Annulus Void Fill Material for Rehabilitated Sliplined Culverts

Volume 1 of 9

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Final Report

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16. Abstract

Sliplining is a method used by transportation agencies to rehabilitate deteriorated culverts. In recent years, ODOT discovered a number of sliplined culverts that did not have their annulus void spaces completely filled. Such culverts experience distortion and settlement as well as reduced structural capacity. Field inspections of several sliplined culverts in Ohio in this study confirmed that the lack of complete annulus void filling is a prevalent problem. Filler grout properties, particularly poor flow characteristics, would prevent the grout from completely filling annulus voids. This led to the investigation of grout properties that are most important to achieve good flow and fillability. New mixture proportions of a controlled low-strength material (CLSM) and cellular grout C40 were developed based on extensive laboratory testing. These improved grouts were also mixed in a batching plant at a larger scale and were pumped over a 200-ft length at an upslope of 2.5% to determine the suitability of these grouts in practical applications. Grouting of the annulus voids of 20-foot-long sections was verified using a 36-inch liner pipe sliplined within a 48-inch host pipe. A suggested basis for changes to the relevant ODOT specifications in SS 837 is recommended.

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Problem Statement

Many culverts managed by state and local transportation agencies in the United States have reached the end of their design life and may be at risk of failure. Perforations in metal culverts or joint failures in concrete culverts can lead to leakage and may adversely affect the hydraulic performance and structural stability of the culverts. In many cases, it is preferable to rehabilitate a deteriorated culvert rather than open cut to replace it with a new one, which disrupts traffic.

Sliplining is a method commonly used to rehabilitate deteriorated culverts. In this method, a new pipe with a smaller diameter is inserted into the existing host pipe, and the annular space between the two pipes is filled with grouting material (Figure 1). In general, the new pipe used as a liner can be made from various materials. The grouting material may be either low-strength material (LSM), non-shrink mortar (NSM), or cellular grout (CG). The success of the rehabilitation method depends primarily on maintaining the integrity of the hardened grout within the annulus void, and annulus voids of sliplined culverts need to be completely filled to achieve the desired performance. Successful rehabilitation of a culvert extends the service life of the culvert.

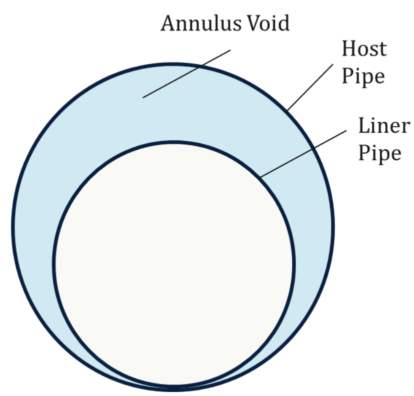


Figure 1: Image (*Left*) and Schematic Diagram (*Right*) of Typical Sliplined Culverts.

Structural design of buried conduits for both rigid and flexible conduits is well understood, and it requires a surrounding soil-structure interaction for stability. Voids present in the soil-structure interaction are problematic and may cause premature structural failure of the conduit due to unsymmetric loading. Likewise, voids between the host and sliplining conduit cause premature structural failure of the sliplined conduit. Limited structural design methods are currently available for the rehabilitation of culverts using grouted slipliners. Additionally, there are no commonly accepted test methods to verify that the annulus void has been completely filled or mostly filled with grout.

The Ohio Department of Transportation (ODOT) Supplemental Specification 837 (SS 837) requires an annulus void to be completely filled by the contractor and specifies the use of either LSM, NSM, or cellular grout. However, ODOT experience has shown in recent void fill operations that the annulus between the host pipe and liner pipe may not be completely filled. This lack of filling is not generally detected during construction and may not be noticed until several years after construction when the liner deforms, or the bulkhead falls out. A lack of fill causes distortion and settlement as well as reduced structural capacity, leading to reduced service life. Therefore, the ODOT Office of Hydraulic Engineering initiated this research project to investigate the reasons why the annulus void was not being completely filled as required by the specifications and to develop a solution to address the problem.

Research Background

ODOT's observations of the presence of incompletely filled annulus void spaces in sliplined culverts were quickly confirmed in this study from the field inspections of several sliplined culverts within the state. At the start of the project, it was suspected that the filler grout properties, particularly poor flow characteristics, would result in the incomplete filling of annulus voids. This required an investigation of grout properties that are most important for causing good flow and fillability. Development of implementable recommendations for grout materials and grouting methods were also needed.

Goals and Objectives

The primary goal of the proposed research project was to develop recommendations for improving ODOT's construction and material specifications for annulus void fill material and void fill operations. A practicable verification process for ensuring the complete or mostly complete filling of annulus voids was also needed. The specific project objectives included:

- Evaluation of the current state-of-practice for sliplined culvert systems and identifying issues associated with current practices.
- Providing recommendations for changes to the current ODOT material specification for void fill materials.
- Creation of suggested construction specification detailing the recommended methodology that is applicable to the chosen void fill material.
- Ensuring that the methodology considers all available liner material options as listed in SS 837 and that it includes a practicable verification process to ensure complete filling of the annulus.

Specific Tasks Accomplished

The following tasks listed in the proposal were accomplished in this project, in addition to participation in a review session (Task 6) and report preparation (Task 9):

- Literature review (Task 1)
- Survey of various organizations involved in culvert sliplining (Tasks 2, 4 and 5)
- Evaluation of void fill materials (Task 3)
- Culvert inspections (Task 7)
- Suggested modifications to material specification (Task 8)
- Conducting field grout pumping tests for selected grout materials (Task 10)
- Conducting large-scale culvert tests to verify the performance of the selected grouting materials (Task 11)

Key Literature Search Findings

The following conclusions are summarized from the findings included in the literature review:

- Sliplining is a simple method for culvert rehabilitation that is widely used by many agencies. As reported in different sources, most pipes in sliplined culverts are round. Corrugated metal pipe (CMP) is the most common host conduit pipe; but for liners, high-density polyethylene (HDPE) or corrugated steel spiral rib pipe is commonly used in culvert rehabilitation.
- A sound grout material that fills the annulus void improves the buckling resistance of the liner pipe and host pipe, and it increases the service life of the culvert. For practical purposes, a grout compressive strength of 100 psi was reported to be adequate. High-density grout (greater than 70 pcf) is recommended if water is present within the annulus during the grouting operation.
- Cementitious grouts are less expensive than chemical grouts, but the installation of such grouts can be more time-consuming than the installation of polymer grouts.
- ODOT C&MS specifies mix designs for common LSM grouts but allows a strength in the range of 50 to 100 psi for alternative mixes. Most state transportation agencies recommend a compressive strength of 100 psi in 28 days. ASTM D6103 is the standard test method used to measure flow consistency of controlled low-strength material (CLSM). No separate guidelines exist for cellular grouts in ODOT SS 837 aside from a reference to ASTM C869.
- A few sliplining contractors and grout manufacturers have their own detailed specifications for sliplining methods. Two types of grouts are generally recommended: flowable fills and cellular grouts. Cellular grouts with a cast-wet density of 20 to 80 pcf are readily available, but they are known to be more expensive than other cementitious grouts. The average 28-day compressive strength of common cellular grouts ranges from 30 psi to 300 psi.
- The load-carrying capacity of a rehabilitated sliplined pipe culvert is generally greater than that of a comparable unlined pipe. Several studies have reported that grout strength can affect the load-carrying capacity and structural response of a rehabilitated pipe.
- Inspections of culverts and the verification of the complete grout filling in the annulus voids have traditionally been performed using the hammer sounding method. While the technology for refined methods is currently evolving, such methods are expensive and are not readily implementable.

Research Approach

Field inspections of several sliplined culverts in Ohio confirmed that the lack of complete annulus void filling is a prevalent problem. At the start of the project, it was suspected that the filler grout properties, particularly poor flow characteristics, would result in incomplete filling of the annulus voids. This led to the investigation of grout properties that are important for achieving good flow and fillability. New mixture proportions for CLSM and cellular grout C40 were developed based on extensive laboratory testing. These improved grouts were also mixed in a batching plant at a larger scale and were pumped over a 200-ft length at an upslope of 2.5% to determine the suitability of these grouts in practical applications. Grouting of the annulus voids of 20-foot-long test culvert sections was verified using a 36-inch liner pipe sliplined within a 48-inch host pipe. A suggested basis for changes to the relevant ODOT specifications contained in SS 837 were developed as well as the construction procedure recommendations that would ensure that the annular spaces were completely filled at the time of construction.

To limit this final report to the maximum allowed page limit, the complete details of the different tasks achieved in this project are presented in the associated appendices. Brief summaries of the key findings for critical tasks are presented in the following sections.

Literature Search

Through the literature review (presented in Appendix A), a further understanding of the sliplining rehabilitation of culvert systems with a particular emphasis on grout materials and methods was accomplished. This review compiled information and data from various published journals, online sources, open-source webpages, and other sources. The current states of practice of other DOTs and locals were also summarized. The following topics were covered:

- Sliplining methods
- Available grout materials and grouting methods
- Study of different types of liner database materials
- ODOT specifications for different grout materials
- Current practice of state and local agencies
- Research sponsored or conducted by state and local agencies
- Guidelines or specifications provided by conduit suppliers
- Verification methods for confirming grout filling
- Ground-penetrating radar (GPR) inspection methods and new technologies

Survey of Various Groups involved in culvert sliplining

An online survey using the Qualtrics survey platform was developed to collect information on practices regarding the materials and methods for rehabilitated sliplined culverts. Five different groups were surveyed: conduit manufacturers, ODOT districts, county/local public agencies, ODOT designers, and ODOT contractors. Complete details of the survey results are presented in Appendix B. In general, the survey results were useful to the extent that they confirmed that much more needs to be done to refine sliplined culvert materials and construction methods.

Culvert Inspections

Field inspections at 30 sites in Ohio were performed to verify the condition of the annulus voids of some existing sliplined culverts. An adequate number of field inspections were included to confirm the significance of the findings, and the details are presented in Appendix C. A subset of culverts inspected by the research team were also inspected by Inversa Systems using their proprietary nondestructive test (NDT) instruments that employed backscatter computed tomography (BCT): a handheld device (Insight Lite™) was used to inspect eight sliplined culverts with different grout materials and grout conditions, and two of these culverts were also inspected using the conventional BCT unit (Insight BCT™). The complete details of the NDT inspections are provided in Appendix D.

It is generally difficult to detect voids in the annulus of a sliplined culvert. A common method for inspecting a culvert is the *sounding method*, in which an inspector taps the inside surface of the liner at close intervals with a metal hammer and listens for changes in tone that can indicate the presence of a void. While this method is subjective, it has been noticed that skilled and experienced culvert inspectors can, more often than not, capture anomalies behind the liner pipe without actually being able to see them.

Twenty-one sliplined culverts were thoroughly evaluated using the sounding method (Figure 2). The inspected culverts were selected in such a way that four distinctly different liner types – corrugated steel spiral rib pipe, steel casing pipe, high density polyethylene (HDPE) pipe, and polyvinyl chloride (PVC) profile wall pipe – would be included in the inspections. Other variables such as the diameter of the liner pipe, the type of host pipe, the age of the sliplined culvert, and the geographic location within the state were also considered.

Figure 2: Sounding Method for Culvert Inspection (*Left*); Endoscope Camera for the Inspection of Voids (*Right*).

The research team was able to detect voids with relative certainty based on the different sounds emanated from hammer tests after a little practice. The sound classification summarized in Figure C.35 in Appendix C was the basis for the interpretation of the sounding test responses. To validate the results from the sounding test, an endoscope camera was inserted into a ½-inch-diameter hole that was drilled in the liner pipe at select locations along the length of the pipe.

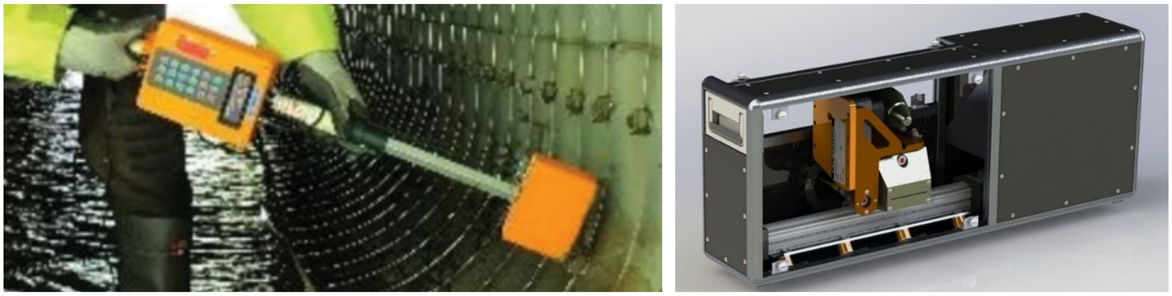
The condition assessment of the annulus voids of the inspected sliplined culverts revealed that complete filling was not achieved at several locations along many of the culvert lengths. Some culverts had entire segment lengths (20-ft. lengths) or limited areas where the annulus was completely empty (Figure 3). The condition assessment also revealed locations of partial filling or places where only thin layers of hardened grout were stuck to the liners (with rest of the void being empty), as shown in Figure 4. Based on the culvert inspections conducted in this project, it was clear that the incomplete filling of annulus voids is a common occurrence for sliplined culverts. This finding has implications for the performance of the liner pipes, as a lack of grout in the annulus voids causes distortions to the liner. The inspections also demonstrated that it is possible to detect different types of annulus void anomalies when using the sounding method.

Figure 3: Images Showing Examples of Annulus Voids that are Completely Empty.

Figure 4: Images Showing Examples of Partially Filled Annulus Voids.

For the culvert NDT inspections in this study, a preliminary assessment was first made using the handheld InSight™ Lite scanner to identify locations where voids might be present, as shown in Figure 5(a). The preliminary scanning was performed at set distances starting from the inlet and continued toward the outlet of the culvert, with scans along the inside diameter of the liner pipe at twelve positions matching the twelve clock positions.

At locations where the preliminary results indicated the presence of possible voids, an in-depth inspection using InSight™ BCT (shown in Figure 5(b)) was performed to help the inspector visualize the conditions behind the liner pipe wall. To accomplish this, the InSight™ BCT unit was first placed in a wood frame to help stabilize the unit during scanning. Next, the BCT scanner was positioned against the pipe wall. The scanning region covered a through-thickness of 8 inches along the pipe wall, and the depth of the image was set to a target depth (through thickness of the annulus) of up to 9 inches from the face of the scanner. For safety purposes, no one was permitted to remain in the culvert while scanning was performed, as the InSight™ BCT unit is known to produce a certain amount of radiation during the scanning process.



(a) InSight™ Lite (b) InSight™ BCT

Figure 5: Inspection Equipment for NDT Evaluation.

Once all InSight™ Lite measurements were captured, they were uploaded to the SoilSight™ portal, where the collected data were processed and the output was presented in the form of two-dimensional maps. Further details of the mapping and the interpretation of the output maps developed by Inversa Systems are also provided in Appendix D.

The findings from the culvert inspections verified and confirmed ODOT engineers' suspicion that a number of sliplined culverts in Ohio have annulus void spaces that were not completely filled. This finding necessitated a detailed investigation of the flow characteristics of the currently used void fill grouts and if it is possible to accomplish complete filling of the annular space in sliplined culverts when using these grouts. Other important conclusions drawn from this task are as follows:

- Sounding tests and examination with an endoscope camera are simple methods that can be used to detect voids and reveal the condition of the annulus behind most liner pipes, except for liner pipes with double layers of polyethylene. Sounding results are inconclusive in double-walled plastic pipes due to the space between the two polyethylene walls (plates).
- It is sometimes difficult to determine the extent or types of voids with sounding, particularly if the fill material is cellular grout. Therefore, the sounding method can be used as a general indicator for sliplined culverts in such cases. When in doubt, drilling a hole in the liner and inspecting with an endoscope camera is necessary to determine the severity of the voids.
- The data obtained from sounding test method assisted the research team in classifying the voids frequently seen in sliplined culverts inspected in the study.
- While the method has some limitations, the sounding test is still an implementable method for detecting voids particularly by skilled and experienced inspectors. Drilling a small hole in the liner and inserting an endoscope camera enables voids to be directly viewed. Therefore, it is simple, reliable, and inexpensive to detect and verify voids in the annulus of a sliplined culvert when using these methods.
- Our field inspections indicated that most of the grouts used in the sliplining of culverts were LSM or non-shrink grouts. Very few culverts inspected in this study were found to contain cellular grout.
- For the sliplined culverts inspected by NDT using InSight™ Lite and InSight™ BCT, the data gathered from the NDT systems mostly matched with the findings from the sounding method and camera inspections.

Evaluation of Void Fill Materials

The lack of grout within the annulus voids of sliplined culverts was discovered during field inspections of several such culverts and this was the basis for determining if flowability was a major factor in successful filling of the annulus void. The void fill materials typically used in Ohio were identified and thoroughly evaluated to document the relative advantages and disadvantages of using various fill materials. Both cellular and non-cellular cementitious materials were included in this evaluation. Some of the important properties of void fill materials are density, unit weight, air content, effectiveness of foaming agents, viscosity, compressive strength, and special conditions needed for grouting. Complete details of the study of void fill material performance and the modifications introduced to improve performance of cellular grout and CLSM grout are included in Appendix E and Appendix F.

After testing several trial mixes in the laboratory, two types of grouts were selected for further study: a modified or improved CLSM and a cellular grout based on C40.

Modified CLSM Grouts

In general, if CLSM is used for annulus grouting in a sliplined culvert without adequately addressing its flow characteristics, it may result in incomplete filling of annulus voids. One way to overcome the lack of flowability of the grout is to use admixtures which can increase the grout flowability and volume by as much as 30% and an appropriate w/c ratio to control bleeding. After conducting many laboratory trials on several mixtures using the tests listed in Table 1, the modified mix proportions shown in Table 2 were found to satisfactorily improve the flowability and reduce bleeding of CLSM. Bleeding occurs when the water content in the mix is excessive, and the water and solid particles in the grout separate resulting in the settlement of the solids at the bottom. The improved CLSM grout contains a mixture of binder materials (such as Portland cement and/or fly ash), fine aggregate, water, and admixtures (as needed) to achieve the desired flow characteristics.

A commercially available flowable fill admixture was incorporated into the CLSM for three reasons: to improve the flowability of the grout, reduce the density by volume expansion, and reduce the water-to-cement ratio (w/c ratio) of the mix. The chosen admixture created numerous air bubbles in the cement paste that caused the mix to expand, and the bubbles also acted as “ball bearings” within the mix to improve its flow characteristics. Similar commercial admixtures are readily available from admixture suppliers, and they can increase the volume of grout mixes by 20% to 35%.

Table 1: ASTM Standard Tests Suitable for the Evaluation of CLSM Grout Performance

Type of Tests	Test	ASTM #
Fresh Grout Properties	Fresh Density	C138
	Fluidity	C939
	Flowability/Spread	D6103
	Air content	C138/C231
	Bleeding test	C940
Hardened Grout Properties	Compressive strength	D4832
	Shrinkage	C596
	Water absorption	C796
	Oven dry density	C495
	Parallel plate loading	D2412

Table 2: Typical Mix Proportions for Modified CLSM Grouts

Material	Quantity
Cement	100 lb/yd^3
Fly Ash (Class F)	350 lb/yd^3
Fine Aggregate (100% passing No. 4)	2600 lb/yd^3
Air Entraining Admixtures	None
Flowable Fill Admixture	3.5 lb/yd^3
Water	325 lb/yd^3

The flowable fill admixture was found to be effective in creating flowable CLSM grout mixes with no measurable or visible segregation of grout components. The wet density of the grouts was reduced by 30%, which made the grouts more pumpable as well as more cost-effective. A minimum compressive strength of 100 psi was developed, which is the minimum compressive strength recommended by most transportation agencies. A substantial reduction or absence of fine aggregates and a higher water content in a grout increases drying shrinkage. As neat grouts with cement and/or fly ash and no fine aggregate will have very high drying shrinkage, these grouts were found to be unsuitable for the filling of annulus voids in sliplined culverts.

Some of the primary conclusions drawn from this task are as follows:

- Fill Flow admixture was effective in producing flowable CLSM mixes with no noticeable segregation. Moreover, the use of this admixture reduced the water demand of the CLSM mixtures, resulting in a flowable mix with no bleeding.
- The wet densities of modified mixtures are reduced by the addition of Fill Flow admixture. The reduction in wet density makes these grouts more pumpable and provides a cost-effective solution for filling annulus voids of sliplined culverts.
- All modified CLSM mixtures developed in this study had a minimum compressive strength of 100 psi, which is the minimum compressive strength recommended by most state transportation agencies. The compressive strength of the CLSM mixes was improved by increasing the cement content, while higher porosity in the CLSM mixtures was found to somewhat reduce the compressive strength.
- The reduction or absence of fine aggregate and the higher water content in a CLSM mixture results in an increase in shrinkage.

<u>Cellular Grout</u>

Cellular grouts are also used to fill annulus voids of rehabilitated culvert systems. Nevertheless, very few studies focused on the use of such grout materials for sliplined culverts. The primary ingredients of cellular grouts are cement, water, and foam. Various foaming agents (Table 3) were mixed into cement slurries in our laboratory to verify their effects on the properties of the resulting cellular grouts. The grouts investigated in this study had densities ranging from 10 to 75 lb/ft^3 (Table 4).

In our laboratory, several different tests were conducted for each cellular grout mixture to determine the grout's fresh and hardened properties. These tests were carried out in accordance with the applicable ASTM standards. The relevant tests used in the study are listed in Table 5.

Table 3: Properties and Composition of Foaming Agents

Product Name	DREXEL F.M.160™	AERLITE™	AERLITE-iX™	AERLITE-R™
Type of foaming agent	Anionic/non-ionic surfactant	Protein concrete foam concentrate	Synthetic concrete foam concentrate	Synthetic concrete foam concentrate
pH	6.0 - 7.5	7.1	7.3	7.3
Relative density (lb./gal.)	8.6	N/N	N/N	N/N
Specific gravity	N/N	1.06	1.04	1.04
Water content	N/N	40% - 50%	45% - 55%	N/N

Note: Further details on foaming agents are presented in Appendix E.

