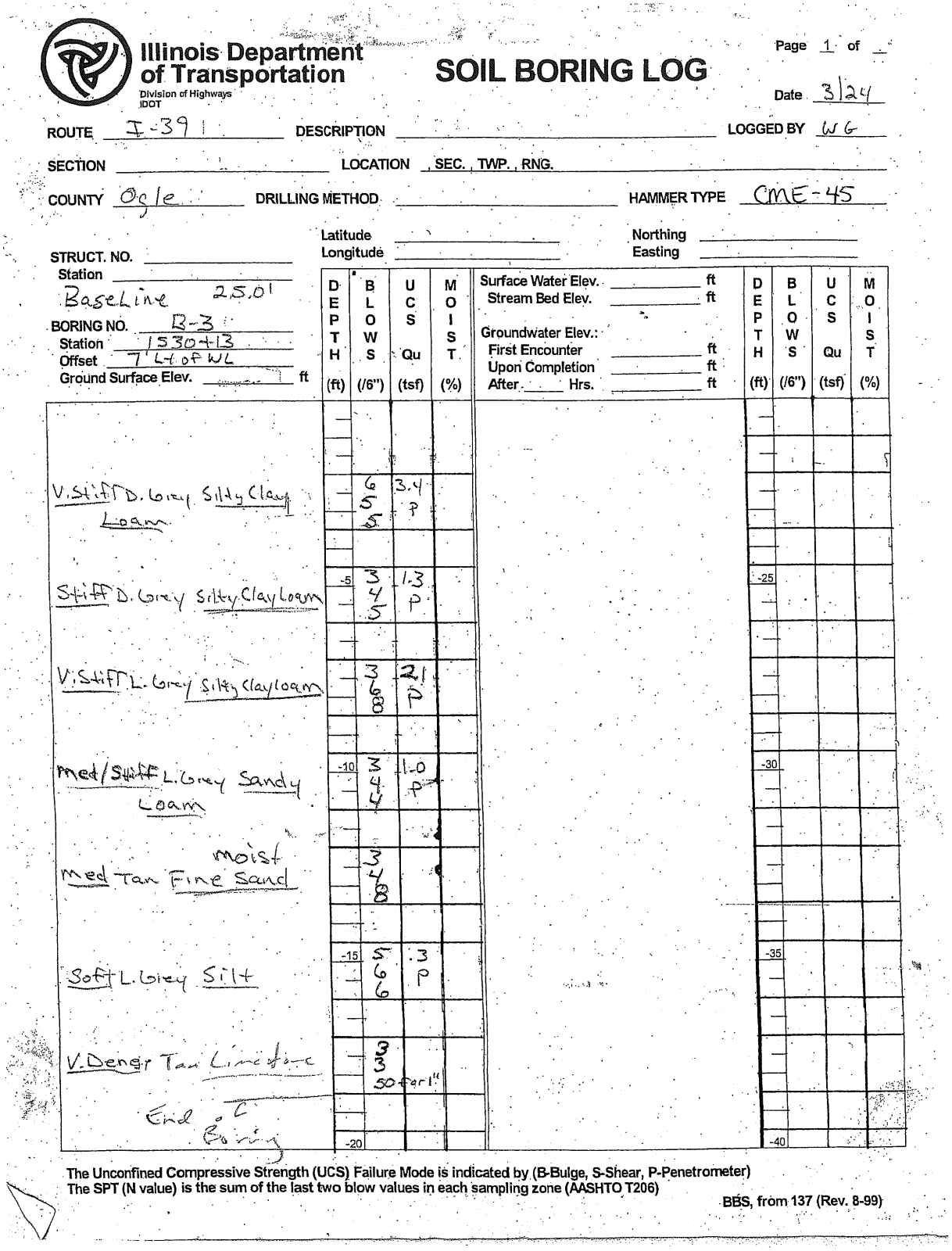
DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)	Soil Description
	7 8	3.3 P		V. Stiff D. Grey Silt Clay Loam w/ Sand Lens
-5	3 6 11	1.4 P		Stiff Grey Loam w/ Sandy Gravel Bottom 6"
	4 8 10	3.0 P		V. Stiff D. Grey Silty Clay Loam
-10	3 3 3	1.8 P		Stiff L. Grey Sandy Loam
	3 7 10			Moist Med Tan Fine Sand
-15	9 9 8	.4 P		Soft Grey Silt
	50 for 12"			V. Dense Tan Limestone
-20				END OF BORING

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)
-25			
-30			
-35			
-40			

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, from 137 (Rev. 8-99)

Figure 466. Chart. Boring log of the bore hole B-2.