Table 4: Mix Proportion for Cellular Grout Mixes Mixed in Laboratory

Mix Component	C10	C20	C30	C40	C55	C65	C75
Cement content Type III (lb/ft^3)	3	10.2	17	24	34	41.5	48
Water content (lb/ft^3)	1.5	5.1	8.6	12	18	21	25
Foam* (lb/ft^3)	5.5	4.7	4.4	4	3	2.5	2
Resulting design density (lb/ft^3)	10	20	30	40	55	65	75

**Foam is defined as the theoretical amount of foam that is produced using a foam generator.*

Table 5: Experimental Tests of Cellular Grout mixtures

Test	Test Standard
Fresh density	ASTM C138
Fluidity	ASTM C939
Flowability/ Spread	ASTM D6103
Air content	ASTM C138/C231
Stability test	Modified ASTM C940
Compressive strength	ASTM D4832
Splitting tensile strength	ASTM C496
Shrinkage	ASTM C596
Water absorption	ASTM C796
Oven dry density	ASTM C495
Parallel plate loading	ASTM D2412

Several foaming agents were able to meet the minimum density requirements for foam as specified in ASTM C796 and ACI 523.3R-14. Mixing the foam with grouts at room temperature prevents instability of the foam volume before the foam is mixed into the cement slurry. In addition, the produced foam should not be exposed to high temperatures before being added to the slurry, as this leads to a decrease in the foam volume. Instability of cellular grout was noted when preparing a cellular grout with an extremely low density (such as C10), which resulted in instability throughout the hardening process (over a 24-hour period) as shown in Figure 6 and also observed by others (Figure 6).

The drying shrinkage was found to decrease with the increase in foam content. This study revealed that mixing and placing cellular grouts at a high temperature (about 100° F) could lead to progressive collapse of the cellular grout. The grout selection needs to be limited to densities ranging from 20 to 75 lb/ft^3. As cellular grouts with density less than 20 lb/ft^3 are unstable and can collapse upon setting, grouts having the mix proportions used in an intended C40 can inadvertently show substantially low density if excess foam is unintentionally added to the mix.

For C40 mixes, the guidelines in ASTM C869/C869M provide that the density of the cellular grout should either fulfill a density after pumping of 40 ± 3 lb/ft^3 or an oven dry density for Type III cement of 30 ± 2.5 lb/ft^3. The fresh density (also known as the cast-wet density) is regarded as the density of the grout after pumping. Cast-wet density was used as the basis for this evaluation. In addition, most of the mixes produced in our laboratory also met the minimum spread suggested by ACI Committee 229 (ACI, 2013), except for two mixes (C20 and C30) when mixed with a surfactant foaming agent (Figure 7). Similarly, the efflux time required for the grout to pass through the stem of a funnel with a diameter of ½ inch when subjected to the force of gravity alone is significantly longer for all grades of cellular grout mixed with surfactant foaming agents but significantly shorter for synthetic and protein foaming agents. According to ASTM C869/C869M, mechanical properties such as compressive strength and split tensile strength were required to have values of 200 and 25 psi, respectively. C40 mixes with any foaming agent included in this study satisfied the ASTM minimum requirements for mechanical properties. In addition, the amount of water that could be absorbed by hardened grout is to be limited to a maximum of 25%, and C40 was compliant with this water absorption requirement. Overall, C40 fulfilled the relevant ASTM and ACI requirements (ASTM C869/C869M for manufacturing cellular grout and the recommendations of ACI Committee 229) and is suitable for use as a grout for sliplined culverts.

Figure 6: Instability of Ultra-Low Cellular Grout: (a) Lab-prepared Grout from Jones et al. 2016 (*left*), (b) Lab-prepared Cellular Grout C10 (*center*), and On-site Instability for Grout Reported by Jones et al. 2016 (*right*).

A summary of the findings from the laboratory tests conducted to evaluate the suitability of cellular grouts as a fill material is given below:

- Foaming agents play a role in determining the density of the resulting foam. Protein-based foaming agents produce a less dense foam than synthetic and surfactant foaming agents. There may be some minor variations in density, but overall, they are well within the range allowed by ASTM C796 and ACI 5283.3R-14.

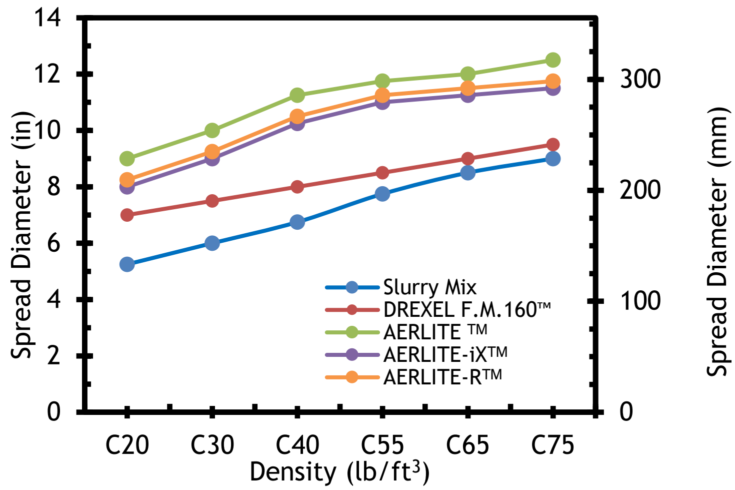


Figure 7: Flowability of Slurry and Cellular Grout Mixes.

- Conditions that may affect foam stability are to be taken into account in studies on foaming stability. For example, it was discovered that mixing foaming agents with high-temperature water (about 100 °F) before adding the foam to the slurry mix will affect the foam's stability and cause the foam to have poor performance. A normal room temperature (68 °F to 72 °F) is preferred for preparing the foam before mixing it with cement slurry.
- Cellular grouts mixed and/or placed at a high temperature (100 °F) will be unstable.
- The w/c ratio considerably impacts the cast-wet density. Adjusting the w/c ratio to 0.5 results in a cast-wet density that falls within the ASTM acceptable range.
- One of the most important endeavors of this project is to guarantee that the cellular grout can flow or spread freely. This was accomplished by using both a spread test and a flow cone test. From the experimental findings, slurry grout mixed with protein-based or synthetic-based foaming agents perform better in the spread test and flow cone test than slurry grout mixed with a surfactant foaming agent. For example, the results of the experimental testing demonstrated that the spread of most cellular grout mixes made in the test program fulfills the minimum ACI spread standards of 8 inches, except for C20 and C30 mixes that were prepared with a surfactant foaming agent. In addition, all cellular grout mixes were found to flow through a discharge tube with a diameter of ½-inch despite having different densities and different foaming agents.
- The volume of plastic air content in cellular grout was determined in this project. A linear relationship was found between the plastic density (cast-wet density) and the air content or the percentage of foam. In addition, mixing different foaming agents with cellular grouts, such as synthetic-based or protein-based foaming agents or surfactants, was found to have only a slight impact on the plastic air content of the cellular grout, despite the fact that the plastic density remains the same for the different cellular grouts.
- Specimens mixed with surfactants or protein foaming agents exhibited lower losses of oven-dry density than those mixed with synthetic foaming agents. However, C40 cellular grout

prepared using any of the four foaming agents meets the requirements of ASTM C796 for the oven-dry density of cellular grout (30.4±2.5 lb/ft^3)

- Water absorption of the cellular grout has a predictable impact, with the experimental results suggesting that water absorption increases gradually with the density of the cellular grout. When cellular grout was mixed with surfactant foaming agents, the percentage of water absorption was found to be the lowest. On the other hand, the water absorption percentage was highest when the slurry mix was mixed with protein-based foaming agents, and grouts prepared with synthetic-based foaming agents showed an average value. According to ASTM C796, the maximum water absorption must be less than 25%, and C40 cellular grout was found to comply with this standard. Conversely, mixtures C55, C65, and C75 exhibited substantial absorption of water because of the lower quantity of foam added to the slurry mix.
- There is a positive relationship between drying shrinkage and the density of the cellular grout. The drying shrinkage values also increase when there is a greater rise in the density of the cellular grout. High-density cellular grouts such as C65 and C75 mixes have a significant amount of drying shrinkage because of their high cement contents and lack of aggregates. In contrast, grouts with lower densities (such as C20 and C30 mixes) exhibit less drying shrinkage due to the high quantity of foam and small quantity of cement. The type of foaming agent used was also found to influence the drying shrinkage. For example, cellular grouts mixed with surfactant foaming agents showed more drying shrinkage than those mixed with protein-based or synthetic-based foaming agents. Despite the fact that different foaming agents have different drying shrinkage rates, most mixtures investigated in this study still conform to the ACI Committee 523.3R limits for cellular grout shrinkage, i.e., within the drying shrinkage rate limits of 0.1% to 0.4%.
- The type of foaming agent was found to affect the mechanical properties of the grout material, including compressive strength and split tensile strength. The results of both tests demonstrated that the performance of the mixtures was significantly improved by adding surfactant foaming agents as opposed to synthetic-based or protein-based foaming agents. The minimum requirements of ASTM C869/C869M-11 for cellular grout are met by mixes C40, C55, C65, and C75 at 28 days, as indicated by compressive strength (minimum of 200 psi) and split tensile strength (minimum of 25 psi).

Parallel Plate Tests

Loading characteristics of plastic pipes are determined by conducting a parallel-plate loading test according to ASTM standard D2412-21. This test method was adopted to sliplined culvert test specimens that simulate a host pipe and a liner pipe with different diameters having the annulus void filled with the desired grout as seen in Figure 8. The contribution of the hardened grout and its contribution to the strength of the culvert segments was determined based on the load-deformation characteristics of such test specimens.

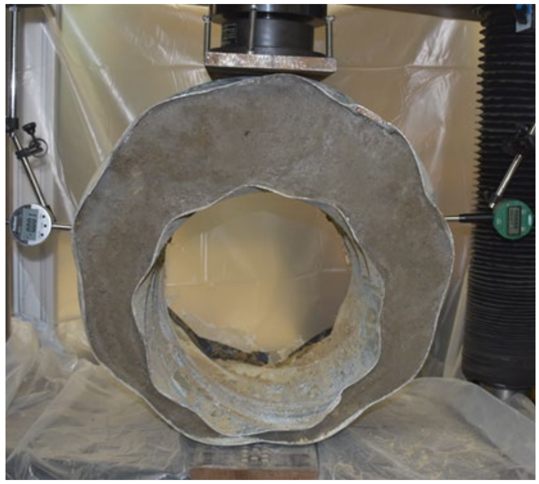


Figure 8: Typical Setup for a Parallel-Plate Loading Test

Tests were conducted to determine the load-carrying capacity of sliplined corrugated steel culverts in order to evaluate the effect of traditional CLSM grouts and the improved CLSM grout mixtures. Parallel plate loading tests were also performed with cellular grout as the annulus void filler. Additionally, to investigate the effect of voids on the structural performance of sliplined culverts, parallel plate loading tests were conducted on a few test specimens with voids at the crown or springline positions. Complete details of these tests are included in Appendix E (cellular grout) and Appendix F (CLSM grout).

The key findings from the parallel plate tests are as follows:

- The test results confirmed that the hardened grout within the annulus voids of sliplined culverts contribute significantly to the load-carrying capacity of the culverts, emphasizing the importance of complete grout filling in such culverts.

- The test results also demonstrated that voids have a substantial influence on the contribution of the grout to the development of the structural strength of sliplined culverts. When compared to the strength of a culvert with a completely filled annulus, the grout's contribution to the strength of a culvert with voids at the springline was lower (about 20% for cellular grout). In contrast, when voids are located near the crown, the grout’s contribution to the strength of the culvert is reduced by 84% as compared to the grout’s contribution in a culvert with a completely filled annulus.

- From these results, it is clear that voids at the crown position of a sliplined culvert are a primary source of vertical and horizontal deformation as well as delamination at the sides of the culvert. Voids at the crown are more detrimental to the structural load-carrying performance than voids at springline positions.

Material Specifications

From the findings presented so far in this report, it was determined that the SS 837 specification in its current form is not conducive to complete filling of the annulus voids of sliplined culverts. Suggested changes to the SS 837 specification for the void fill and construction methods for a practicable method to install fill material in the void between the host conduit and liner pipe were investigated in this study, and the relevant details are presented in Appendix H. Guidance on an annulus void fill grouting and a verification process is also included in that appendix.

In summary, grouts and mortars made using ODOT C&MS Items 613 and 602 are not suitable for sliplined culverts and should be removed from SS 837. Recommendations for a new CLSM grout specification are also presented in Appendix H. Specific requirements in addition to those given in ASTM C869 for cellular grouts were also recommended and included in this appendix.

Field Grout Pumping and Large-Scale Culvert Tests

The modified CLSM and cellular grouts with improved flow characteristics and properties were tested at a larger scale to determine if they are suitable for annulus void filling in real projects (Figure 9). Firstly, the selected grouts were mixed in a commercial batching plant to verify the successful upscaling of mixes developed in the laboratory. Three cubic yards each of the improved CLSM and cellular grouts were batched in a commercial batching plant. The wet and hardened grout properties of these mixes were determined and were found to satisfy the relevant ASTM requirements. The test methodology and the relevant details are given in Appendix G.

CLSM Mix A5: Adding Fill Flow to the Mix — Cellular Grout Mix C40: Adding Foam to the Mix — Grout Test Setup

Figure 9: Commercial Scale Mixing of the Proposed CLSM or Cellular Grout C40.

Pumping tests were performed to evaluate the performance of the mixes for possible field implementation. The pumping of grouts is expected to cause a loss of volume and/or loss of air content when the grouts are pumped over long distances. The CLSM and cellular grouts were pumped through a 2-inch-diameter polyvinyl chloride (PVC) pipe over a length of about 200 ft. with an upslope gradient of 2.5% (see Figure 10). The density and air content of the grouts at three locations along the length of the PVC pipe were determined. Other wet and hardened grout properties were also determined to document how pumping grouts over such lengths might affect these properties.

Figure 10: Field Pumping Tests of the Proposed CLSM or Cellular Grout C40.

After successful grout pumping tests, it was further recognized that larger-scale culvert tests were also needed to verify the fillability of the selected grouts in the annulus voids of culverts. Two large-scale culvert tests were completed by filling the annulus voids of two 20-foot-long test sections with CLSM and cellular grouts. The host conduit of the test culverts were 48-inch corrugated metal pipes, and the liner pipes were 36-inch diameter corrugated metal rib pipes. The suitability of the improved grouts for filling annulus voids at this larger scale was verified from the field tests. Wet and hardened grout properties were also determined at various locations and stages of pumping to document grout performance during the filling of annulus voids of sliplined culverts. The typical field culvert test setup is shown in Figures 11 and 12.

The two large-scale culvert test specimens were cut into four equal segments to inspect the condition of the hardened grout within the annulus voids of the culvert specimens. The cut surfaces of the two culverts are shown in Figure 13. The solid-looking surfaces as seen in the figure demonstrate complete filling of the annulus voids in the two test specimens with CLSM and cellular grouts over the entire culvert length. Complete details of the field tests are provided in Appendix G.

Figure 11: Culvert Grouting Tests: Setup of Two 20-ft.-Long Test Specimens.

Figure 12: Culvert Grouting Tests: End Details and Instrumentation Details.

Figure 13: Cut Surfaces of Test Specimens for Culvert Grouted with CLSM (left) and Culvert Grouted with Cellular Grout (right).

Research Findings and Conclusions

In recent years, ODOT has discovered a number of sliplined culverts that did not have their annulus void spaces completely filled with grout. Sliplined culverts with annular spaces that are not completely filled experience severe distortion and settlement as well as reduced structural capacity. Field investigations of several sliplined culverts in different districts of the state confirmed that the lack of complete annulus void filling is a prevalent problem. Filler grout properties, particularly poor flow characteristics, would cause the grout to not completely fill the annulus voids. Several conclusions were drawn based on culvert inspections, laboratory tests, and field pumping and grouting tests conducted in this project.

Culvert Inspections

Sounding tests and visual inspections with an endoscope camera are simple methods that can be used to detect voids and reveal the condition of the annulus behind most liner pipes. The sounding results are inconclusive for liner pipes that are double-layered polyethylene pipes due to the space between the two polyethylene walls and for annulus voids filled with cellular grouts due to the low density of the grout. As long as these limitations are recognized, the sounding test is an implementable method to detect voids within the annulus of a sliplined culvert. At the locations of additional concern, voids can also be directly viewed with an endoscope camera. Therefore, the combined method of sounding assisted with an endoscope camera is a reliable and inexpensive method to detect voids in the annulus. A classification of common defects was developed and proposed based on sounding tests conducted during the inspection of sliplining culverts (Appendix C).

In this study, only four liner pipe types were included for culvert inspections, and the diameters of the liner pipes were mostly larger than 50 inches but less than about 72 inches. The usefulness of the non-destructive tests experimented in this project was rather limited for the culvert inspections in this study. Further investigations on the validity of the sounding method during the placement of grout will also be helpful for developing inspection methods to be used during construction.

Void Fill Materials

CLSM Grouts

One of the primary goals in this project was to evaluate the different fill materials included in SS 837 and to develop improved mix proportions for CLSM grout (alternatives to LSM) for filling the annulus voids of sliplined culverts. Several CLSM mix design alternatives were investigated in this research by modifying the characteristics of grouts to potentially make the grouts suitable for annulus filling applications. These properties included flowability, bleeding, unconfined compressive strength, and drying shrinkage. Characteristics of the modified CLSM mixtures were compared to those of the traditional LSM and NSM mixes that are currently mentioned in SS 837 as annulus void fill materials. The following specific conclusions for CLSM grouts were drawn based on the findings of this study:

- Fill Flow admixture is a volume-expansion admixture that increases the volume of the mix by as much as 30% by introducing numerous air bubbles to the wet mix. It is effective in producing flowable CLSM mixes with no noticeable segregation or bleeding. Moreover, the use of this admixture reduces the water demand of the CLSM mixtures, resulting in a flowable mix with no bleeding.
- The wet densities of modified mixtures from Group A and Group B (i.e., Mix A-4, Mix A-5, and Mix B-2 described in Appendix F) were reduced by the addition of Fill Flow admixture. The reduction in wet density makes these grouts more pumpable and provides a more cost-effective solution than traditional mixes.
- All modified CLSM mixtures developed in this project had a minimum compressive strength of 100 psi, which is the minimum compressive strength recommended by most state transportation agencies.
- The reduction or absence of fine aggregate and the higher water content in a CLSM mixture were found to result in an increase in drying shrinkage. Therefore, neat cement grout mixes or neat fly ash grout mixes should not be allowed for filling annulus voids in sliplined culverts.
- The ultimate load-carrying capacities of sliplined culvert test specimens grouted with a improved CLSM mixture were considerably greater than those for culverts grouted with a traditional LSM mixture.
- It was found that the hardened grout of a completely filled annulus void of a sliplined culvert made the maximum contribution to the load-carrying capacity in the structural load tests on culvert specimens sliplined with corrugated metal pipes. This demonstrates the importance of complete grout filling of the annulus of a sliplined culvert.
- For a sliplined culvert with a partially filled annulus, a void at the crown has more adverse effect on the structural performance of the culvert than voids at the springline positions. The contribution of the annulus grout to the load-carrying capacity is reduced substantially, and the sliplined culvert exhibits significant deflection as well as delamination when voids are present in the annulus, particularly at the crown. The sliplined culverts distorts vertically and horizontally in the presence of a void at the crown position. Any distorting noticed during inspections is a clear sign of the lack of grout in the annulus void.
- An improved CLSM grout (referred to as CLSM Mix A5 in Appendix F) with modified mixture proportions was developed that can be used to better fill the annulus in a sliplined culvert. This grout was one of the two grouts that demonstrated to have superior flow and better wet and hardened grout properties than the grouts currently specified by ODOT.

Cellular Grouts

Cellular grouts are grouts made with cement, water, and foam that is prepared using a foaming agent. A foaming agent is a material such as a surfactant or a blowing agent that facilitates the formation of foam. The following conclusions were drawn based on the fresh and hardened properties of the cellular grouts tested in this study:

- Foaming agents play a major role in determining the density of the resulting foam. Protein-based foaming agents produce a less dense foam than synthetic and surfactant foaming agents.

- Preparing foam with high-temperature water (at about 100 °F) affects the foam's stability and causes the foam to have inferior performance. Water temperatures between 68 °F and 72 °F are suitable for preparing foam from foaming agents before mixing it with cement slurry.
- Cellular grouts can be made with densities ranging from 10 to 75 lb/ft^3. Placing cellular grout with an exceptionally low density (such as C10 mix) will lead to progressive collapse of the hardened grout within the first few hours after casting. Therefore, C10 grout is too unstable to use for culvert rehabilitation.
- The w/c ratio considerably impacts the cast-wet density. After multiple trials, it was determined that a w/c ratio of 0.5 would result in a cast-wet density that falls within the acceptable range of within ±3 lb/ft^3 of the design density.
- One of the most important properties needed for sliplined culvert application is to guarantee that the cellular grout can flow and spread freely. Slurry grouts mixed with protein-based or synthetic-based foaming agents perform better in the spread test and flow cone test than slurry grouts mixed with a surfactant foaming agent.
- The drying shrinkage values increase with the increase in density of the cellular grout. High-density grouts such as C65 and C75 have a significant amount of drying shrinkage because of the high cement content and the lack of aggregates. Cellular grouts mixed with surfactant foaming agents showed higher drying shrinkage than those mixed with protein-based or synthetic-based foaming agents. The mechanical properties of hardened grouts with surfactant foaming agents are superior to those with synthetic-based or protein-based foaming agents.
- Parallel plate loading tests conducted on representative culvert test specimens with cellular grout C40 as the annulus void fill material showed trends similar to those for culverts with CLSM grouts. These tests demonstrate (i) a need to completely fill the annulus for good structural performance and (ii) the effects of the presence and locations of voids on the structural load carrying capacity of the culvert. In both cases (CLSM and cellular grout), the adverse effects of voids produced due to incomplete filling are similar.

Material Specifications

C&MS Items 613 (LSM) and 602 (NSM) are two of the grouts included in SS 837. These two grouts were found to be unsuitable for use as annulus void fill materials because of the lack of flowability and poor spread characteristics. It is therefore concluded that the use of these grouts should be discontinued by ODOT. The modified CLSM (Mix A5) with a volume-expanding admixture like Fill Flow was found to be a good alternative to the grouts described in Items 613 and 602. Cellular grout C40 was also found to be a suitable annulus void filler. However, additional requirements for cellular grouts are necessary to be included in SS 837 specification to ensure the required performance of the grout for annulus void filling. Those additional requirements are compiled and suggested in Appendix H.

Field Grout Pumping and Large-Scale Culvert Tests

It was demonstrated from the grout pumping tests and large-scale culvert grouting tests that with suitable modifications to grout mix proportions as determined from the laboratory tests, it is feasible to smoothly pump and completely fill the annulus voids of sliplined culverts. The modified CLSM (referred to as Mix A5 in Appendix F) and C40 cellular grout were both determined to be suitable for sliplined culvert applications.

Recommendations for Implementation

Based on the laboratory tests and large-scale field tests performed in this project, the following changes are recommended for consideration when revising SS 837:

1. Grouts and mortars made using C&MS Items 613 and 602 are not suitable for sliplined culverts and should be removed from SS 837.
2. For specifications on cellular grouts, SS 837 refers to ASTM 869 and Item 499. It is recommended that a detailed specification listing the specific requirements be included in SS 837 for C40.
3. It is recommended that CLSM and cellular grout C40 options specific to annulus voids of sliplined culverts be introduced in ODOT C&MS as separate items without reference to Items 613 or Item 602.
4. The requirements listed below may be included for CLSM grouts in the revised specification. The suggested mix proportions for CLSM are shown in Table 6. A list of tests that must be performed on this type of grout is included in Table 7.

Table 6: Suggested Mix Proportions for the Modified CLSM Grouts

Materials	Amount
Cement Type I (lb/yd^3)	100–130
Fly Ash, Class C (preferred) or Class F (lb/yd^3)	350–370
Fine Aggregate (lb/yd^3)	2700–2750
Water (gallon)	35–40
w/c ratio	0.6–0.7
***Volume-expanding admixture (lb/yd^3)**	As recommended by the supplier
****Air Entraining Agent Admixture (oz)**	As needed
Target Density (lb/ft^3)	93 ± 4

** Minimum 30% volume expansion is needed; add admixture at the site, not at the batching plant.*
***Can be added to the mix to meet the target density after adding the required amount of admixture.*

5. The following requirements may be included for cellular grouts: cellular grouts conforming to ASTM C869 are acceptable to be used as an annulus void grout. The suggested mix proportions for a C40 cellular grout that can be used for filling the annulus voids of sliplined culverts are shown in Table 8. A list of tests that must be performed to demonstrate compliance of this type of grout is presented in Table 9. Additionally, all other requirements specified in ASTM C869 standard must also be satisfied. The limits included in Table 9 supersede any discrepancies between the requirements given in this table and those in ASTM C869.

Table 7: Suggested List of Tests for Modified CLSM Grouts

Test	ASTM Reference	Limits
Fresh Grout Properties to be Met Before Pumping is Allowed at Site		
Fresh Density	ASTM C138	Before Pumping: 93 ± 4 (lb/ft^3)
Flowability/Spread	ASTM D6103	Minimum 9 in.
Air Content	ASTM C138/C231	30% ± 3%
Temperature	ASTM C1064	60–70 (^{o}F)
Hardened Grout Properties		
Bleeding Test	ASTM C940	No Bleeding (0 ml)
Compressive Strength	ASTM D4832	Minimum 200 psi
Split Tensile Strength	ASTM C496	Minimum 25 psi
Water Absorption	ASTM C796	Maximum 25% by Volume
Oven Dry Density	ASTM C495	90 ± 4 (lb/ft^3)

Table 8: Suggested Mix Proportions for C40 Cellular Grouts

Materials	Amount
Cement Type I (lb/yd^3)	Minimum 700
Water (gallons)	39–42
w/c ratio	0.46–0.50
***Foam (lb/yd^3)**	0.6
Target density (lb/ft^3)	40 ± 3

* *Added at the site, not at the batching plant.*

Table 9: Suggested List of Tests for C40 Cellular Grouts

Test	ASTM Reference	Limits
Fresh Grout Properties to be Met Before Pumping is Allowed at Site		
Fresh Density	ASTM C138	Before Pumping: 40 ± 3 (lb/ft^3)
Fluidity	ASTM C939	Can vary between 35 and 60 seconds
Flowability/Spread	ASTM D6103	Minimum 8 in.
Air Content	ASTM C138/C231	50% to 70 %
Temperature	ASTM C1064	50 to 75 °F
Stability Test	Modified ASTM C940	No Collapse (0 in. height change)
Hardened Grout Properties		
Compressive Strength	ASTM D4832	Minimum 200 psi
Split Tensile Strength	ASTM C496	Minimum 25 psi
Water Absorption	ASTM C796	Maximum 25% by Volume
Oven Dry Density	ASTM C495	30 ± 3 (lb/ft^3)

List of citations

Citations are listed at the end of each of the appendices for this report.

List of Appendices

Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX A

Literature Review

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Prepared for:
The Ohio Department of Transportation,
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U.S. Department of Transportation
Federal Highway Administration

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APPENDIX A

LITERATURE REVIEW

A.1 Introduction

A.1.1 Motivation of the Research and Problem Statement

Culverts are pipes which are typically located under roadways or embankments and facilitate the flow of water. The definitions of culverts are traditionally based on the span length rather than the function of the pipe or the type. According to the Federal Highway Administration (FHWA) Bridge Inspector's Training Manual 70, structures that are longer than 20 feet in span length parallel to the roadway are usually classified as bridges, while structures with a span length of less than 20 feet are classified as culverts (Hartle et al. 2002). Ohio uses a span of 10 feet to define a bridge per ORC. AASHTO (1991) defines a culvert as a structure that is 20 feet or smaller in length between extreme ends of openings. According to the ODOT Bridge Design Manual 2022, structures that are longer than 10 feet in span length parallel to the roadway are classified as bridges while structures with a span length of less than 10 feet are classified as culverts.

The superimposed dead and live loads are considered in the design of culverts, and culverts are classified into two basic types based on their load-carrying behavior: rigid culverts and flexible culverts (Figure A.1). Unreinforced or reinforced concrete culverts are rigid culverts; they show little deformation and experience large bending moments. Metal or thermoplastic culverts are flexible culverts; they can experience little bending moment but significant deformations. Reinforced or unreinforced concrete, corrugated metal, and polymer (either corrugated, ribbed, or plain) are the common materials used for culverts (Allouche et al. 2007, NCHRP14-19 2010).

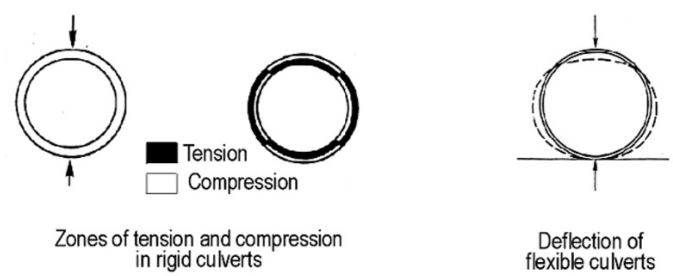


Figure A.1: Load-carrying behavior of rigid and flexible culverts (NCHRP 14-19, 2010).

In the United States, culverts are managed by state and local transportation agencies. Many existing culverts have reached the end of their design life and are in a deteriorated state (Yang et al. 2009, Rahmaninezhad et al. 2019). As a result, several cases of road collapse due to culvert failures have been reported across the country (Perrin et al. 2004). Additionally, deterioration-induced perforations in metal culverts and crack development and joint failures in concrete culverts can lead to leakage, which can affect the hydraulic performance and structural stability of the culvert. Perforations in metal culverts may also cause erosion of surrounding soil and may adversely affect the structural stability of a flexible culvert (Meegoda et al. 2009). In the case of deteriorated reinforced concrete (RC) culverts, groundwater infiltration or stream water exfiltration from the culvert may result in the formation of soil voids below the road surface (Ballinger et al. 1995). To prevent further deterioration and avoid the expense of replacement, deteriorated culverts need to be rehabilitated.

Sliplining is one of the most preferred rehabilitation methods for deteriorated culverts (Rahmaninezhad et al. 2020) because it is suitable for both metal and RC culverts. Nonetheless, no specific design methods are available for the rehabilitation of culverts using grouted slipliners. In addition, there are no specific standard guidelines for verifying that the annular void has been filled with grout. Therefore, there is a need for research to create technical guidelines for sliplining methods and grouting. Moreover, the interaction between the liner and the existing culvert structure needs to be studied, and the interaction between the grouts used in annular voids and the two pipes (both the new liner pipe and the host pipe) needs to be investigated.

The Ohio Department of Transportation (ODOT) and other state DOTs use a sliplining approach for rehabilitation of deteriorated culverts. ODOT Supplemental Specification 837 (SS 837; ODOT, 2019) requires the void to be filled completely by the contractor and specifies the use of either low-strength mortar backfill (ODOT CMS Item 613), mortar (ODOT CMS Item 602), or cellular grout (ASTM C869 or modified ODOT CMS Item 499). Current void fill operations have been found to not completely fill the annulus between the host and liner pipe; however, this is not generally detected during construction. ODOT District personnel have reported an absence of annulus void fill material in previously rehabilitated culverts that was only discovered several years after construction. A verification process that confirms the complete filling of the annulus void does not currently exist.

A.1.2 Goals and Objectives

The primary goal of the research project is to develop a specification for annulus void fill materials and standard operating procedures. The specific project objectives are as follows:

1. To provide a specification for the void fill materials and identify the applicability of different materials according to site conditions and liner type.
2. To include both high-strength and low-strength void fill materials in the specification and provide details about the applicability of the chosen material in the designer note.
3. To create a construction specification with a detailed methodology for the specific void fill material.
4. To ensure the methodology will consider all liner materials as listed in SS 837 (ODOT, 2019).
5. To include a practicable verification process for ensuring complete filling of annulus voids.

A.1.3 Scope of this Literature Review

The objective of this literature review is to develop a further understanding of the process for sliplining rehabilitation culvert systems with a particular emphasis on grout materials and methods. This review includes a summary of information and data collected from journal publications, online sources, and other sources as well as from the current practices of various state and local transportation agencies.

This review provides information about the following topics:

- Sliplining methods
- Available grout materials and grouting methods
- Different types of liner materials used as conduits
- ODOT specifications for different grout materials
- Current practice of state and local agencies
- Research sponsored or conducted by state and local agencies
- Guidelines or specifications provided by conduit suppliers
- Verification methods for confirming grout filling
- Ground-penetrating radar (GPR) inspection methods and new technologies

A.2 Culvert Rehabilitation Techniques

A.2.1 Introduction

Culverts and other drainage infrastructure constructed since the 1950s will soon reach the end of their service life. As replacement of these culverts is expensive (due to the cost of excavation, removal of the old culvert, placement of new components, and soil compaction at installation), several transportation agencies are using trenchless rehabilitation techniques to reduce project costs. Sliplining is the most popular method used for the trenchless rehabilitation of culverts. This section provides a review of several trenchless rehabilitation approaches, details about sliplining techniques, and a brief summary of the standards associated with sliplining.

A.2.2 Culvert Rehabilitation

The culvert rehabilitation process involves a number of steps, such as identifying the problem, determining the causes of deterioration, evaluating the hydraulic and structural condition, evaluating rehabilitation options, and implementing the selected technique. To determine the causes of deterioration, there are some key culvert observations or preferred tests as listed in Table A.1 (Wagener et al. 2014).

Table A.1: Key Culvert Observations (Wagener et al. 2014)

All Culverts	• Horizontal and vertical deflections of pipe • Size and location of voids visible through separated joints and holes in the culvert • Sounding of the culvert interior with a hammer to listen for "hollow" sounding areas that may indicate voids outside the culvert • Width of separated or deflected joints • Misalignment of pipe joints • Camber (bend) or settlement of pipe alignment
Rigid Pipe Culverts	• Crack size, location, length, and extent of reinforcement corrosion. Corrosion typically occurs in crack widths exceeding 0.02", especially in the presence of chlorides • Depth of invert erosion. If reinforcement is exposed, the amount of section loss • Sounding of walls and invert to locate areas of delaminating concrete due to slabbing (radial tension failure) or corrosion of reinforcement
Flexible Pipe Culverts	• Composition and compaction of pipe bedding materials. • Cracks or tears in the pipe wall • Crimping of pipe (corrugated metal pipe (CMP) only) • Tearing at bolt holes (CMP only)

If the condition of the culvert is fully deteriorated (as described in Table A.2), the culvert should be rehabilitated, and the following conditions need to be considered:

- Stability of the culvert during construction to prevent additional distress to the culvert and ensure worker safety.
- Transfer of load into the rehabilitated culvert section. If the culvert is not unloaded before rehabilitation, the rehabilitated culvert section will contribute until additional loading is applied.
- Preventing live load from being applied to the culvert until rehabilitation work is completed and the culvert is capable of carrying the load.

Table A.2: Typical Conditions of a Fully Deteriorated Culvert (Wagener et al. 2014)

Rigid Pipe Culverts	• Longitudinal cracks in the crown or invert wider than 0.20 inch • Longitudinal cracks in the crown or invert wider than 0.10 inch with signs of reinforcement corrosion • Slabbing of the culvert wall • Erosion of culvert invert with 20% or more exposure of reinforcement in two or more successive culvert segments • Delamination of the concrete down to the reinforcement level
Flexible Pipe Culverts	• Deflections in excess of 10% or evidence of buckling • Cracks or tears through culvert wall at more than two locations • Crimping of the culvert wall (corrugated steel pipe (CSP) only) • Tearing at the bolt holes (CSP only) • Erosion/corrosion of invert with 20% or more cross-section loss • A hole that is 1 inch or larger

The open-cut method (shown in Figure A.2) is a traditional method that is widely used to repair or replace a culvert due to its simple approach and the familiarity of workers with the technique. The open-cut method does have drawbacks in that it may cause increased traffic delays on roadways that may result in increased economic, social, and environmental impacts. Consequently, many state and local agencies have adopted in recent years trenchless renewal techniques for culvert rehabilitation rather than culvert repair or replacement (Thornton 2005).

Figure A.2: Open-cut methods (Jin 2016).

A.2.3 Review of Various Trenchless Culvert Rehabilitation Methods

In the case of culvert rehabilitation, trenchless technologies (listed in Figure A.3) are popular because the installation is fast and the environmental impacts can be minimized (Jung et al. 2004). Moreover, trenchless technologies can keep traffic disruptions to a minimum and lower the installation costs. Several relining techniques for culvert rehabilitation can also be accomplished using trenchless methods. In this rehabilitation process, a new pipe material (a rigid or flexible liner pipe) is inserted and held in place either by using grout (for a rigid-wall liner) or by employing a heat- and pressure-based curing process (for a flexible liner) in order to extend the service life of an existing pipe (Najafi et al. 2005).

Based on the different installation processes and types of materials, culvert rehabilitation techniques can generally be divided into three main groups:

- Spray-applied pipe linings (SAPLs)
- Cured-in-place pipe (CIPP), and
- Metal liner pipes or plastic-based linings made of polyvinyl chloride (PVC), polyethylene (PE), a blend of low-density PE and ethylene propylene diene rubber (PE/EPDM), high-density polyethylene (HDPE), polypropylene (PP), or glass-fiber reinforced plastic (GRP).

Sliplining, close-fit lining, or spirally wound lining are some of the common practices adopted by various state and local agencies. Among the plastic-based lining techniques, sliplining is the simplest and well-established method (Syachrani et al. 2010). Furthermore, the sliplining approach of rehabilitating culverts can lower the construction, social, and environmental costs (Kanters et al. 2007).

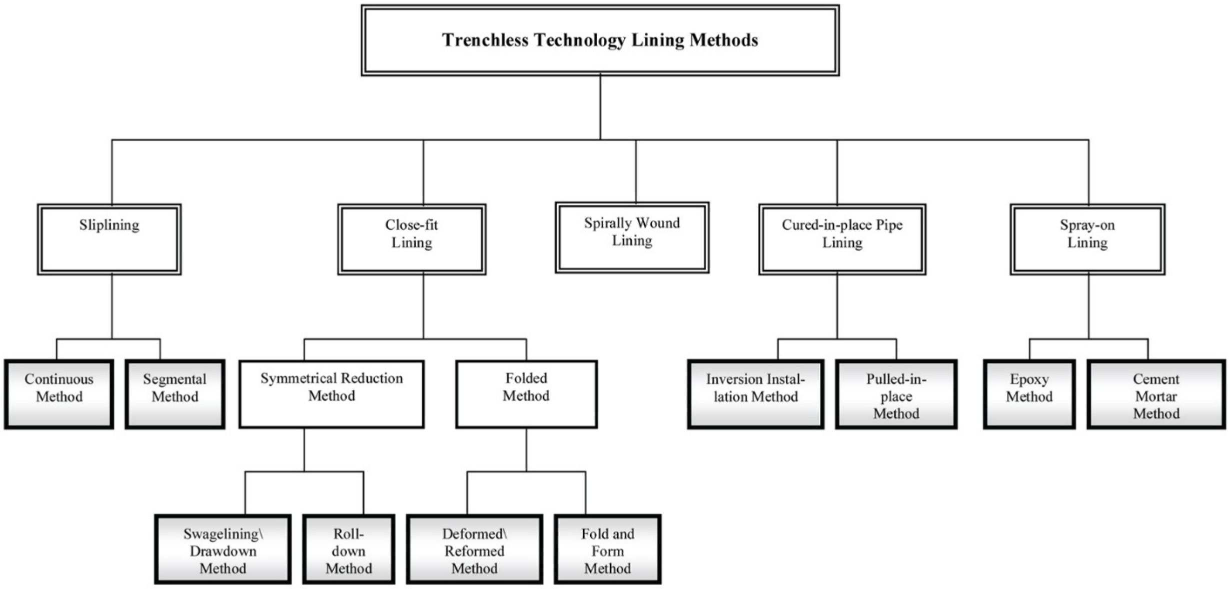


Figure A.3: Types of Trenchless Technology Lining Methods (Thornton 2005).

Syachrani et al. (2010) conducted a survey of state transportation agencies to determine their current practices for culvert rehabilitation. Transportation professionals in 20 of the 50 states responded to their questionnaire. Respondents from eleven states (Ohio, Connecticut, Florida, Minnesota, New Hampshire, New Jersey, New Mexico, South Carolina, Tennessee, Utah, and Vermont, representing 55% of the total responses) indicated that they perform drainage structure rehabilitation and maintenance. The respondents were asked to rate the level of popularity of the trenchless methods of rehabilitation on a scale of 1 to 4 (where "1" is Very Unpopular and "4" is Very Popular). Equation (A.1) was used to calculate the overall ranking of the popularity:

$$Popularity\ index = \sum \alpha \left\{\frac{f}{N}\right\} \frac{100}{4} \quad \text{(A.1)}$$

where
a = constant expressing the weight given to each scale
f = frequency of the responses
N = total number of responses for each type of trenchless techniques

Of the trenchless techniques used in state department of transportation (DOT) maintenance programs for culverts (presented in Table A.3), the authors found that sliplining is the most popular method of culvert rehabilitation. Other popular rehabilitation methods were (in order of decreasing popularity) cured-in-place lining, invert repair, close-fit lining, spirally wound lining, and joint repair. They also showed the range of application of the three relining techniques (Thornton 2005), as presented in Table A.4.

Table A.3: Popularity of trenchless techniques among state DOTs (Syachrani et al. 2010)

Trenchless Technique	**Degree of popularity (out of 11 responses)**				**Popularity Index**	**Rank**
	Very popular	Popular	Unpopular	Very Unpopular		
Sliplining	9	1	1	--	93.2	1
Cured-in-place lining	1	4	1	--	75.0	2
Invert repair	1	--	1	--	75.0	2
Close-fit lining	--	1	3	--	56.3	4
Spirally wound lining	--	-	--	3	25.0	5
Joint repair	--	--	--	1	25.0	5

Table A.4: Range of application of relining techniques (Syachrani et al. 2010, Thornton 2005)

Detailed application	**Sliplining**	**Cured in place lining**	**Spirally wound lining**
Culvert shapes	Mostly circular shape	All shapes	Mostly circular shape
Existing culvert material	Applicable to all types of materials	Applicable to all types of materials	Applicable to all types of materials
Diameter range	0′-4″ to 5′-3″ (0.1–1.6 m)	0′-4″ to 8′-10″ (0.1–2.7 m)	0′-4″ to 10′ (0.1–3.05 m)
Maximum installation	1,000′ (305 m)*	275′ (83.8 m)	Unlimited
Grouting	Full length grouting required	Not required	Grouting required if expandable joints are used
Flow bypass	Not required	Required	Not required

* A maximum length of 5,248 ft. (1.6 km) was reported for segmental sliplining by Najafi (2010).

In a more recent study, Serajiantehrani (2020) collected data (presented in Table A.5) from seven state DOTs (including Ohio) for the life-cycle cost analysis of trenchless spray-applied pipe linings (SAPL), cured-in-place pipe (CIPP), and sliplining renewal methods. The analysis of the data considered several parameters such as the location of the culvert, type of trenchless renewal method, diameter of the culvert, length of the culvert, thickness of the trenchless renewal method, and other factors. The most commonly reported shape for culverts was a round shape, and the most commonly used culvert material was corrugated metal pipe (CMP). Moreover, the analyzed data showed that sliplining is the most frequently used method for all DOTs (Figure A.4), and a common material used for sliplining is HDPE.