Illinois Department of Transportation
Division of Highways
IDOT

SOIL BORING LOG

Page 1 of _

Date 3/24

ROUTE I-39 | DESCRIPTION | LOGGED BY WG

SECTION | LOCATION , SEC. , TWP. , RNG.

COUNTY Ogle | DRILLING METHOD | HAMMER TYPE CME-45

STRUCT. NO.
Station
Baseline 25.01
BORING NO. B-3
Station 1530+13
Offset 7' Lt of WL
Ground Surface Elev. ft

Latitude
Longitude
Northing
Easting

Surface Water Elev. ft
Stream Bed Elev. ft
Groundwater Elev.:
First Encounter ft
Upon Completion ft
After Hrs. ft

DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)	DEPTH (ft)	BLOWS (/6")	UCS Qu (tsf)	MOIST (%)
V. Stiff D. Grey Silty Clay Loam	6 5 5	3.4 P					
-5 Stiff D. Grey Silty Clay Loam	3 4 5	1.3 P		-25			
V. Stiff L. Grey Silty Clay Loam	3 6 8	2.1 P					
-10 Med/Stiff L. Grey Sandy Loam	3 4 4	1.0 P		-30			
Med Tan Fine Sand moist	3 4 8						
-15 Soft L. Grey Silt	5 6 6	.3 P		-35			
V. Dense Tan Limestone	50 for 1"						
End of Boring							
-20				-40			

The Unconfined Compressive Strength (UCS) Failure Mode is indicated by (B-Bulge, S-Shear, P-Penetrometer)
The SPT (N value) is the sum of the last two blow values in each sampling zone (AASHTO T206)

BBS, from 137 (Rev. 8-99)

Figure 467. Chart. Boring log of the bore hole B-3.

G.9.7 Performance Metrics

G.9.7.1 Surface Deformation

Not available.

G.9.7.2 Long-Term Measurements:

Not available.

G.9.8 Lessons Learned

The main lessons learned from Rochelle case history include the following:

- HDD installations that pass through mixed soil conditions, and especially soil-rock interface pose considerable technical challenges and elevated levels of risk. Controlling the alignment in those installations is usually harder, and repeated attempts might remove excessive amounts of soil, which may result in sinkholes.

- It is preferable, if possible, to conduct the whole drilling in one soil or rock type, as this eliminates the soil-rock interface challenges.

- Monitoring the rig pressure can give a good idea about the strength and sometimes the type of soil or rock that is being drilled or reamed.

- Soil investigation is essential for HDD projects, especially those that pass under critical structures. It helps identify possible challenges early and allows for design and construction adjustments to be made.

- In critical projects, enough offset from the entry and exit points to the limits of the highway should be maintained. This would create a buffer zone, so that, even if frac-outs happen, they would occur in this buffer zone rather than on the highway. The length of this buffer zone should depend on the depth of embedment, the length of the installation, the ground conditions, and the importance of the overlying structures and utilities.

- Inadvertent returns are more likely to occur in areas with weaker soils. In this project, they occurred in the relatively weaker, recently filled sinkholes.

G.9.9 References

Twardowski, Jan. 2016. *Soils Report – Permit Bore.* Illinois Department of Transportation Memorandum.

G.10 USER GUIDANCE

Most of the data and information included in each of the case histories was provided by either the Contractor or IDOT. This appendix synthesizes these data and information.

APPENDIX H: INDUSTRY SURVEY QUESTIONNAIRE

H.1 QUESTIONS ABOUT YOUR EXPERIENCE IN HDD 622

H.2 QUESTIONS ABOUT HOW YOU PERFORM HDD 622

H.3 QUESTIONS ABOUT PROBLEMS ENCOUNTERED DURING HDD 624

H.4 FEEDBACK ABOUT GUIDELINE DOCUMENTS 625

This questionnaire is part of the R27-198 research project conducted by the Illinois Center of Transportation (ICT) for the benefit of the Illinois Department of Transportation (IDOT).