Table A.5: Summary of the data collected by Serajiantehrani (2020)

Time range	Trenchless method	Rehabilitation thickness for SAPL method (in.)	Diameter (in.)	Length (ft)	Unit cost (per ft.)
2010–2019	Sliplining, CIPP, SAPL	0.5–2.25	30–108	5-5000	$105-$1,275

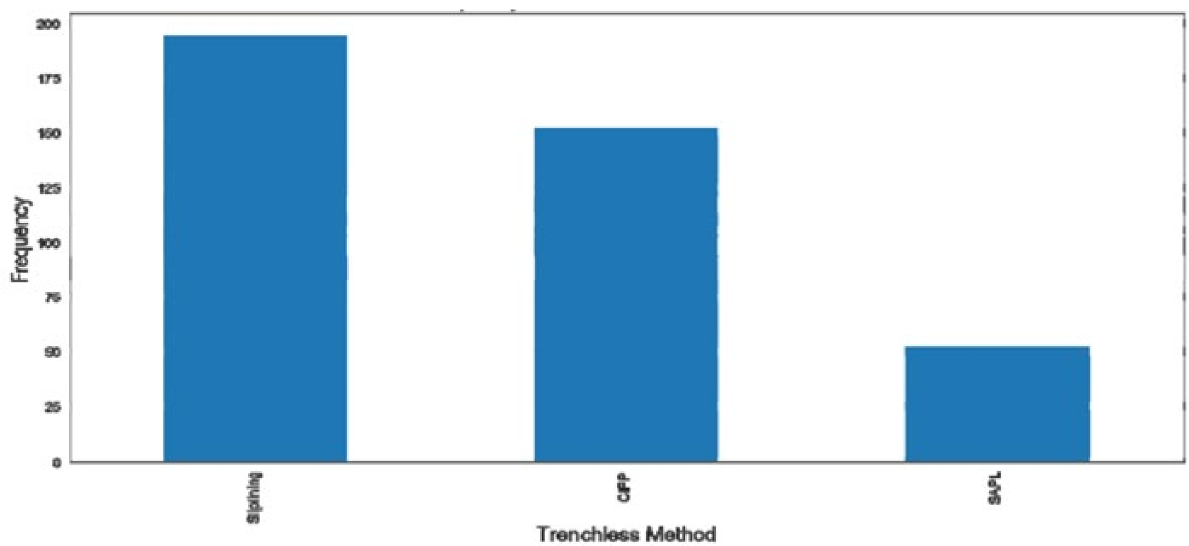


Figure A.4: Frequency of trenchless methods used by DOTs (Serajiantehrani 2020).

A.2.4 Sliplining method

Sliplining (shown in Figure A.5) is the simplest technique among all the plastic-based relining methods used for culverts. In this technique, a new pipe having a smaller diameter is inserted into an existing pipe, and the annular space between the two pipes is filled with grouting materials. In a typical application, the outside diameter of the liner is at least 10% smaller than the inside diameter of the host pipe, which creates an annulus between the two pipes. This annulus may or may not be grouted. If the annular space is grouted, the grouting can prevent leaks and provide additional structural support. If the annulus is not grouted, the liner is not considered to be a structural liner. Any pipe material can be used as the liner pipe including corrugated metal pipe, reinforced concrete pipe, fiberglass reinforced pipe (FRP), and plastic pipes such as PVC and HDPE; however, HDPE, PE, PVC, FRP, and GRP are the most common pipe materials used for sliplining. The handling and weight of the liner and the construction footprint are the main factors that should be considered when choosing a material for sliplining according to the environment and the physical needs of the installation (Caltrans 2013, Jin 2016).

Figure A.5: A culvert renewed by sliplining
(Source: Terrafix Geosynthetics Inc., Salem et al. 2010).

After sliplining, the inner diameter of the opening is decreased and, therefore, the flow capacity may be reduced if the liner pipe is placed at the middle of the host pipe with no eccentricity. The close-fit lining technique (illustrated in Figure A.6) can be used to minimize issues related to the reduced flow capacity of the pipe. In this technique, a thermoplastic pipe is inserted that has an outside diameter equal to or slightly larger than the inside diameter of the existing pipe. By swaging, rolling, or folding, the new pipe can be inserted into and closely fitted to the existing pipe. Application of pressure or a combination of pressure and heat following the insertion of the pipe will ensure a close fit between the new pipe and the existing pipe, and no grouting is needed (Zhao et al. 2003, Dave 2019, Syachrani et al. 2010, Serajiantehrani 2020, Thornton 2005). Even though sliplining decreases the total cross-sectional area of a culvert, using a smoother pipe material with a smaller Manning's roughness coefficient may eliminate the issues of the reduced cross section (Salem et al. 2010).

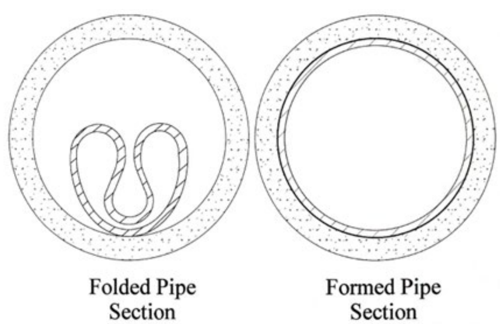
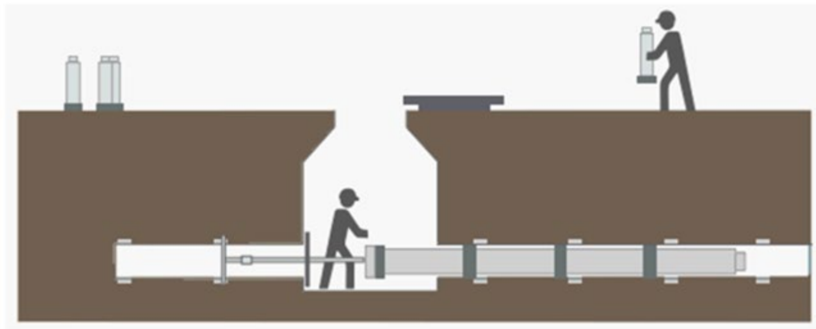
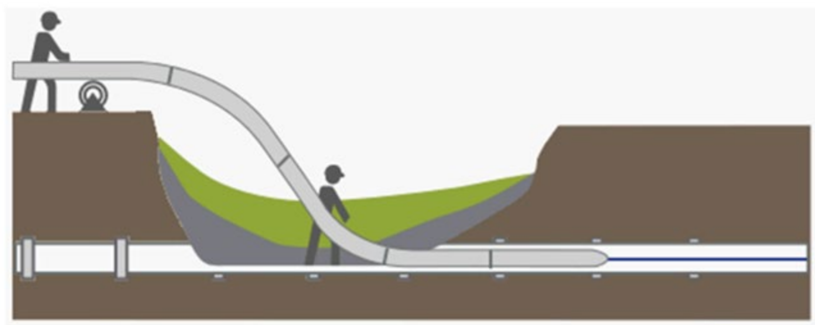


Figure A.6: Fold and Form Method for Close-fit Lining (Thornton 2005).

Sliplining methods can be categorized into two categories: segmental sliplining and continuous sliplining (as shown in Figure A.7). In segmental sliplining, a liner is assembled from short pipe segments at the entry point of the existing pipe, and the liner is pulled/pushed into the pipe for the length of each added segment. In contrast, for continuous sliplining, the liner is manufactured as a continuous pipe or is assembled in the field (e.g., by fusion of HDPE pipes) to match the entire length of the existing pipe prior to insertion. Thornton (2005) provides the general characteristics and effective use of segmental sliplining (Table A.6) and continuous sliplining (Table A.7).



(a) Segmental sliplining



(b) Continuous sliplining

Figure A.7: Sliplining Installation (Serajiantehrani 2020).

Table A.6: General Characteristics and Effective Use of Segmental Sliplining (Thornton 2005)

Application	**Diameter Range**	**Liner Material**	**Maximum Installation**
Gravity and Pressure Pipelines	4 – 157.5 in. (100 mm – 4.0 m)	PE, HDPE, PP, PVC, GRP	5,248 ft. (1,600 m)

Table A.7: General Characteristics and Effective Use of Continuous Sliplining (Thornton 2005)

Applications	**Diameter Range**	**Liner Material**	**Maximum Installation**
Gravity and Pressure Pipelines	4 – 63 in. (100 mm – 1.6 m)	PE, HDPE, PP, PVC, PE/EPDM	5,248 feet (1,600 m)

A.2.4.1 Installation guidelines for sliplining method

Syachrani et al. (2010) mentioned sequential construction activities required for each culvert rehabilitation technique based on the information collected from several sources such as literature reviews, contractors, relining technology vendors, and culvert design and construction engineers at state DOTs. The procedure is outlined in Figure A.8. Sliplining can be used to install a new pipe that is a maximum of 10 percent smaller in diameter as compared to the culvert. The greater of either the outside diameter of the slipline pipe or the coupler (if applicable) should be compared to the inside diameter of the culvert. This may be accomplished by attempting to pull a short section of pipe (~5 feet in length) through the culvert as a trial run. The culvert should be clean and free from sediments and debris so as to not interfere with the installation of the liner pipe.

Sliplining installations may be subject to thermal length changes. To accommodate these changes, the installation should be designed with a minimum clearance between the outside diameter of the liner pipe and the inside diameter of the culvert. Typical insertion length limits are product-specific and can range from 200 ft to 2,000 ft. Some items that need to be considered when evaluating sliplining lengths are anticipated frictional forces and the strength of the product needed to offset these forces. The anticipated frictional forces will be dependent on the condition of the culvert. Since these factors are project-specific, additional coordination with the product manufacturer is recommended.

Continuous sliplining joints are typically butt-fused, while push-together joints are typically used for segmental sliplining to provide a leak-free seal. The new pipe segments are joined together, inserted into the existing pipe, and are properly positioned. A maximum of one degree of joint misalignment can be accommodated in either method (Salem et al. 2010).

Thornton (2005) provided the following general list of installation guidelines for segmental sliplining:

- Thoroughly inspect the existing culvert to determine the smallest diameter located within the culvert to be lined (structural deterioration and wall collapse may have reduced the original culvert diameter). For non-man entry culverts, a “pig” (a foam bullet-shaped device used for cleaning) can be used to determine the smallest diameter.
- Inspect the existing culvert for lateral and service connections as well as protrusions such as roots and sediment.
- Clean and clear the existing culvert.
- Determine the diameter of the liner (in general, the outside diameter of the liner should be at least 10 % smaller than the inside diameter of the existing culvert. A 5% reduction should be sufficient for existing culvert diameters greater than 24 inches.

- Determine the material of the liner. The material chosen should meet the designed load requirements. Factors to be considered in design load requirements include, but are not limited to, hydraulic loads caused by groundwater, soil conditions and loads, traffic loads, and temperature.
- If excavation is required, excavations should be minimal and comply with local, state, or federal regulations regarding excavation safety. Excavations at elbows minimize the total number of excavations required because the liner can be installed in two directions from a single location.
- Determine if the bypassing of flow is necessary. Flow bypass is necessary if the annular space and pulling head openings are incapable of handling the existing flow capacity. Maintaining the flow will often reduce the force required for installation, but it may cause access problems and other difficulties for workers.
- Cut the existing culvert and initiate installation. Install the liner segments either with the push method or the pull method by assuring the proper connection of liner segments. Continue the installation until the entire section of the existing culvert has been lined.
- Once the installation has been completed, a 24-hour relaxation period is recommended before reopening lateral and service connections.
- Inspect the completed lining by closed-circuit TV or manually if the diameter permits man-entry. The liner should be continuous over the entire length.
- If leakage or other testing is required, perform testing to specifications prior to reopening the lateral and service connections.
- Reopen lateral and service connections. Depending upon installation conditions, reconnection may be possible from within the lined culvert or may require point excavation.
- After lateral and service connections have been reopened, reconnected, and stabilized, make the terminal connections. Fill the annulus space between the liner and the original culvert with grout or another cementitious material. The allowable grout pressure of the liner should not be exceeded during the grouting process. Hydrostatically pressurizing the liner will allow for higher grouting pressures and help prevent the collapse of the liner during the grouting process.
- Finally, restore flow if a bypass was required and initiate site cleanup.

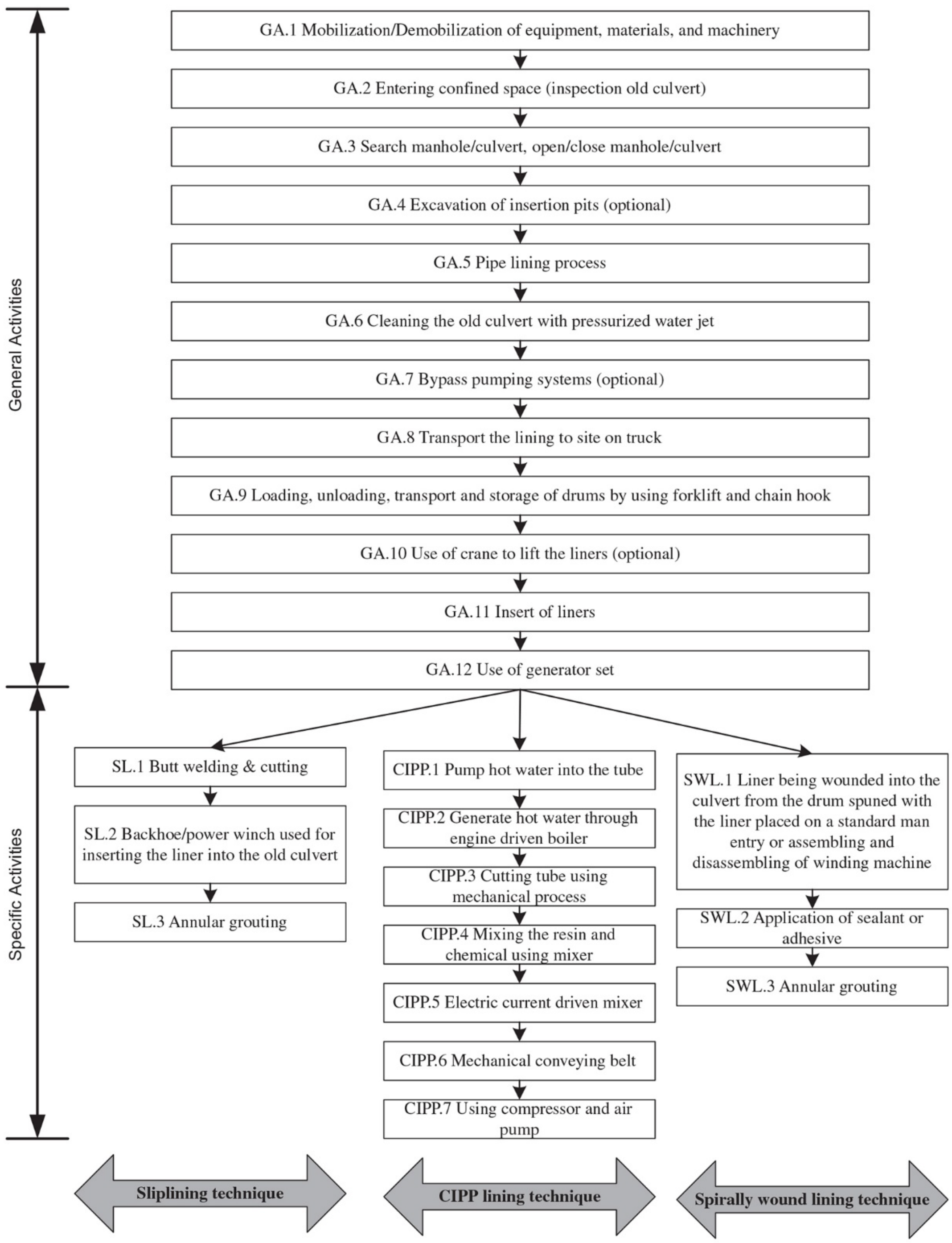


Figure A.8: Installation procedures of culvert relining methods (Syachrani et al. 2010).

The segmental sliplining method has advantages and limitations (see Table A.8).

Table A.8: Advantages/Limitations of Segmental Sliplining
(Thornton 2005, Salem et al. 2010)

Advantages	Limitations
Access pit (no digging) may be avoided with short lengths	Existing culvert must be longitudinally uniform (diameter changes or discontinuous culverts are not suitable for this method)
Applicable to all types of existing culvert materials	Reduction in flow capacity may be significant
Existing pipe can be corroded, deformed, badly damaged, and/or at near collapse	Annular space grouting is generally required
Custom shaped liner installation possible	Numerous joints
Simple method	Excavation required for lateral reconnection and sealing

A general list of installation guidelines for continuous sliplining was provided by Thornton (2005):

- Thoroughly inspect the existing culvert to determine the smallest diameter located within the culvert to be lined (structural deterioration and wall collapse may have reduced the original culvert diameter). For non-man entry culverts, a “pig” may be used to determine the smallest diameter.
- Inspect the existing culvert for lateral and service connections as well as any protrusions such as roots and sediment.
- Clean and clear the existing culvert.
- Determine the diameter of the liner. In general, the outside diameter of the liner should be at least 10% smaller than the inside diameter of the existing culvert. A 5% reduction should be sufficient for existing culvert diameters greater than 24 inches.
- Determine the material of the liner. High-density or medium-density polyethylene is generally chosen for the liner material. The material chosen should meet the designed load requirements. Factors to be considered in design load requirements include, but are not limited to, hydraulic loads caused by groundwater, soil conditions and loads, traffic loads, and temperature.
- Excavate insertion pits to a 2.5H:1V slope from the ground surface to the top of the existing culvert. Excavation should comply with local, state, or federal regulations regarding excavation safety. The length of level excavation should be at least twelve times the outside diameter of the existing culvert. Insertion pit width should be a minimum of the outside diameter plus 12 inches for culverts smaller than 18 inches in diameter, or a minimum of the outside diameter plus 18 inches for culverts less than 48 inches in diameter, or a minimum of the outside diameter plus 24 inches for culverts greater than 48 inches in diameter.

Excavations at elbows minimize the total number of excavations required because the liner can be installed in two directions from one location.

- Determine if the bypassing of flow is necessary. Flow bypass is necessary if the annular space and pulling head openings are incapable of handling the existing flow capacity. If possible, maintain the flow. It is noted that maintaining the flow will often reduce the force required for installation, but it may cause accessibility problems and difficulty for workers.
- Cut the existing culvert and initiate installation. Join/fuse the liner segments above ground before insertion. Thermal butt fusion or thermal welding are the general methods of joining liner segments. Once joined, use the push method, the pull method, or a combination of both to install the liner into the existing culvert. Continue the installation until the entire section of the existing culvert has been lined.
- Once the installation has been completed, a 24-hour relaxation period is recommended before reopening the lateral and service connections. If the pull method was used for liner insertion, stretching of about 1% of the total length may be observed.
- Inspect the completed lining by closed-circuit TV or manually if the diameter permits man-entry. The liner should be continuous over the entire length.
- If leakage or other testing is required, perform testing to specifications and prior to the reopening of lateral and service connections.
- Reopen lateral and service connections. Dependent upon installation conditions, reconnection may be possible from within the lined culvert or may require point excavation.
- After lateral and service connections have been reopened, reconnect and stabilize the terminal connections. Fill the annular space between the liner and the original culvert with grout or another cementitious material. The allowable grout pressure of the liner should not be exceeded during the grouting process. Hydrostatically pressurizing the liner will allow for higher grouting pressures and will help prevent collapse of the liner during the grouting process.
- Finally, restore flow if the bypass was required and initiate site cleanup.

The continuous sliplining method has some advantages as well as limitations (see Table A.9).

Table A.9: Advantages / Limitations of Continuous Sliplining (Thornton 2005, Salem et al. 2010)

Advantages	Limitations
▪ Applicable to all types of existing culvert materials ▪ Capable of accommodating large radius bends ▪ Few or no joints ▪ Flow bypass is seldom required ▪ Simplistic method ▪ Existing pipe can be corroded, deformed, badly damaged, and/or near collapse	▪ Existing culvert must be longitudinally uniform (diameter changes or discontinuous culverts may prohibit use of this method) ▪ Reduction in flow capacity may be significant ▪ Annular space grouting is usually required ▪ Excavation required for access pits ▪ Excavation required for lateral reconnection and sealing

Syachrani et al. (2010) listed some of the potential hazard and safety measures associated with the sliplining method based their discussions with practitioners and using Occupational Safety and Health Administration (OSHA) standards (see Table A.10).

Table A.10: Potential hazards and safety measures of the sliplining method (Syachrani et al. 2010)

Activity	Potential hazard	Safety measures
Butt welding and cutting	Machinery hazards, fire burns, explosions	- Utilize proper personal protection equipment (PPE) such as eye protection - Keep a fire extinguisher ready and available - Always secure while transporting in the vertical position - Always mark gas cylinders - Use special devices or chains to keep cylinders from being knocked over. - Keep the gas cylinder in an upright position at all times except for short periods when hoisting and carrying - Ensure that workers are well trained
Backhoe/power winch used for inserting the liner into the old culvert	Hits from backhoe's boom, accidents, and potential body injuries or property damage	- Utilize proper PPE - Use spotters or signal persons around operating equipment - Wear seat belts at all times - Keep workers outside the area of the backhoe's boom swing - Require regular inspections - Ensure that workers are well trained
Annular grouting	Hits from drums falling from heights, grout spills that can cause skin and eye irritation	- Utilize proper PPE - Provide eye/face wash stations at the work site - Shut off the source of a leak, if it is safe to do so - Ensure that workers are well trained

A.2.4.2 Standards Associated with the Sliplining Method

The current standards and specifications associated with segmental sliplining and continuous sliplining are shown in Table A.11.

Table A.11: Standards Associated with the Sliplining Method (Thornton 2005)

Standard/Specification	Description
ASTM D 3212 – Standard Specification for Joints for Drain and Sewer Plastic Pipes Using Flexible Elastomeric Seals (1996)	Covers joints for plastic pipe systems intended for drain and gravity sewage pipe at internal or external pressure less than 7.6-meter (25-foot) head using flexible watertight elastomeric seals. Test requirements, test methods, and acceptable materials are specified.
ASTM F 585 – Standard Practice for Insertion of Flexible Polyethylene Pipe Into Existing Sewers (2000)	Describes the design considerations, material selection considerations, and installation procedures for the construction of sanitary and storm sewers by the insertion of polyethylene pipe through the existing pipe, along the previously existing line and grade.
NASSCO Specification for Sliplining, Segmented, Polyethylene (as provided by Duratron Systems for BUTTRESS-LOC® Pipe) (1999)	Describes the specifications, design considerations, and installation procedures for the segmented sliplining utilizing polyethylene liners.
NASSCO Specification for Sliplining, Segmented, PVC (as provided by Lamson Vylon Pipe for large diameter Vylon® Slipliner Pipe) (1999)	Describes the specifications, design considerations, and installation procedures for the segmented sliplining utilizing large diameter PVC liners.
NASSCO Specification for Sliplining, Segmented, PVC (as provided by Lamson Vylon Pipe for small diameter Vylon® Slipliner Pipe)	Describes the specifications, design considerations, and installation procedures for the segmented sliplining utilizing small diameter PVC liners.

A.2.5 Summary of Culvert Rehabilitation Techniques

Based on the studies and the guidelines associated with sliplining, it is apparent that sliplining is the most popular method for culvert rehabilitation due to the simple installation process, the maximum installation length that can be accommodated using this method, and the reduced cost for rehabilitation.

A.3 Annular Grouting

A.3.1 Introduction

In the sliplining method, grouting is used to fill the annular space between the new lining pipe and the existing culvert. Grouting must be completed in phases to prevent the lining material from floating and to ensure good bonding between the lining material and the existing culvert (Salem et al. 2010). A schematic of the structure when sliplining is completed is presented in Figure A.9. In this section, the guidelines for grouting the annulus voids, the effect of grout on the performance of the liner, and different standards and specifications for grouting will be discussed. The discussion will mainly focus on the available grouting materials and the methods for their installation.

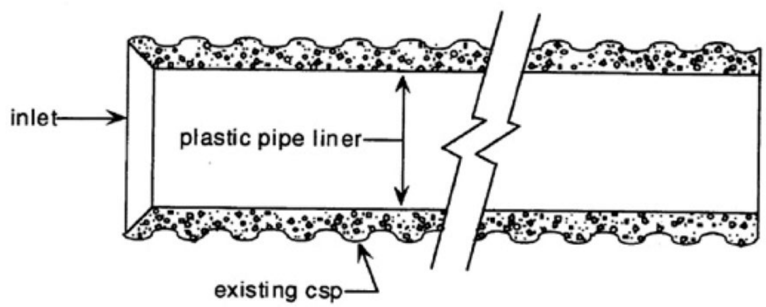


Figure A.9: Grouting of annular space between inserted pipe and culvert (Caltrans 2013).

A.3.2 Guidelines for grouting the annular space

Grout may be either gravity-fed into the annular space between the liner and the existing culvert or pumped into the space using a hose or small-diameter pipes (1-½ inch to 2-inch PVC) that are arranged in a suitable layout in the annular space. For pumping, the recommended maximum grouting pressure for watertight pipe products is 5 psi. As gravity feeding of grout will be difficult for a lining that is 100 feet or longer, additional openings in the top of the existing culvert can be made to facilitate the installation of the grout. In cases where field conditions are difficult, small pipes or hoses can be attached to the liner using “tees” placed at intervals of approximately 5 ft. Any small pipes or hoses that are used to install grouting are removed as the annulus space is gradually filled with grout.

The grout needs to be placed in lifts to ensure a uniform grout thickness around the liner pipe and to prevent the liner from floating. Each lift of grout should be allowed to set before continuing further up the culvert walls; otherwise, the liner can be plugged at the ends and filled with water to prevent floating during the grouting operation. Blocks can be used as spacers (at least two sets per pipe section) to effectively lock the liner and to keep the existing culvert in position (Salem et al. 2010, Caltrans 2013).

The guidelines suggested by Stephens (1996) for grouting the annular space of a sliplined pipe is provided below:

- The grout design should specify the mix design (proportions of constituents), the density of slurry (cement, cement/fly ash, and water), and the density of grout (after dispersant is added), as well as the viscosity, the initial set time, the target 24-hour and 28-day compressive strengths, the shrinkage, stability, and “bleed” (i.e., loss of fluid).
- The initial setting time is extremely important. The grout mix must remain fluid and not thicken for at least two hours. Grout should be tested in accordance with ASTM C939 (ASTM, 2010).
- Fly ash–based lightweight grouts are not recommended for slipliner grouting if the grout would be exposed to excessive water infiltration before it sets.
- If the existing pipe has deflected from a straight alignment, there is the possibility that trapped air within the annulus can result in discontinuous grout.
- Grout injection should start at the upstream end of the pipe and progress toward the downstream end to more easily displace water and debris. Suitable injection tubes must be inserted at the upstream end. Vent pipes installed at the downstream end should be 150% larger than the injection tubes to minimize the potential for clogging.
- Each batch of grout should be tested for density and viscosity at the culvert site.
- Any suspected voids in the soil must be pressure-grouted before inserting the liner pipe.
- Maximum grout injection pressure must not exceed the slipliner manufacturer’s recommendations.

A.3.3 Effect of the grout on the performance of liner

Zhao et al. (2003) studied the effect of the grout on the performance of liner pipe (Table A.12). They also stated that the decision on annular space grouting is mainly based on its impact on construction and cost. Grouting the annulus minimizes the buckling potential due to water accumulation in the annulus and freeze-up when the pipe is installed within the frost susceptible depth in cold regions.

Table A.12: Advantages and Disadvantages of Grouting the Annular Space in Sliplining (Zhao et al. 2003, Allouche et al. 2010)

Advantages	Disadvantages
▪ Increases buckling resistance of the liner pipe ▪ Increases buckling resistance of the host pipe ▪ Eliminates sharp loading edges on the liner pipe from the failed host pipe ▪ Reduces longitudinal movements due to differential temperatures, thus minimizing shear-off potential at lateral connections ▪ Increases the service life	▪ Increased construction cost and longer installation time ▪ Potential collapse of liner pipe during grout injection ▪ Requirement for blocking of all openings that may allow grout to escape during filling ▪ Requirement for a proper grout injection procedure ▪ Additionally, the new pipe may float or move laterally.

A.3.4 Standards and Specifications for Annular Grouting

Table A.13 shows the standards and specifications for annular grouting with cement mortar.

Table A.13: Standards/Specifications for Annular Grouting with Cement Mortar (Thornton 2005)

Standard/Specification	Description
ASTM C 109 – Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (ASTM, 2001a)	Provides a method to determine the compressive strength of hydraulic cement mortars using 2-inch cube specimens.
ASTM C 138 – Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete (ASTM, 2001b)	Provides a method to determine the weight per cubic foot or cubic meter of freshly mixed concrete. Provides formulas for calculating the yield, cement content, and the air content of the concrete (where yield is defined as the volume of concrete produced from a mixture of known quantities of the component materials).
ASTM C 144 – Standard Specification for Aggregate for Masonry Mortar (ASTM, 2003)	Specifies aggregates to be used in masonry mortar.
ASTM C 150 – Standard Specification for Portland Cement (ASTM, 2002)	Specifies the use of eight (8) types of Portland cement.
ASTM C 403 – Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance (ASTM, 1999a)	Provides a method to determine the setting time of concrete with slump greater than zero by means of penetration resistance measurements on mortar sieved from the concrete mixture.
ASTM C 495 – Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance (ASTM, 1999b)	Provides methods to prepare specimens and to determine the compressive strength of lightweight insulating concrete having an oven-dry weight not exceeding 50 lb/ft. This test method covers the preparation/testing of molded 3” × 6” cylinders.
ASTM C 618 – Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete (ASTM, 2003a)	Specifies the use of coal fly ash and raw or calcined natural pozzolan in concrete where cementitious or pozzolanic action (or both) are desired, where other properties normally attributed to fly ash or pozzolans may be desired, or where both objectives are to be achieved.

A.3.5 Available grout materials and grouting methods

To be used for filling the annular void in the sliplining method, the grout material needs to have suitable characteristics. Wagener and Leagjeld (2014) listed the following characteristics:

- Easily placed/pumpable over large distances
- Flows easily/self-leveling; completely fills the annulus between the culvert and liner pipe
- Low compressive strength of 100 psi should be adequate in most cases

Some state transportation agencies (including the Minnesota Department of Transportation (MnDOT)) recommend using low-density cellular concrete because the characteristics of this material meet the above-mentioned requirements. If grouting operations need to be conducted in the presence of water, the density of the grout should be greater than 70 pcf; this can help to displace the water during operation. The advantages and disadvantages of cellular grout are listed in Table A.14.

Table A.14: Advantages and Disadvantages of Cellular Grout (Wagener et al. 2014, ACI 2006)

Advantages	Disadvantages
▪ Buoyant forces on the pipe are less than those for normal weight grout. ▪ Placement pumping pressures are less than those for normal weight grout.	▪ Standard concrete mixing equipment is not suitable because such mixers do not combine the ingredients at the desired speed and mixing action. A high-speed paddle mixer is preferable because it properly combines the ingredients and blends the preformed foam rapidly and efficiently to produce a uniformly consistent low-density cellular concrete mixture. Other mixers and processes that produce uniform mixtures include high-shear mixers. This will result in increased cost from the unique equipment requirements. ▪ Excessive pressures can collapse the slipliner.

Nonshrink mortars conforming to ASTM C 1107 (ASTM 2020a) are sometimes used for grouting the annular spaces of sliplined culverts. Such mortars are required to have a minimum 28-day compressive strength of 5,000 psi for the retained grout at the maximum working time. Low-strength mortar (LSM), non-shrink mortar grout, and cellular grout are the most common types of grouts that are recommended by most state and local transportation agencies. In addition, a few new types of grouts are available, such as Elastizell PS, chemical grouts, two-component grouts, geothermal grouts, and expandable silicate-based grouts. These grout materials are effective within certain ranges of ground conditions (see Figure A.10).

A.3.5.1 Elastizell PS (Pipeline Solution)

Elastizell PS (Pipeline Solution) is a grouting material to use for the annular space in sliplined culverts or casings and carrier sewer pipeline applications because of its stability, low density, and flowability. The stability of Elastizell PS assures a consistent material that meets acceptable design criteria. The low density of Elastizell PS permits installation in a single lift, which reduces the chances of movement (floating) of the liner pipe. Precautions for preventing liner pipe buoyancy should be considered in the design. In addition, the flowability of Elastizell PS permits pumping at low pressures to reduce the risk of damage to the liner pipe, which may otherwise occur with heavier and less flowable grouts. The high fluidity of Elastizell PS completely fills the voids. Another product, Elastizell EF mix, has demonstrated flowability of up to 600 feet; it can be pumped for great distances (thousands of feet) and does not require compaction. While the manufacturer prefers PS 120 for standard pipeline fills, the specific densities and strengths can be customized for a specific application. The grouting procedure using this material is illustrated in Figure A.11, and the basic properties of this grout are listed in Table A.15.

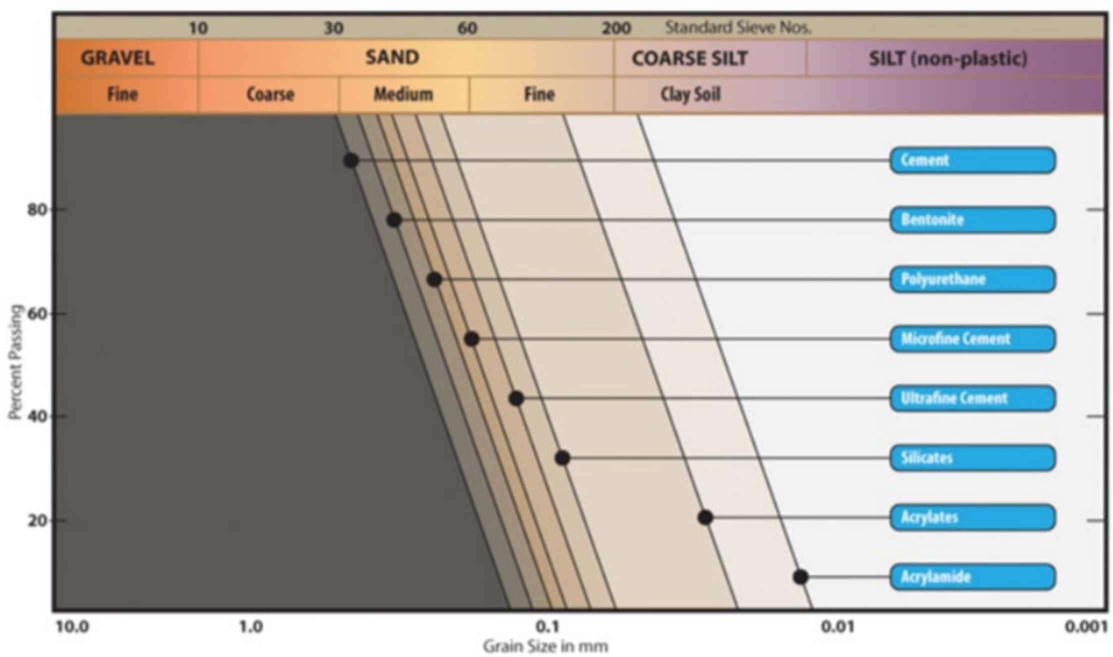


Figure A.10: Percent passing vs. grain size for different grout materials (Babcock 2016).

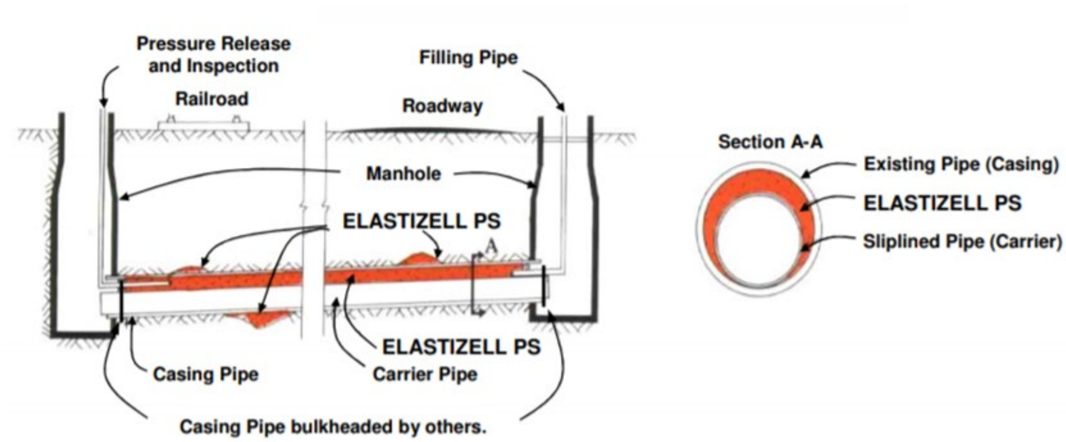


Figure A.11: Schematic of a pipe sliplined using Elastizell PS
(Source: Elastizell Corporation 2018).

Table A.15: Basic Physical Properties of Elastizell PS

Product code	Bearing capacity (tons/ft^2)	Cast density (lb/ft^3)
PS 030	2.2	28
PS 060	4.3	34
PS 120	8.6	38
PS 200	14.4	42
PS 300	21.6	48
PS 500	36.0	52
PS 500 SG	36.0	70

A.3.5.2 Chemical grout

The family of chemical grouts includes sodium silicate, acrylic gels, and polyurethane expansive foams. The primary types of chemical grouts (silicates, acrylics, and polyurethanes) have unique compositions. These grouts are similar to “true solution” grouts and have a high degree of penetrability into soils and rock. The comparison between chemical and cement grouts is presented in Table A.16.

Table A.16: Comparison of Chemical and Cement Grouts (Babcock 2016)

Grouts	Description	Cost per mixed gallon
Sodium silicate	A two-component grout that typically has very low viscosity but will often expunge water after gelling by a process called syneresis. Depending on the chemistry of the soils, longer life spans can be obtained when using silicates.	\$2 to \$3
Colloidal silica grout	A grout with sodium silicates that was developed to reduce the issue of syneresis, provide better control of gel times and achieve a lower viscosity.	\$13 to \$15
Acrylics ("true solution" grouts)	A grout that is free of suspended solids and has an extremely low viscosity. Gel times range from 3 seconds to 10 hours. The life span is expected to be greater than 300 years.	\$8 to \$10
Polyurethane grouts	Two primary types of polyurethane grouts are available: hydrophilic and hydrophobic. Hydrophilic grouts are typically single-component systems that react with water and cure to an expansive flexible foam or a non-expansive gel; they require a moist environment after curing. Hydrophobic expansive foams require approximately 4% water and can easily withstand wet/dry cycles. Hydrophilic and hydrophobic foams expand 4 to 6 times and up to 20 times the original volume, respectively, and they may cure flexibly or rigidly. The expected life span of polyurethane foam, as indicated by the manufacturers, is approximately 75 years.	\$60 to \$80 (before expansion); the price may vary based on the expansive component of the material
Cement grouts	Cement grouts are considered to be suspended solids grouts. Their expected life spans range between 100 and 200 years.	\$1 to \$2 (ordinary Portland cement); \$3 to \$4 (microfine/ ultrafine cements)

In a project in Boaz, Alabama, which was conducted for the Alabama Department of Transportation (ALDOT), URETEK Holdings filled the "annular" space between the carrier and host pipes with a geotechnical polymer grout to anchor the two pipes together and prevent relative slippage. For most projects, the installation of the polymer grout can be completed within one hour after the insertion of the liner. During installation (shown in Figures A.12 and A.13), the chemical grout is attracted to deteriorated areas of the host pipe and is pushed through openings in the pipe to fill voids, thereby stabilizing the host pipe. Once installation of the grout was complete, a tight seal between the two pipes was formed. Typically, following installation, the end of the carrier pipe will be trimmed so that it is flush with the culvert; in this case, ALDOT planned to widen the road above and kept the pipe untrimmed to accommodate a future connection (Armstead 2015).

Figure A.12: URETEK team works to inject grout in between the pipes (Armstead 2015).

Figure A.13: After grouting, the pipes are sealed tightly together (Armstead 2015).

A.3.5.3 Expandable Silicate-based grout

Soucy et al. (2018) described an expandable silicate-based material and explained the chemistry, development, and application of the grout. The properties of this silicate-based grout are shown in Table A.17. The grout is able to expand and set within minutes to days. The author developed a formulation for the expandable silicate-based grout, and the calculated expansion rate was approximately 15%. The authors conducted two field trials, and they found this grout to be stable and able to withstand harsh environmental conditions.

Table A.17: Properties of Sodium Silicate Solution (Soucy et al. 2018)

Silicate	Setting agent	Filler	Expanding agent	Final density	Compressive strength
75 g	6 g	25 g	1 g	1.3 g/cm^3	~1000 psi

A.3.5.4 Two-component grout

Another type of grout material is two-component system comprised of an “A” component grout (typically cement, fly ash, bentonite, and a retarder/stabilizer) and a “B” component accelerator (sodium silicate or “water glass”). They are thus sometimes referred to as “A/B type” or “bi-component grouts” and have been used in Japan for more than 30 years. These materials offer a host of operational benefits over thick mortars, such as reduced settlement (Feddema et al. 2005) and effective penetration of the void space, with lower energy and reduced strain on the segmented linings (Robinson et al. 2007). Two-component grouts are highly mobile and can be pumped over distances of many kilometers. The use of a retarder/stabilizer can also extend the shelf life of the “A” component grout for several days while the early strength of the accelerated grout stabilizes the ground and provides immediate support of the segmental liner (Reschke et al. 2016). Water-to-cement ratios (w/c) in this component are typically between 2 and 3 in order to create a low-viscous fluid. In order to prevent significant bleed, which would occur from an over-saturated cement solution, bentonite is mixed with the water before the cement is added. The high swelling capabilities of bentonite allow it to absorb water and prevent the separation of water from the cement mixture. Fly ash is a common pozzolan that can be used as supplementary cementitious material and can contribute to the final strength gain (Kravitz 2018).

As two-component type grouts have several advantages over mortar type grouts (Feddema et al. 2005, Peila et al. 2011, and Pellegrini and Perruzza 2009), they continue to gain popularity. One of the main practical benefits of colloidally mixed grouts and/or slurries is their near immiscibility in water, which allows the mix to resist washout or contamination by groundwater. In addition, the mix is stable and fluid enough to allow it to be pumped over considerable distances. The slurry is able to permeate uniformly into voids. Moreover, the segregation of sand, if incorporated in the mix, is virtually eliminated. The grout or slurry exhibits less settlement (bleed) of the cement when stationary and has higher compressive strength than mortar type grouts.

More fluid ingredients are desirable, as they are injectable into the annulus space and can gain strength instantaneously to provide immediate support for the liner. For two-component annular grouts, Antunes (2012) and Reschke et al. (2016) indicate that the following properties must be considered in order to obtain a stabilized and effective two-component grout:

- Flowability/viscosity as determined by ASTM C939 (ASTM 2010). This is critical to pumping requirements and the flow of grout in the annular space. The flowability of the "A" component is important for predicting the pumping requirements and pipeline specifications. Higher flowability is advantageous, as it implies lower pump and pipeline pressures as well as lower power consumption. It is beneficial to pair the flowability readings with the viscosity (obtained using a viscometer), as these can be used to calculate pump requirements and the head losses in the pipe network.
- Bleeding of the grout, as measured by ASTM C940 (ASTM 2016). Limiting the bleeding is critical to the stability of the grout in the pipeline. Grout bleed can lead to accumulation in the pipe invert that will reduce the cross-sectional area of the pipe. This, in turn, will lead to higher pumping pressures, lower flow rates and, ultimately, the complete blockage of the pipe. Bleed is a measure of the percentage of water separation from the cement solution and is often designed to be less than 5%. This percentage will allow the mixed grout to remain in the pipes and be immediately available even after an unexpected delay of 72 hours or more.
- Gel time. Rapid gelling is needed to lock the pipe segments in place. Soon after the "A" and "B" components are combined, the grout ceases to be fluid. The time required to form an initial set is commonly referred to as the *gel time*. Gel time is an important consideration, as the grout needs sufficient time to distribute throughout the annulus; however, the grout needs to gel quickly in order to prevent the pipe segments from floating. Two-components grouts achieve these requirements, as they are flowable mixes that can gel within 20 seconds and can rapidly gain strength over time (Yang et al. 2009; Pelizza et al. 2010; Azadi et al. 2017; Sharghi et al. 2017). If the material gels too quickly, it can clog the mixing pipe chamber. However, if it takes too long to gel, the implications for the liner design will increase.
- Compressive strength. Designers and contractors typically specify the strength requirement for the grout. Typical early strength requirements are between 14.5 psi to 44 psi (0.1 to 0.3 MPa) for 1 hour (Bernat and Cambou 1998; Hashimoto et al. 2004; Pellegrini and Perruzza 2009). The final strength is typically regarded as less consequential than the short-term strength, and the final design strength varies between 145 psi to 435 psi (1 to 3 MPa) in studies in the literature (Bernat and Cambou 1998; Hashimoto et al. 2005; Pellegrini and Perruzza 2009). As there are no directly applicable ASTM standards for the testing of the relatively low 1-hour strengths, contractors and suppliers have adapted or developed their own methods to verify grout strengths. These methods vary from penetration resistance tests, tests using a modified Vicat apparatus, shear strength tests, and unconfined compressive tests.

Table A.18 shows the typical mix designs for two-component grout, and Table A.19 shows a comparison between the two-component grout and the LSM grout.