This questionnaire aims at surveying the HDD industry in the US, especially in Illinois, inquiring about the current practice including contractors' design and execution methods and issues faced, and asking for suggestions to clarify and improve the permitting process.

For further information, please contact: Heather Shoup (Heather.Shoup@illinois.gov), Professor Youssef Hashash (hashash@illinois.edu), or Omar Baltaji (baltaji2@illinois.edu).

This form is composed of 4 sections including 31 short questions in total. Estimated time to complete this form is around 20 mins.

Email address:

Name (optional):

Phone (optional):

Company/Organization (optional):

H.1 QUESTIONS ABOUT YOUR EXPERIENCE IN HDD

1- How many years have you been working on HDD?

2- What type of rig you typically use?

- Maxi (typically used to install pipes greater than 24 in. [60.1 cm] in diameter)
- Midi (typically used to install pipes 12 in. [30.5 cm] to 24 in. [60.1 cm] in diameter)
- Mini (typically used to install pipes less than 12 in. [30.5 cm] in diameter)

3- What is the diameter of the biggest boring (not pipe) you ever bored (in in.)?

4- What is the length of the longest boring you ever bored (in ft)?

H.2 QUESTIONS ABOUT HOW YOU PERFORM HDD

1- What is the percentage of HDD projects for which you had soil data (soil borings, etc.)

available for you before the start of operation?

2- What does this soil investigation typically include?

- Ground surface inspection results
- Observations from test pits
- Borings
- Lab Testing
- Other:

3- What is the type of design typically provided for you?

- No design
- Entry and exit points
- Full profile
- Other:

4- What is the minimum depth of cover from the road pavement do you use (in ft)?

5- What is the minimum vertical and horizontal cover from utilities do you use (in ft)?

6- What drill bits rigs do you use? Do you make different choices for different soil conditions?

7- What reamers do you use? How do you make different choices for different soil conditions?

8- What type of tracking system do you use?

- walkover system
- magnetic wireline system
- gyroscopic wireline system
- surface magnetic coil
- Other:

9- How do you design your drilling fluid for coarse-grained soils (sand or gravel)? Can you give mix details?

10- How do you design your drilling fluid for fine-grained soils (silt or clay)? Can you give mix details?

11- How do you test your drilling fluid before pumping it?

- 2-speed viscometer
- 6-speed viscometer
- None
- Other:

12- How do you estimate the pressure in the boring? How do you estimate the failure pressure?

13- How do you monitor fluid pressure during installation?

14- How is the health of pipes tested after installation? Do you do it or does the owner do it? Is it always done?

15- How do you check the impact of the HDD on the ground surface?

- visual inspection for cracks
- ground level surveys
- None

Other:

16- How do you typically move your heavy equipment (excavators etc.) on site to cross

roads?

- Using neoprene pads
- Using trailers even for short distances
- Other:

H.3 QUESTIONS ABOUT PROBLEMS ENCOUNTERED DURING HDD

1- Have you encountered inadvertent returns? What were the causes? How did you deal with it?

2- Have you encountered hydro fracture (fracking)? What were the causes? How did you deal with it?

3- Have you experienced ground heave or ground settlement? What were the causes? How did you deal with it?

4- Have you encountered a sinkhole? What were the causes? How did you deal with it?

5- Have you encountered an unknown utility or an unexpected underground obstacle during drilling? How did you deal with it?

6- Have you ever had to abandon a boring? What were the reasons? What did you do to the abandoned boring?

7- Have you experienced any other major issues during HDD? What were the causes? How did you deal with it?

H.4 FEEDBACK ABOUT GUIDELINE DOCUMENTS

1- What HDD guidelines documents do you usually use to plan, design or set performance criteria for your HDD projects (if any)?

2- Does this document provide all what you need to design and execute an HDD project? What does it miss? What would you like to see in a guidelines document?

3- Are you interested in a follow-up conversation to help us better understand your feedback?

4- Do you have any other suggestions, comments or feedback?


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