Table A.18: Typical Two-Component Grout Mix Designs (Antunes 2012)

Mix	Water (kg)	Cement (kg)	Bentonite (kg)	Retarder (L)	Accelerator (L)	Water:cement ratio	Specific gravity
1	792	337	35	3.51	82.9	2.35	1.28
2	796	361	30	3.76	82.7	2.2	1.30
3	772	386	30	4.012	88.3	2.00	1.32

Table A.19: Comparison Between the Two-component Grout and LSM Grout

Properties	Mix 1	Mix 2	Mix 3	LSM grout
Flow (sec) (ASTM C939) /viscosity (cps) immediately after mixing	10.1 / 44	9.7 / 32	10.1 / 40	Maximum 20 sec
Penetration resistance, psi (MPa) (ASTM C403)	115 (0.79)	88.5 (0.61)	180 psi (1.24)	Minimum 100 psi (0.7 MPa)
8 hr bleed (%)	0.6	1.2	1.2	
Compressive strength, psi (MPa) @ 28 days	566 (3.9)	522 (3.6)	595 (4.1)	In the range of 50 to 400 psi

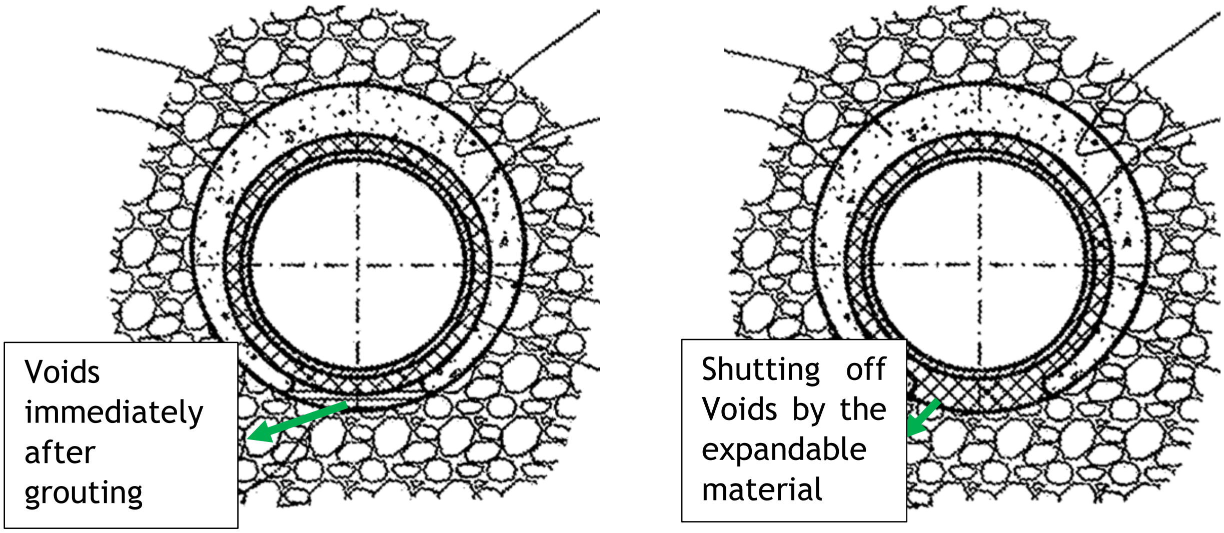
Two-component grout displays high early strength and provides early support to the lining. However, in the long term, traditional cement grout provides higher compressive strength. But higher strength of the backfill grout is not a prerequisite for an ideal grout, because the main function of the backfill grout is to transfer the load to the segmental lining, not to bear the load itself. Backfill grout helps to resist not only loads from the ground but also lining forces, thrusting, and forces caused by the movement of the wheel set of the backup trailer on the newly formed rings. It also prevents the choking of the pipelines owing to its long-lasting workability. In fact, the inherent fluidity of a two-component grout makes it more convenient to transport and pump, whereas a single-component grout becomes more difficult to pump into the annular gap as time progresses. Finally, a two-component grout will also show satisfactory performance in saturated ground because no dilution of the grout occurs during the rapid gelling of the mix (Shah et al. 2018), as shown in Figure A.14.

Figure A.14: Two-component grout after gelling (Shah et al. 2018).

A.3.5.5 Expandable material for sealing voids

It is very difficult to achieve complete filling of an annulus void using a casting material, and it is difficult to drain the fluid that collects in voids on the underside of the pipe. For cases where the cast material has cured but does not fill the annulus void, Freyer (2014) devised and employed a method for sealing the voids by implementing an expandable material that can expand in contact with water, oil, gas, or other suitable materials. The swellable material that enables the expansion can be a material such as an EPDM rubber, styrene/butadiene, natural rubber, ethylene/propylene monomer rubber, or styrene/propylene. In addition, rubber in a mechanical mixture with polyvinyl chloride, methyl methacrylate, acrylonitrile, ethyl acetate, or other polymers would provide another alternative, as these materials expand on contact with oil.

The diagram in Figure A.15 (a) represents a casing that was placed in an approximately horizontal borehole in the ground, where cast material was placed into the annulus between the casing and the borehole wall and the casing was provided with sleeves of an expandable material. In Figure A.15 (b), the opening has been sealed with the expandable material. The sleeve-shaped plug of expandable material was partially in contact with fluid and partially in contact with cast material. Because of the diffusion of the fluid in the expandable material or swelling on contact with the fluid, the expandable material was able to displace the adjacent fluid and eventually seal the annulus.



(a) Immediately after casting

(b) After the grouting and sealing of voids with expandable material

Figure A.15: Cross-sectional view of a sliplined culvert (Freyer 2014).

A.3.5.6 Geothermal grout

Konczak (2012) created a thermally enhanced grout (a geothermal grout) from recycled materials. Geothermal grout has a single component, is thermally enhanced, and is comprised of class F fly ash (approximately 50% to 80%) and cement kiln dust (approximately 20% to 50%). Konczak provided a procedure to prepare the grout. Initially, a dry grout mixture needs to be made by combining ~50%–80% class F fly ash and ~20–50% cement kiln dust. Next, water is added to the dry mixture at a ratio of five gallons of water to 70 lbs of dry grout mixture, followed by a water reducer in the amount of 0–8 fluid ounces per hundredweight of dry grout mixture. Finally, 0–12 dry ounces/hundredweight of dry grout mixture of dry sodium hydroxide is added. This geothermal grout, which is marketed as Geo SuperGrout™, has a high degree of thermal conductivity, can resist shrinkage and cracking, and can harden within 24 to 48 hours.

A.3.5.7 Tunneling Annulus Grout

Osborne (2014) created a grout composition for application to a tunneling surface that contains at least one hydration stabilizer, at least one polycarboxylate-based high-range water reducer, and at least one viscosity modifier. When water is added, the grout mixture forms a slurry that can achieve a flow of approximately 12 seconds or less (when using a conventional grout flow cone) or approximately 4 minutes or less (when using a Marsh funnel) over at least 1 hour. The compressive strength of the grout achieves a minimum of 0.1 MPa (14.5 psi) in an hour. The grout mixture has a cement content ranging from about 15% to 100% and a fly ash content up to 85%. The preferable w/c ratio ranges from 0.6 to 0.3. To provide stabilization of the cement for 1 to 18 hours, a total of 0.5–30 ounces of stabilizer per 100 pounds of cementitious material (oz/cwt; preferably 2-6 oz/cwt) needs to be used. The w/c ratio will be reduced from 1.0 to 0.1, with a preferred ratio in the range of 0.6 to 0.3, and a ratio of about 0.5 will be achieved when including a polycarboxylate-based high-range water reducer. The author also provided example grout mixtures which are summarized in Table A.20.

Table A.20: Composition of Different Tunnel Annulus Grouts (Osborne 2014)

						3%. SureShot @ 2 hours			SureShot @ 2 hours	
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10
Cement (g)	700	700	700	1300	1300	700	1000	1300	1000	1300
Fly ash (g)	1300	1300	1300	700	700	1300	1000	700	1000	700
Water (g)	760	800	900	900	900	900	900	900	900	900
w/c	0.38	0.4	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Eucon WO (oz/cwt)	0	3	3	3	3	2	2	2	2	2
Eucon ABS (oz/cwt)	0	5	5	5	5	5	5	5	5	5
Plastol 6200 (oz/cwt)	14	5	5	8	8	5	6	6	5	5
Batch water (g)	741.8	783.1	883.1	879.2	879.2	884.4	883.1	883.1	884.4	884.4
Initial Flow	5:30	3:40	2:25	1:52	2:02	1:57	2:08	2:01	3:05	2:31
1 hour (MPa)	-	-	-	-	-	0.15	0.19	0.24	0.21	0.25
2 hour (MPa)	-	-	-	-	-	0.25	0.34	0.36	0.29	0.3
3 hour (MPa)	-	-	-	-	-	0.34	0.52	0.69	0.6	0.7
1 Day (MPa)	-	-	-	-	-	1.1	1.26	1.33	1.26	1.31
7 Day (MPa)	-	-	-	-	-	2.9	3.11	3.6	3.14	3.55

Unit conversion: 1 gram = 0.00220462 lb, 1 MPa= 145.038 psi

A.3.5.8 Summary of Information on Grouting Materials

This section presented guidelines for the grouting of annulus voids and also highlighted several advantages for using grouts. The properties of several grouts, such as chemical grouts, expandable grout, two-component grout, geothermal grout, and tunneling annulus grout were discussed. Most of these grouts are new to the culvert industry, and future research work can be conducted to examine these grouts to ascertain their structural behavior and how they interact with the liner pipe and the host pipe.

A.4 Liner Materials used for Sliplining Rehabilitation of Culverts

A.4.1 Introduction

In the sliplining rehabilitation of the culvert, the liner may contribute to increase the ability of the rehabilitated pipe to support external forces. The structural strength and hydraulic capacity of the rehabilitated host pipe depend on the liner materials used in sliplining. This section focuses on common pipes used as liners, the liners specified by ODOT, the advantages and disadvantages of using different liners, and the various types of external and internal loads that act on the liner.

A.4.2 Liners Commonly used for Sliplining

Liner construction for a sliplining project involves considerable uncertainties owing to the complex nature of the pipe–soil interaction. In the design of pipeline systems, the pipe and soil are typically considered to be integral systems, and the construction process needs to achieve this design objective. A pipe surrounded by soil is both loaded and supported by the soil and porewater.

According to Water Research Centre (WRC) *Sewerage Rehabilitation Manual* (WRC 2001), liners are classified into two categories based on the interaction between the liner and the surrounding grouted annulus:

- Type 1: Systems where the liner, grouted annulus, and existing culvert structure are fully bonded (no slip condition) such that composite action develops in the structure.
- Type 2: Systems where the liner does not bond to the grout or the structure and, therefore, acts independently of the surrounding structure (full slip condition).

WRC Type 1 design is based on the development of a rigid composite structure to carry both soil loads and live loads. WRC Type 2 design is based on an existing deteriorated rigid structure and surrounding soil support that has sufficient stability under soil pressures. The liner in a Type 2 design acts only to restore the hydraulic performance and to resist external fluid pressure. The type of liner pipe used for sliplining depends on the following factors (Wagener et al. 2014):

- Cost for materials and installation
- Structural capacity
- Ability to carry the installation load
- Hydraulics
- Ability of the pipe joint to prevent grout leakage

The selection of the appropriate liner material should take into account the cause and mode of failure of the existing pipe. High-density polyethylene and polyvinyl chloride pipes in both solid wall and ribbed profiles have become common materials for the sliplining of culverts. High-density polyethylene (HDPE) liners are the most commonly used liners because of their high density-to-weight ratio, very good abrasion resistance, and smooth internal walls that help to maintain the culvert’s hydraulic performance (Mitchell et al. 2005). Polyethylene (PE) large-diameter profile wall sewer and drain pipe, as specified in ASTM F 894, is available in diameters up to 120 inches (Caltrans 2013). The design and selection of the soil materials are important, since the pipe does not act as an isolated structural element subjected to clearly defined loads but as one component in the complete pipe–soil system. The pipe carries part of the pressures of the surrounding soil; the rest is distributed around the pipe through the backfill. The stiffness and uniformity of the backfill soil influences both the proportion of loads reaching the pipe and the pipe's load-carrying ability.

Table A.21 presents a summary of six different pipe categories that includes a stiffness classification and details of key performance limits. As can be noticed from this table, a wide variety of materials are used in pipe manufacturing (including ceramics, metals, and polymers), and the stiffness, strength, ductility, and durability characteristics of the materials can vary greatly. The pipes can vary widely in terms of pipe wall geometry (plain, corrugated or profiled, uniform or composite systems). However, regardless of the pipe used, the stiffness and configuration of the soil around the pipe can affect pipe performance. In the table, performance limits significantly influenced by the surrounding soil are identified; the table also includes the categories of pipe stiffness relative to the surrounding ground. Relative stiffness is influenced by two different types of pipe and soil deformation: bending (associated with non-uniform external pressures, leading to deformations from circular to oval or other non-circular shapes) and hoop compression (associated with uniform and non-uniform pressures that can reduce the pipe circumference). Pipe stiffness categories include the following:

- Rigid: The pipe stiffness in bending and ring compression is very large relative to the soil. Examples of such pipes include reinforced concrete and clay pipes.
- Semi-flexible: The pipe stiffness in bending is of similar magnitude to the soil, but the stiffness in ring compression is very large. Examples include pipes constructed from long-span reinforced concrete, ductile iron, or rib stiffened corrugated steel.
- Flexible: The pipe is flexible in bending relative to the soil, but the stiffness in ring compression is very large. Examples include pipes constructed from corrugated steel or aluminum, PVC, glass-reinforced plastic, polypropylene, or plain polyethylene.
- Compressible: The pipe is flexible in bending relative to the soil, and the stiffness in ring compression is similar to that of the soil. Profiled polyethylene is one example.

Table A.21: Liner Stiffness Categories and Typical Performance Limits (Moore 2001)

Pipe Materials	Stiffness	Failure types	Deflection	Buckling	Durability Issues
Clay	Rigid	Cracking	None	None	Abrasion
Reinforced concrete	Rigid	Concrete cracking, steel yielding	None	None	Abrasion, corrosion
Cast iron	Rigid	Cracking	None	None	Corrosion
Ductile iron, aluminum, corrugated steel	Semi-flexible, flexible	Yielding or crushing	Ovaling	Global	Abrasion, corrosion
Thermoplastics (PVC, HDPE, PP)	Flexible, compressible	Short-term yield, long-term cracking	Ovaling and hoop compression	Global, local	UV degradation, solvents
Glass-reinforced plastic	Flexible	cracking	Ovaling	Global	Solvents

Rigid and flexible pipes differ in the way they transfer the applied loads to the surrounding soil structure. Figure A.16 shows a simplified illustration of the load transfer mechanism due to vertical soil pressures for both types of pipe. This figure indicates that rigid pipes sustain vertical loads by virtue of the material strength alone and with very little deflection. On the other hand, flexible pipes tend to deflect and use the horizontal passive resistance of the soil on the sides. This difference in behavior has important consequences in the analysis, design, and installation of pipelines.

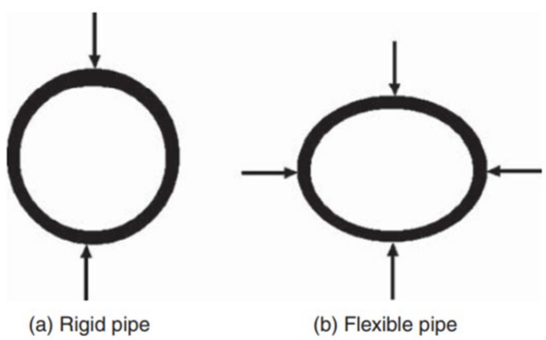


Figure A.16: Load transfer mechanisms for rigid and flexible pipes (Najafi 2010).

Failure mechanisms for rigid pipes and flexible pipes differ in several respects. In general, if the imposed loads exceed the pipe's inherent strength, rigid pipes will fail in tension and cracking rather than by deformation. Clarke (1968) reported the following major causes of failures in rigid pipelines:

- Inadequate load-carrying capacity of the pipes
- Nonuniform bedding
- Inappropriate construction methods (e.g., excessive trench widths)

- Use of rigid jointing material, resulting in a lack of axial flexibility and extensibility in the pipeline
- Differential thermal deformation or moisture movement
- Differential settlement

Flexible pipes generally do not crack; instead, they fail by excessive deformation, buckling, or pipe flattening. In addition, these pipes are more accommodating of faulty installation of embedment, bedding, or foundation because of their ability to deform. However, improperly placed embedment material could lead to the loss of side support, which is vital for flexible pipes and could result in over-deflection or flattening. Farshad (2011) reported the following major causes of failure in flexible pipelines:

- Fracture, buckling
- Weathering, color, and dimensional changes
- Voids, blisters, and delaminations
- Fatigue, corrosion, and clogging of the pipe system.

Rigid pipe failures occur when the performance limits for the pipe material are reached. Performance limits for rigid pipes may be categorized into the following:

- Ring flexure
- Longitudinal flexure
- Shear
- Radial tension
- Longitudinal tension
- Cracking
- Wall crushing

Loads on buried pipes arise in several ways, due to the influence of geostatic stresses (loads associated with soil weight), surface live loads, fluid loads, loads induced by ground movements and dynamic events, and other load sources (Moore 2001). Some of these loads can be effectively characterized through the use of simple equations. Others are more difficult to quantify due to the complexity of the mechanical response of the system or because of the vagaries of the load source.

One important source of applied loading relates to temporary construction loads during placement of soil at the sides and on top of a buried pipe (McGrath et al. 1999). These are associated with transient loads from construction vehicles, compaction equipment, and the influence of unbalanced earth loads (when backfill is not placed evenly on both sides of the pipe). While earth loads generally dominate the design and performance of deeply buried pipelines, construction loads can be critical for pipelines buried at shallow depths.

Another example framework is set out by the British Standards Institution (BSI) in BS EN 13689 (BSI 2002; which has been replaced by BS EN ISO 11295, BSI 2022) which characterizes various aspects of the liner system, both for gravity flow and pressure pipes. The standard suggests that the following issues be considered during the design of liners within gravity flow pipes:

Installation loads

- Lining pipe preparation forces (e.g., section reduction, spiral winding)
- Insertion forces (tensile, compressive, bending, torsion)
- Reversion forces (pressure, thermal)
- Grouting forces (external pressure, flotation)
- Residual effects of the above installation forces in the permanent works

Internal loads:

- Surcharge pressure
- Thermal loads due to the temperature of transported fluid

External loads:

- Transferred soil loads from overburden soil weight, traffic surcharge, etc.
- Ground movements from differential settlement, frost action, earthquakes, etc.
- Point loads from irregularities of the existing pipeline
- Thermal loads due to the environment
- Groundwater pressure and/or negative pressure (vacuum)

The German framework ATV M127, explained in Falter (2001), includes the classification of deteriorated structure into three categories:

- The host pipe structure is considered safe, but it is leaking; no cracks exist except those resulting from shrinkage.
- The host pipe–soil system is considered safe; however, four longitudinal cracks are present that indicate a deformation mechanism, and the deformations (changes in diameter) are less than 5% of the diameter of the pipe.
- The host pipe–soil system is not considered safe for long-term conditions; four longitudinal cracks exist, and the deformations are larger than 5% of the diameter.

Various liner materials have both advantages and disadvantages, as summarized in Table A.22.

Thomas (1991) discussed the liner pipe type and the selection of the pipe type for sliplining projects in the Vincennes District of the Indiana Department of Transportation (INDOT). They used five criteria: (1) scouring, (2) acid conditions, (3) deep fill sections and high traffic volumes, (4) resurfaced roads, and (5) cost. At locations of heavy scouring, it was recommended to use polyethylene liner. Polyethylene liner was also recommended for use at locations with acidic conditions, as conditions where the pH is

5 or less were reported to be detrimental to metal, aluminum, and galvanized steel pipe. On the other hand, polyethylene pipes are highly acid-resistant.

A.4.3 Specified Liner Materials on ODOT Specification

ODOT Supplemental Specification 837 permits the use of the following liner types:

- Corrugated steel pipe (ODOT Construction & Material Specifications (CMS) Item 707.01 or 707.02) (ODOT; 2019)
- Structural plate corrugated steel structure (Item 707.03)
- Precoated, galvanized steel culvert (Item 707.04)
- Polymer-precoated corrugated steel spiral rib pipe (Item 707.11)
- Corrugated steel spiral rib pipe (Item 707.12)
- Polymer precoated, galvanized steel conduit (Item 707.18)
- Aluminum coated steel conduit (Item 707.19)
- Galvanized coated steel conduits (Item 707.20)
- Corrugated aluminum alloy pipe (Items 707.21 or 707.22)
- Aluminum alloy structural plate conduit (Item 707.23)
- Corrugated aluminum spiral rib pipe (Item 707.24)
- Corrugated polyethylene smooth lined pipe (Item 707.33)
- Polyethylene plastic pipe based on the outside diameter (OD) (Item 707.34)
- Polyethylene profile wall pipe (Item 707.35)
- Polyvinyl chloride corrugated smooth interior pipe (Item 707.42)
- Polyvinyl chloride profile wall pipe (Item 707.43)
- Steel casing pipe (Item 748.06)
- Steel reinforced thermoplastic ribbed pipe (ODOT SS 938)
- Glass-fiber-reinforced polymer mortar pipe (Item 707.75)

Table A.22: Slipliner Material Advantages and Disadvantages (Wagener et al. 2014)

Liner Material	Advantages	Disadvantages
CSP	Lower material cost; more dimensionally stable; pipes with smooth interior are lightweight, readily available, and can be manufactured to any size	Susceptible to corrosion and abrasion, high Manning's coefficient for pipes without a smooth interior, more difficult to slide into place due to corrugation (skid may be required)
Solid Wall HDPE per ASTM F714	Fused joints are watertight and can withstand pulling forces; resistant to impact, corrosion, and abrasion	Less dimensionally stable
Corrugated HDPE with Smooth Interior, AASHTO M 294 Type S	Lightweight, impact, corrosion and abrasion resistant, watertight/soil tight joints	Less dimensionally stable, more difficult to slide into place due to corrugation (skid may be required)
Profile Wall HDPE, ASTM F894	Lightweight, impact-resistant, corrosion and abrasion resistant, watertight joints	More difficult to slide into place due to corrugation (skid may be required)
Closed-profile HDPE	Smooth exterior makes installation easier, joints can withstand pulling forces, impact resistant, corrosion and abrasion resistant	Higher capital cost
Steel Reinforced HDPE, ASTM F2562	High strength-to-weight ratio, corrosion and abrasion resistant	More difficult to install due to corrugation (skid may be required), higher capital cost
Dual Wall Corrugated PVC, ASTM F949, AASHTO M 304	Lightweight, corrosion and abrasion resistant	Brittle in cold temperatures
Closed Profile PVC, ASTM F1803	Lightweight, corrosion and abrasion resistant	Brittle in cold temperatures
Open Profile PVC, ASTM F794	Lightweight, corrosion and abrasion resistant	Brittle in cold temperatures
Solid Wall PVC, ASTM F679 AASHTO M 278	Corrosion and abrasion resistant	Brittle in cold temperatures
Fiberglass Sewer Pipe (FSP), ASTM D3262	More dimensionally stable, high strength to weight ratio, corrosion and abrasion resistant	Higher material cost

Table A.23 represents the database of the several liner types, lengths, heights, conduit and liner diameters as reported in ODOT CMS 2019.

Table A.23: Liner Types, Conduit and Liner Diameters (ODOT CMS 2019)

Pipe Materials	CMS Item	Complies to Std.	Liner size	Wall thickness
Corrugated steel pipe	707.01 or 707.02	AASHTO M 36/M 36M	Nominal inside diameter under 707.01: 6″ to 84″; under 707.02: 36″ to 120″	Under 707.01: 0.052″ to 0.168″; under 707.02: 0.064″ to 0.109″
Polymer-precoated corrugated steel spiral rib pipe	707.11	AASHTO M 36, Type IR	Nominal inside diameter of 18″ to 90″	0.064″ to 0.138″
Corrugated steel spiral rib pipe	707.12	AASHTO M 36, Type IR	Nominal inside diameter of 18″ to 90″	0.064″ to 0.138″
Polymer precoated, galvanized steel conduit	707.18	AASHTO M 245/ M 245M, Type IA	Nominal inside diameter of 100 mm to 3600 mm	Thickness of metallic coated steel sheet: 1.02 mm to 4.27 mm
Precoated, galvanized steel culvert	707.04	AASHTO M245/ M 245M, as modified by ODOT CMS 707.01 and 707.02	Nominal inside diameter under 707.01: 6″ to 84″; under 707.02: 36″ to 120″	Under 707.01: 0.052″ to 0.168″; under 707.02: 0.064″ to 0.109″
Aluminum coated steel conduit	707.19	AASHTO M 274 (for corrugated exterior conduit); ODOT CMS 707.04 (for smooth interior liner); provide as per 707.01 and 707.02	As above	As above
Galvanized coated steel conduits	707.20	AASHTO M 218 (for corrugated exterior conduit); ODOT CMS 707.04 (for smooth interior liner); provide as per 707.01 and 707.02	As above	As above

Table A.23: Liner Types, Conduit and Liner Diameters (ODOT CMS 2019) (Continued)

Pipe Materials	CMS Item	Complies to Std.	Liner size	Wall thickness
Corrugated aluminum alloy pipe	707.21 or 707.22	AASHTO M 196	Nominal inside diameter under 707.21: 6″ to 72″; under 707.22: 36″ to 120″	Under 707.21: 0.048″ to 0.164″; under 707.02: 0.060″ to 0.164″
Corrugated aluminum spiral rib pipe	707.24	AASHTO M 196, Type IR	Nominal inside diameter of 18″ to 66″	0.060″ to 0.135″
Corrugated polyethylene smooth lined pipe	707.33	AASHTO M 294, Type S, Type D or SP	Nominal inside diameters of 4″ to 60″	0.9 mm to 1.8 mm
Polyethylene plastic pipe based on outside diameter	707.34	ASTM F714	Outside diameters of 10″ to 63″	1.938″
Polyethylene profile wall pipe	707.35	ASTM F894	Inside diameters of 12″ to 132″	0.18″
PVC corrugated smooth interior pipe	707.42	ASTM F949	Nominal diameter 4" through 48"	0.022″ to 0.165″
PVC profile wall pipe	707.43	ASTM F794	Nominal diameter 18" through 48"	0.058″ to 0.2″
Steel casing pipe	748.06	ASTM A139/A139M, Grade B or ASTM A 53, Grade B	Pipe diameter: 4″ to 24″ or more	0.237″ to 0.5″
Steel reinforced thermoplastic ribbed pipe	SS 938	ASTM F2562	Nominal inside diameter of 12″ to 120″	0.082″ to 0.22″
Glass fiber-reinforced polymer mortar pipe	707.75	ASTM D3262 (for non-pressure applications); ASTM D3754 (for pressure applications)		

A.4.4 Summary of Information on Liner Materials

This section discussed the types of liners commonly used for sliplining projects, external loads acting on the liner pipe, the effect of the slip liner, and the performance of several different liner materials. This information will help construction engineers to select an appropriate liner material and to properly design the slipline rehabilitation.

A.5 ODOT Specifications for Sliplining

A.5.1 Introduction

Current ODOT Supplemental Specification (SS) 837 (ODOT 2019) is specific to slipliner pipe materials, installation, and methods of measurement. SS 837 requires the void to be completely filled by the contractor and specifies the use of low-strength mortar backfill conforming to CMS Item 613 (LSM), mortar/non-shrink mortar conforming to CMS Item 602 (or CMS Item 705.22 NSM), or cellular grout (ASTM C869). The grout properties specified by ODOT are summarized in Table A.24. This section includes a review of the ODOT and ASTM specifications for sliplining grouts and includes details about the recommended properties of the three types of grouts.

Table A.24: Grout Properties (ODOT CMS 2019)

Grout Properties	**CMS Item 613 LSM Grout***	**CMS Item 613 LSM Alternate (ASTM D4832)**	**Non-shrink Grout CMS Item 602 (CMS Item 705.22/ ASTM C1107)**	**Cellular Grout****
Compressive strength	--	50 to 100 psi; 12-month maximum of 100 psi (CMS 613)	Minimum (ASTM C1107) 1 day: 1,000 psi 3 days: 2,500 psi 7 days: 3,500 psi 28 days: 5,000 psi	--
Fluidity	--	--	Minimum flow is 125 @ 5 drops of the flow table in 3 seconds	--
Density	--	--	--	--
Slump	--	Without vibration, average spread diameter 8″ to 12″ (ASTM D6103)	--	--
Water-to-Cement ratio	Varies	--	--	--
Other	Furnish air-entraining admixture	--	Height change maximum of 4%	--

*Not mentioned in CMS Item 613 for standard mixes in Table 613.03-1.
**Supplied specified.

A.5.2 LSM Grouts – ODOT CMS Item 613

In CMS Item 613, ODOT specifies a low-strength mortar for backfills around conduits. The following are some of the requirements specified for LSM.

Materials:

I. *Cement*: CMS Item 701.01 (Air-entraining Portland Cement ASTM C150, Type IA) or CMS Item 701.04 (Portland Cement ASTM C150, Type I).

II. *Fly ash for use in Portland Cement Concrete*: (ASTM C618, Class C or F, except ensure a maximum loss on ignition (LOI) of 3%).

Class F fly ash that meets the applicable requirements for this class, which has pozzolanic properties.

Class C fly ash that meets the applicable requirements for this class. In addition to having pozzolanic properties, this class of fly ash also has some cementitious properties.

Class F fly ash is typically produced from burning anthracite or bituminous coal, but it may also be produced from sub-bituminous coal and from lignite. Class C fly ash is typically produced from burning lignite or sub-bituminous coal and may also be produced from anthracite or bituminous coal.

Other pozzolans that can be used are slag cement, micro silica, and Class N Natural Pozzolan.

III. *Fine aggregates*:

Sources of fine aggregates are foundry sand, natural sand, and sand manufactured from stone, gravel, or air-cooled blast furnace slag.

Table A.25 and Table A.26 present the sieve analysis and physical properties, respectively, of the fine aggregates. Air-entraining admixtures used in low strength mortar, also named as controlled density fill or flowable fill. The mix proportion per cubic yard for the suggested ODOT standard mixes for LSM are presented in Table A.27.

Table A.25: Fine Aggregate Gradation for LSM Mixes (CMS Item 703.05)

Sieve Size	**Total Percent Passing**
3/8 in.	100
No.4	90–100
No.8	65–100
No.16	40–85
No.30	20–60
No.50	7–40
No.100	0–20
No.200	0–10
Screening	
3/8 in.	100
No.4	85–100
No. 100	10–30

Table A.26: Physical Properties of Fine Aggregates for LSM Mixes (ODOT CMS 2019)

Property	Maximum
Loss, sodium sulfate soundness test	15%
Aggregations of soil, silt, etc., by weight	0.5%

Table A.27: Mix Proportions per Cubic Yard for LSM Mixes from CMS Table 613.03-1 (ODOT CMS 2019)

	Type 1 Mix (lb/yd^3)	Type 2 Mix (lb/yd^3)	Type 3 Mix (lb/yd^3)
Cement	50	100	0
Fly ash class F	250	25% entrained air	1500
Fly ash class C	0	0	297
Fine aggregate	2910	2420	0
Water (target)	500	210–300	850

Bulkheads should be constructed at the existing conduit ends to contain the backfill material. It is important to ensure bulkheads are constructed to allow grout return ports or visual verification methods. The annular space around the outside of the liner pipe should be filled completely with the backfill material. Moreover, it should be ensured that the liner pipe maintains the designed line and grade while the backfill material is being placed.

A.5.3 Mortar Grouts – ODOT CMS Item 602

ODOT CMS Item 602 specifies the use of nonshrink mortar conforming to ASTM C1107 with the following characteristics:

- Minimum 28-day compressive strength (ASTM C109) of the retained grout at maximum working time is 5,000 psi.
- Maximum early height change (ASTM C 827) 4.0 % at the time of final setting.

The following is the modification to ASTM C1107:

Fluidity of the grout (ASTM C1437) at the maximum water content is at least equal to a flowable mixture as defined in Section 8.2.2 of ASTM C827, and the minimum flow is 125 @ 5 drops of the flow table in 3 seconds.

According to Section 8.2.2 of ASTM C827, if ASTM C1437 is used, the flow after 5 drops of the flow table in 3 seconds is 145 or less. A plastic mixture should have a flow of 100 to 125, and a flowable mixture should have a flow above 125 when tested by the preceding modification of ASTM C1437 but not less than 30 seconds when tested using the flow-cone procedure of ASTM C939. A fluid mixture should have a time of efflux of 10 to 30 seconds when tested by the flow-cone procedure. The water required to produce the specified consistency is determined by tests on trial batches. Fresh materials are to be used in each trial. If not specified or recommended otherwise, use sufficient mixing water to produce a flow of 125 ± 5. For premixed mortars or grouts, use the amount of water suggested by the manufacturer for the intended application. The consistency should be determined and the values recorded for all tests. ASTM C827 also provides a method for determining the change in height of cylindrical specimens from the time of molding until the mixture has hardened.

A.5.4 Cellular Grout – ASTM C869

Cellular grout is a low-density material having a homogenous void or cell structure which is formed by the addition of foam or by the generation of air within a fresh cementitious mixture. Generally, the as-cast density of cellular grout ranges from 20 lb/ft^3 to 120 lb/ft^3. Density control is accomplished by adding a calculated amount of a preformed foam to a cementitious slurry with or without the addition of sand or other materials. The air cells created by the preformed foam can account for up to 80% of the total volume. Cellular grout can be classified based on the density range and the components used the mixture, such as neat-cement cellular concrete (50 lb/ft^3), sanded cellular concrete (50–120 lb/ft^3), and lightweight aggregate cellular concrete (50–120 lb/ft^3), as defined in Lamond and Pielert (2006).

ASTM C869 provides standard specifications for foaming agents specifically formulated for making preformed foam for use in the production of cellular concrete. ASTM C796 provides a test method to measure the laboratory performance of a foaming chemical to be used in producing foam (air cells) for making cellular concrete. The physical properties of the test batch should conform to the requirements mentioned in ASTM C869 (Table A.28). For example, the type of cement should be Type I or Type III. The water-to-cement ratio (w/c) will vary, depending on the cement type: the w/c is 0.58 for Type I cement and 0.64 for Type III cement. Nevertheless, if a cement or foaming agent made using these w/c values does not produce a satisfactory mix, a trial mix should be made with a different w/c. Furthermore, the foam volume should be adjustable for the batch to produce a density after pumping of 40.0 ± 3.0 lb/ft^3.

Table A.28: Physical Requirements for Cellular Concrete (ASTM C869, ASTM C796)

Properties	Requirements
*Density after pumping	40.0 ± 3.0 lb/ft^3
*Over dry density: For Type I Cement For Type III Cement	 30.4 ± 2.5 lb/ft^3 30.0 ± 2.5 lb/ft^3
Compressive strength, minimum	200 psi
Tensile splitting strength, minimum	25 psi
Water absorption, maximum	25% by volume
Loss of air during plumbing, maximum	4.5% by volume

*The density should satisfy either density after pumping or oven-dry density.

The specifications of cellular concrete from different sources (such as transportation agency specifications, ASTM C869, ACI 523.3R-14, and supplier information, have been summarized in Table A.29.

Table A.29: Comparison of Specifications for Cellular Concrete

Agency/supplier/ standard	Density (pcf)	Compressive strength (psi)	Tensile splitting strength (psi)	Water absorption (%)
ODOT (follows ASTM C869)	--*	--*	--*	--*
Iowa DOT	Minimum 70 (cannot be dewatered); minimum 30 (no water present)	Minimum 100	--	--
Florida DOT	20 to 80	Minimum 150 (28 days)	--	--
New York State DOT	Type A: 30 Type B: 42	Type A: 40 Type B: 100 (minimum 28 days)	--	--
Minnesota DOT	30 ± 3 to 70 ± 3	75 to 400 (Low- to high-density)	--	--
Texas DOT	40 to 80	n/a	--	--
Indiana DOT report (Thomas 1991)	20 to 80	75 to 500	--	--
ASTM C869	Type I: 30.4 ± 2.5 Type III: 30 ± 2.5	Minimum 200	Minimum 25	Maximum 25% by volume
ACI 523.3 R-14	50 to 120	250 to 520	--	--
SnapTite (ISCO Industries)	30 to 80	200 to 1000	--	--
Elastizell Corp.	30 to 80	Minimum	--	--
CEMATRIX Corp.	24 to 50	Minimum 43 to 362 (28 days)	--	--
Cellular Concrete Inc.	30 to 42	Minimum 40 to 120	--	Maximum 14 to 20 (120 Days)
MixOnSite USA, Inc.	As cast: 20 to 48 As dry: 16 to 41	20 to 300	--	--

*Project specific/as per plan items.

A.5.5 Summary of Grout Specifications

This section provided details about the standard specifications of LSM, mortar grouts (ODOT CMS Item 602), and cellular grout (ASTM C869). The comparison of several specifications and standards shows that ODOT has no specific recommendations for the properties of cellular grouts, but the requirements are called out by plan notes. The information in this section will guide ODOT in the development of a standard guidance for cellular concrete grout. The recommended guidance for cellular grouts will be based on the laboratory studies and field implementation trials completed in this project and are included in Appendix H.

A.6 Current Practices of Other Transportation Agencies

A.6.1 Introduction

In this section, the common practices of different transportation agencies along with ODOT are compared to observe the variations in guidance regarding grouting materials and the practices for grouting the annulus voids. The properties recommended by different agencies regarding the compressive strength, density, and fluidity for the various types of grouts are compared to identify any major differences between ODOT guidance and the specifications of agencies in other states. This information will support recommendations regarding the properties of grouts and the development of ODOT specifications for new grout materials.

Requirements for grouts/cellular concrete properties and recommendations for sliplining methods from the specifications of 26 state departments of transportation, Unified Facilities Guide Specifications (UFGS), the U.S. Army Corps of Engineers (USACE), the U.S. Department of Agriculture (USDA), and public service departments of five U.S. cities were compiled and are included in Attachment A. Different characteristics of low-strength mortar grouts such as compressive strength, density, and fluidity are presented from Tables A.48 to A.57. Several properties of non-shrink mortar grouts such as the compressive strength, fluidity, volume change, and water-to-cement ratio (w/c) are listed in Tables A.58 to A.63. Furthermore, cellular grout properties (including density, compressive strength, slump value, and w/c) are presented in Tables A.64 to A.68. Other additional and special requirements such as minimum annular space, bulkhead requirements, and grouting pressure are summarized in Tables A.69 to A.77.

Current practices followed by several other state transportation agencies, the USACE, USDA and local public agencies are summarized below.

A.6.2 Grouts for Annulus Voids

USACE classifies grouts for annulus voids between culvert liners and host culverts as one of two types: non-structural or structural. Structural grouts are generally specified as non-shrink mortars (NSM) with high compressive strengths and are mostly governed by the requirements of ASTM C1107. Non-structural grouts can be low-strength mortars (LSM), which are also referred to as *low-density flowable backfills* or *controlled low-strength material* (CLSM). Very low-density cellular concretes have also been used in more recent times and are gaining acceptance by several state transportation agencies.

The type of grout to use is generally based on the type of slip liner system provided. If the pipe liner provided cannot meet the stated requirements for factor of safety against buckling or crushing, then a structural grout must be used regardless of the liner system used for the pipe. All other grouts may be non-structural.

A brief summary of the range of specifications for the three types of grouts is presented in Tables A.30 through A.32. The key differences between ODOT specifications and those followed by other agencies are highlighted. All agencies provide specifications for at least one or two types of mortar backfills that can be used for culvert annulus void grouting applications. The type of LSM to be used depends on the water level and the potential for the grout to be in proximity to water. Additionally, several agencies are beginning to specify cellular grout to various degrees as well. For cellular grouts, transportation agencies mainly rely on suppliers for specifications and compliance tests.

Table A.30: Summary of Specifications for LSM

Description	ODOT Specifications	Other agencies
LSM	Item 613	Comparable with non-excavatable, flowable grout backfill, CLSM, etc.
Compressive strength		Minimums specified. Range from 40 psi to maximum 300 psi (mostly 100 psi in 28 days)
Penetration resistance		Min. 100 psi after 24 hours (ASTM C403)
Basis for strength		Min. 100 psi in 24 hours using ASTM C942 and Min. 350 psi in 28 days using ASTM C495 cylinder tests
Mix types		Several types with different options are specified (e.g., with or without flyash, with or without admixtures, critical or non-critical fluidity)
Density		Depending on classification, there is a wide range in density: 80–145 pcf
Fluidity		Efflux time of 10–26 sec.
Slump		Some specify slump (~ 3″), but most specify a spread of 9–14″. Not to cause segregation
Air content		5–25%
Grout temperature		At point of delivery: 35 °F to 50 °F In cold weather, > 60° F In hot weather, < 90° F Pump within 45 minutes

Table A.31: Summary of Specifications for NSM

Description	ODOT Specifications	Other agencies
NSM	Item 602 (ASTM C1107)	Comparable with high-density non-shrink grouts. Most agencies do not mention the use of NSM for culvert annulus void applications. Some point to ASTM C1107.
Compressive strength	Min. 5,000 psi after 28 days	2,500 psi after 1 day 4,000 psi after 7 days 5,000 psi after 28 days TxDOT: 5,800 psi after 28 days
Consistency	Fluid: Grout consistency having a time of efflux of 10 to 30 s when tested by the flow cone procedure in ASTM C939. Plastic: Grout consistency having a flow of 100 to 125 by the flow test method in ASTM C1437; the flow after 5 drops of the flow table in 3 s	
Set time		Maximum of 8 hours
Early height change (max. % at time of final setting)	+4%	
Height change of moist-cured hardened grout	0.0 to +0.3%	
Air content		3 to 9% (a few agencies mentioned this)
Water-to-cement ratio		0.45 (WisDOT) and 0.6 (IDOT)
Shrinkage		Max. 1% by volume

IDOT = Illinois Dept. of Transportation; TxDOT = Texas Dept. of Transportation; WisDOT = Wisconsin Dept. of Transportation.

Table A.32: Summary of Specifications for Cellular Grouts

Description	ODOT Specifications	Other agencies
Cellular grout	ASTM C869 (which also refers to ASTM C796)	Most refer to ASTM C869 or ASTM C796
Density after pumping	40 ± 3 lb/ft^3	20 to 80 pcf Min. 30 pcf where no water is present Typically, where water is present, use NSM
Oven dry density	30 ± 2.5 lb/ft^3	
Compressive strength	200 psi	Min. 80 psi, 100 psi, 75 psi (low-density) or 400 psi (high-density). USACE: 75–500 psi
Tensile splitting strength	25 psi	
Water absorption	25% by volume	
Loss of air during pumping	4.5% by volume	
Slump		10 ± 1 inch (only MnDOT)
Water-to-cement ratio		0.5 (only MnDOT)
Foam		20 cu. ft. (low density) 13.5 cu. ft. (high density)

A.6.3 Summary of Common Practices used for Installation

- Grouting is used for filling annulus voids of 1 inch or more in thickness.
- Grouting pressures: Some agencies have specified a pressure head (2 ft.) and others recommend a specific pressure (maximum of 2 psi to 5 psi). Caltrans specifies a pressure based on the liner stiffness.
- Liner pipe deflection limit: 1.5%.
- Grout making and pumping:
    - The grout is mixed in small quantities and pumped in a continuous operation.
    - Grout pressure and volume are monitored with gauges during the installation.
    - Illinois Department of Transportation (IDOT) allows three pumping methods: intermittent, bracing, and water fill methods.
    - Many agencies require pumping in lifts, and some even require staged lifts (where the grout in lower lift is allowed to set before the next lift is installed).
    - Two filling methods are allowed: gravity flow (for short liners up to 80 ft in length) and pressure grouting (for longer liners).
    - Continue pumping the grout until the discharge is within 0.3 pounds per gallon of the specified grout injection density. This is intended to ensure that all the extraneous water within the annulus is discharged and any diluted grout resulting from the grout mixing with the water within the annulus is removed.
- Special requirements
    - Many agencies require grouting in lifts, and some required staged grouting.

- Process control relies on measurements of air content, mix temperature, and slump.
    - Use low-density CLSM at locations with no water issues; use high-density CLSM when it is not possible to dewater (in this case, multiple lifts will be required).
    - Grout is not required for pipes with diameters of 12” to 36” when justified by structural calculations.
    - For each batch of grout, density and viscosity tests are performed, and foaming agents are added at the site.
    - The drilling of injection holes — either from the surface or through a liner pipe — to facilitate grouting is prohibited.
- Inspections
    - For pipes with diameters greater than 30”, visual or video inspections of the inside of the pipe are needed.
    - To verify complete filling of the annular voids, core holes are cut at the farthest point from the location where the grout is inserted into the void.
    - Sounding method is specified for inspections except for pipes with diameters less than 48”. A closed-circuit camera and display are specified for visual inspections if the pipe diameter is less than 48”.
    - Grout pressure gages and recorders are installed next to injection ports; actual grouting pressure (to an accuracy of ± 0.5 psi) versus time is continuously recorded on paper.
    - Sampling and compressive strength testing at a minimum frequency of once per day or 100 yd^3 at the point of placement using 3” × 6” cylinders.
    - Minimum compressive strength of 4,000 psi after 7 days and bond strength of at least 1,000 psi are specified (Virginia Department of Transportation).
    - The grout temperature is verified to be greater than 50° F prior to installation.
    - Liner is placed a minimum of 24 hours prior to grouting to allow the liner temperature to become equalized within the host pipe prior to grouting.
    - Admixtures are widely used, and the use of pre-mixed grouts is permitted.
    - Liner deflection after grouting is measured in the presence of an engineer.

In one documented early study, Thomas (1991) described the grout types and procedure used to fill the annular voids in a sliplining project. He reported that the contractor used two grout designs (Table A.33). The initial grout design did not work well due to the higher sand content, as too much sand was settling out and piling up at the inlet. The final design worked well, and they were able to complete the grouting of the 60-foot-long conduit within 3 hours. Holes were made at each end of the existing pipe, and Duracal® patching material was placed to hold the pipe in place.

Table A.33: Two Grout Types used in a Sliplining Project Reported by Thomas (1991)

Initial Grout Type	Final Grout Type
▪ 395 lbs. cement ▪ 79 lbs. fly ash ▪ 1421 lbs. dry sand ▪ 229 lbs. water (includes water in sand) ▪ 11.9 cu. ft. preformed foam	▪ 300 lbs. cement (Type I) ▪ 1500 lbs. fly ash (Type C or F) ▪ 1200 lbs. fine aggregate (SSD) ▪ 156 oz. super plasticizer (Rheobuild 1000) ▪ Air entraining admixture to obtain 10% air content as needed ▪ 375 lbs. water
Compressive strength: 150 psi @ 28 days	Compressive strength: 4000 psi @ 28 days

Table A.34 presents a summary of several completed sliplining projects that were reported by different agencies.

Table A.34: Summary of Project-specific Case Studies (Thornton 2005)

	Oregon DOT	**Vermont Agency of Transportation**	**USFS (Cass Lake, Minnesota**	**USFS (Ironwood, Michigan)**	**USFS (Cleveland, Ohio and Tennessee)**
Project name	Foster Reservoir Culvert	Brighton Culvert Relining (VT 105, BR 90)	Forest Road 2171 Third River Road	Paulding Creek Dam Repair	Peavine-Sheeds Creek Road
Project description	Lining 85.4 m (280 ft) of 76-cm (30") deteriorated corrugated metal pipe	Lining 25 m (82 ft) of 213-cm (84") deteriorated corrugated metal pipe	Bituminous overlay and culvert rehabilitation	Lining existing 1.2-m (48") corrugated metal spillway pipe	Lining two existing 45.7-cm (18") deteriorated corrugated metal pipe
Type of liner used	Continuous sliplining using 12-m (40-ft) fusion-welded segments	Sliplining	Sliplining	Sliplining	Sliplining
Time to complete installation	5 days	25 days	10 days	16 to 24 hr	2 days
Year project completed	2002	2002	2002	2002	2000

Table A.34: Summary of Project-specific Case Studies (Thornton 2005) (Continued)

	Oregon DOT	**Vermont Agency of Transportation**	**USFS (Cass Lake, Minnesota**	**USFS (Ironwood, Michigan)**	**USFS (Cleveland, Ohio and Tennessee)**
Cost of project	$45,000	$70,460	$350,000	approx. $25,000	$2,700
Length of pipe lined	85.4 m (280 ft)	25 m (82 ft)	236.3 m (775 ft)	14.6 m (48 ft)	27 m (90 ft)
Size of host pipe	760 mm (30”)	2.13 m (84”)	380 mm (15”)	1.2 m (48”)	457 mm (18”)
Host pipe material	Corrugated metal pipe	Corrugated metal pipe	Corrugated metal pipe	Corrugated metal pipe	Corrugated metal pipe
Deciding factor for choosing liner type	Cost: Sliplining was most cost-effective; grout was used to fill voids around the deteriorated pipe	n/a	Availability, cost, and the contractor’s ability to install it	n/a	Availability and type of installation
Liner performance	As expected	Reported when liner was only in service a few months	So far, so good	Liner in service for a little under one year	Good

A.6.4 Summary of Grouting Specifications Used by Other Transportation Agencies

The requirements regarding the desirable properties for grouts and cellular concrete as well as recommendations for the use of sliplining methods from the specifications of several transportation agencies have been summarized in this section. This information will guide ODOT as it considers changes or additions to the guidance provided in its specifications.

A.7 Guidelines and Specifications used by Suppliers

A.7.1 Introduction

Many sliplining companies and grouting manufacturers have developed their own specifications and protocols for sliplining and grouting methods. However, the specifications for cellular concrete can vary greatly from one supplier to another. Some of the specifications and guidelines used by manufacturers and suppliers are summarized in this section.

A.7.2 Snap-Tite®

ISCO Industries, the maker of the Snap-Tite® joint and installation system, is one of the specialist companies in sliplining applications. This subsection focuses on guidance for using non-cellular grouts and cellular grouts, which are the two grout materials specified for sliplining applications where Snap-Tite® is used.

A.7.2.1 Non-cellular grouts

Non-cellular grouts, which are mixed according to the traditional Portland cement formulation, are typically referred to as *flowable fills*. These products are used in many applications including those for grouting annulus voids created by liner pipes. Non-cellular grouts can be classified as follows:

- Flowable fill grouts are mainly composed of water, cement, and sand, and the unit weight of these grouts ranges from 130 to 135 pcf. Chemical admixtures are sometimes incorporated to enhance properties of the grout mix, and a portion of the cement may be replaced with fly ash for cost savings and to enhance certain properties of the mix. Project specifications might call for three, four, or five sacks of flowable fill, and this refers to the amount of cement added to each cubic yard of grout mix. Due to their high density, flowable fill grouts have a high viscosity that limits the traveling distance to a maximum of 50 ft.
- Reduced density flowable fills have the same components as flowable fill grouts except that chemical admixtures are used to reduce the density of the grout to below 100 pcf. A density ranging from 75 to 100 pcf can be achieved by using a foaming generator.

A.7.2.2 Cellular grout

Cellular grout is a low-density grout mix that is composed of water, foam, and cement with or without fly ash. The wet density of cellular grout ranges from 30 to 80 pcf. Because of their lower unit weight, cellular grouts apply a lower hydrostatic pressure on the liner than flowable fill grout or reduced density flowable fill. Furthermore, cellular grouts have the ability to travel a longer distance within the sliplined pipe system and are able to flow through holes or separated joints of the host pipe. Typical mix proportions and properties for cellular concrete grouts with densities of 40, 55, and 75 lb/ft^3 are shown in Tables A.35, A.36, and A.37, respectively.

Table A.35: Cellular Grout Mix Design for 10 yd^3 to Achieve a Density of 40 lb/ft^3 (ISCO Industries, 2013)

Component		Units	Weight (lbs)	Volume (yd^3)	Component	Amount
Type III Portland Cement	6,950	lbs	6,950	1.4	Varimax HS-320	62 oz
Water	418	gal	3,488	2	Water	83 gal
Foam	179	ft^3	716	6.6	Mix together and run through foam generator for 8 minutes	
	Mix totals		11,154	10		
Net wet cast density =			41.3	lb/ft^3		

Table A.36: Cellular Grout Mix Design for 10 yd^3 to Achieve a Density of 55 lb/ft^3 (ISCO Industries, 2013)

Component		Units	Weight (lbs)	Volume (yd^3)	Component	Amount
Type III Portland Cement	9,700	lbs	9,700	1.8	Varimax HS-320	49 oz
Water	584	gal	4,877	2.9	Water	66 gal
Foam	143	ft^3	572	5.3	Mix together and run through a foam generator for 6 min. and 30 sec.	
	Mix totals		15,149	10		
Net wet cast density =			56.1	lb/ft^3		

Table A.37: Cellular Grout Mix Design for 10 yd^{3}to Achieve a Density of 75 lb/ft^3 (ISCO Industries, 2013)

Component		Units	Weight (lbs)	Volume (yd^3)	Component	Amount
Type III Portland Cement	13,368	lbs	13,368	2.5	Varimax HS-320	36 oz
Water	805	gal	6720	4	Water	44 gal
Foam	95	ft^3	380	3.5	Mix together and run through a foam generator for 4 min. and 51 sec.	
	Mix totals		20,468	10		
Net wet cast density =			75.8	lb/ft^3		

A.7.2.3 Grout Selection and Application

The selection of a grout depends on a number of factors, as described below.

A.7.2.3.1 *Condition of Host Pipe*

The condition of the host pipe is essential for determining the liner and grout requirements. If the host pipe has lost its ability to handle soil and highway loads, the liner and grout must be selected to handle the loads the culvert will need to resist. In most cases, a liner with a dimensional ratio (ratio of the nominal outside pipe diameter to the minimum wall thickness) of 32.5 and a low-density foam grout with a unit weight equal to 40 pcf or more will be suitable. However, if the host pipe is considered to be in good condition (i.e., if it does not have corrosion holes or separation of pipe joints), grouting may or may not be needed. The long-term site conditions should be evaluated to determine the advantages and drawbacks of grouting.

A.7.2.3.2 *Length of Host Pipe*

The length of the host pipe is an essential consideration when selecting the grout type. If the host pipe is short (i.e., the length of the liner is less than 60 ft.), any grout — such as flowable fill grout, reduced density flowable fill grout or cellular grout — can be used with low pressure. The pumping pressure needs to be increased if the liner is greater than 60 ft. in length.

A.7.2.3.3 *Volume of Annular Space*

If the annular space (the area between the liner and the host pipe) is small, it will be difficult to fill the space without applying high pressure. For a small annular space, a low-density grout (cellular grout) is recommended, and it should be pumped at a low pressure (2 psi or less than 5 ft. in static head), as pumping at a higher pressure will compress cellular grouts and result in volume reduction. A high-density grout containing light aggregates such as sand often requires a higher pumping pressure and using a grout that contains sand in a small annular space might cause the fill tube to clog during the grouting process. High-density grouts are also not preferable for applications with a large diameter difference between the host pipe and the liner, as the self-weight of the grout will apply a large pressure to the liner during installation.

A.7.2.3.4 *Flotation*

Flotation is one of the major concerns during grouting, since lightweight liners like HDPE may float in the grout material and rise to the top of the host pipe, which would change the hydraulic characteristics and the water flow in the liner. Many remedial measures can be adopted to help control this problem. One method is to insert wooden, plastic, or metallic blocks (spacers) inside the culvert, along the top of the host pipe or the top of the liner itself (as shown in Figure A.17) to maintain the alignment of the liner during grouting. Other methods to prevent flotation are to weight the liner with bags of sand or other materials to prevent the liner from floating or to partially/fully fill the liner with water to help neutralize any buoyancy force.

(a) before sliplining

(b) with the liner inserted

Figure A.17: Wooden Spacers Attached to the Inside of the Culvert (Source: ISCO Industries 2013).

A.7.2.3.5 *Elevation Change*

When the difference in elevation between the ends of the pipe that will be sliplined is large, the grout will exert a large pressure not only on the liner material but also on the bulkhead at the downstream end of the lined culvert. When the elevation difference is greater than 5 ft, the method of grout installation should be evaluated to prevent the hydrostatic collapse of the liner. Grouting in lifts, as shown in the diagram in Figure A.18, is often the best method to prevent issues such as liner collapse, leaking at the bulkhead, and other potential problems.

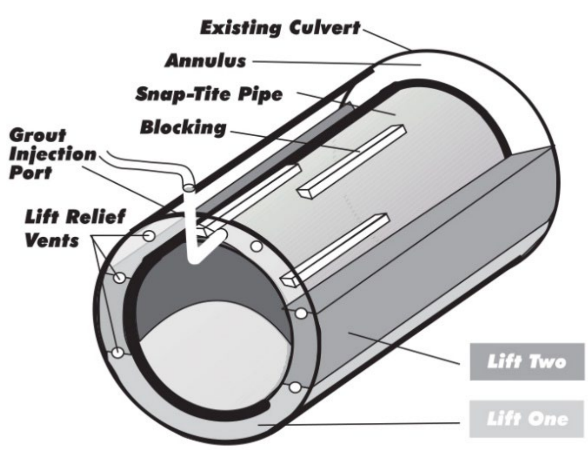


Figure A.18 : Grouting in lifts (ISCO Industries 2003).

A.7.2.3.6 *Unconstrained Buckle and Grout Pressures*

The following equation can assist the designer to evaluate an allowable load on the HDPE liner:

$$P_{WU} = \frac{f_0}{N_S}\frac{2E}{(1-\mu^2)}\left\{\frac{1}{DR-1}\right\}^3 \quad \text{(A.2)}$$

where

P_{WU}= allowable unconstrained pipe wall buckling pressure, psi
DR = dimensional Ratio (ratio of outer diameter of the pipe to the minimum wall thickness)
E = apparent modulus of elasticity of pipe material, psi
f_0 = ovality correction factor (as shown in Figure A.19).
N_S = safety factor
μ = Poisson's ratio

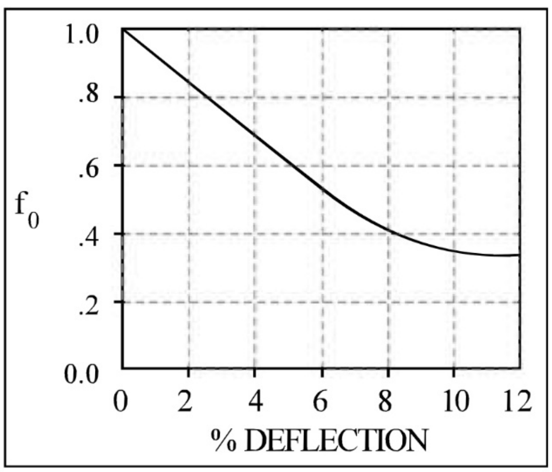


Figure A.19 : Ovality Compensation Factor, f_0 (ISCO Industries 2013).

A.7.2.3.7 *Culvert Circumstances*

The specific culvert circumstances have the greatest impact on the type of grout that should be used to fill the annular space. The information provided by ISCO Industries (Table A.38) can assist in the selection of the grout; however, it should not be considered as a definitive recommendation for culverts. It is a general guide for selecting the type of grout to use for any application. Cellular grouts are listed as being suitable for all host pipe conditions, lengths, and circumstances. The heavier flowable fill grouts (130-135 pcf) seem to be suitable only if the host pipe is in good condition, and the host pipe lengths are smaller than 50 ft. for any culvert circumstances.

Table A.38: Aid for determining grout to use for any particular application (ISCO Industries 2013)

		Condition of host pipe		Length of host pipe (linear feet)			Culvert circumstances	
	Density (pcf)	**Good**	**Failed or Failing**	**< 50**	**50-125**	**> 125**	**Light traffic**	**Heavy traffic**
Three sacks of flowable fill	130–135	x		x			x	x
Reduced density flowable fill	90–120	x	x	x	x		x	x
Cellular grout	40–80	x	x	x	x	x	x	x

A.7.3 Pacific International Grout Company Practices

Pacific International Grout Company provides a grout that is cement-based and made from the materials that are readily available in any city. Moreover, they claim it is easy-to-use with the quality well tested. This grouting material flows easily using gravity feed or pumps and can be placed at distances of 500 feet from a single injection point in the liner annulus. Additionally, the surface disruption that is caused by this grout is minimal. Each particular job/condition requires a specially designed grout with a particular density and compressive strength.

A.7.3.1 Characteristics of Low-Density Cellular Concrete

In 1988, Pacific International Grout Company developed a cellular concrete grout (LDB 662) specifically for the backfilling of high-density polyethylene (HDPE) slipliners. This patented grout material is ideally suited for the use in slipliner grouting. The properties of LDB 662 are suitable for backfilling pressure-sensitive sliplined pipes. Fluidity and long-term protection result in reduced costs to the owner. The properties of LDB 662 are shown in Table A.39.

Table A.39: Properties of LDB 622 (Pacific International Grout Co. 2020)

Properties	Explanation
Viscosity	LDB 622 can flow easily into small areas and cracks in the annulus as well as voids created by leakage outside the defective pipe, even at low injection pressures.
Density	The load-bearing density can be field-adjusted from 25 to 110 pcf based on the particular job requirements.
Non-shrinking	The grout can maintain its volume in the annulus after hardening (i.e., it is non-shrinking).
Compressive strength	The compressive strength of the grout varies on-site from 30 to 1,000 psi while maintaining maximum fluidity for low injection pressures.
Long-term stability	The grout can resist deterioration due to environmental changes, including changes in moisture and temperature.

A.7.4 Geofill Cellular Concrete

Geofill LD grout, which is produced by Geofill Cellular Concrete, is a low-density cellular concrete that does not contain any aggregates. It is a non-pervious closed-cell material that can be used to fill the annular space between the existing pipe and liner pipe. This grout helps to fill the annulus void completely, and it is designed to provide long-term stability as well as protection from corrosion. The density and compressive strength properties of Geofill LD are shown in Table A.40. According to the specification for Geofill LD low density cellular concrete (LDCC) for annular space grouting, the range of the cast density of Geofill LD would be between 35 pcf to 45 pcf and the 28-day compressive strength should be a minimum of 200 psi; additionally, the flow consistency (as determined using ASTM D6103) should be greater than 7 inches (Geofill Cellular Concrete 2020a).

Table A.40: The density and compressive strength of Geofill LD (Geofill Cellular Concrete 2020b)

Class	Density (as cast pcf)	Density (as dry pcf)	Compressive strength (min psi)
I	20–24	16–20	20
II	24–30	19–25	40
III	30–36	24–30	80
IV	36–42	30–36	120
V	42–48	35–38	160
VI	48 and over	41 and over	300

Geofill LD was utilized by MixOnSite for the annular space grouting of water transmission pipelines in San Diego, California (MixOnSite, 2020). In this project, a very flowable material was required for that project to ensure that no voids would be left in the 1.5-in. annulus around the pipe. Geofill LD Class VI material with a density of 50 pcf and a compressive strength of 500 psi was utilized for the project. The average pumping distance was more than 1,500 linear feet. During placement, the required pumping pressure was less than 3 psi.

A.7.5 Elastizell Corporation of America

Elastizell Corporation of America produces cellular concrete for engineered fill applications. The Elastizell Engineered Fill (also called Elastizell EF) is a mixture of cement, water, and preformed foam. The density of Elastizell EF varies from 20 pcf to 120 pcf (Table A.41). ELASTIZELL concrete mixing process is shown in Figure A.20. This is an excellent fill material for filling the annular spaces of sliplined pipes.

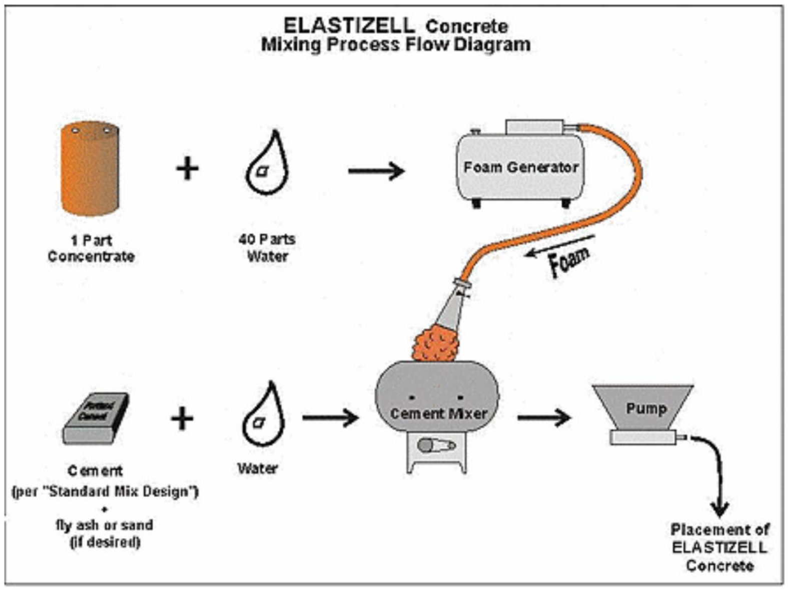


Figure A.20: Elastizell concrete mixing process (Elastizell Corporation 2020).

Table A.41: Properties of Elastizell EF (Elastizell Corporation 2020)

	CLASS II	CLASS III	CLASS IV	CLASS V	CLASS VI
Maximum cast density (pcf)	30	36	42	50	80
Minimum compressive strength (psi) @ 28 days	40	80	120	160	300

A.7.6 CJGeo Contractors

CJGeo is a factory-trained installation contractor for Aerix Industries (formerly Cellular Concrete Solutions) geotechnical products and is based in Virginia. They perform annular space grouting using both the cellular concrete grouts and polyurethane grouts.

A.7.6.1 Cellular Grout

CJGeo most commonly uses cellular concrete for the grouting of annular spaces because this grout is a reliable and economical material. Typical cellular concrete has a wet-cast density of 30 pcf and an average 28-day compressive strength of 125 psi. Each cubic yard in place contains 512 lbs of Portland cement, 256 lbs of water, and 20.3 cubic feet of preformed Aerlite foam. In general, CJGeo performs the pipe grouting by pumping, with a typical installation pressure below 10 psi. In some cases, gravity placement is also used. However, there are some drawbacks to using cellular concrete if the annular space cannot be dewatered, if large amounts of groundwater have infiltrated into the annulus, or if the annular space volume is very small. In these cases, it is more economical to use polyurethane grout rather than cellular concrete.

A.7.6.2 Polyurethane Grout

For annular space grouting with polyurethane, it is important to use a low exotherm undersealing polyurethane grout. This grout can exert an expansive force of up to 30 psi. CJGeo installs this type of grouting around a solid wall HDPE, corrugated HDPE, CMP, SSP or other structures. Typically, this grout cannot be pumped long distances because it cures very quickly; thus, it is limited to pipes that are 80 linear feet or less in length.

A.7.6.3 Completed Sliplining Project in Baltimore

In Baltimore, Maryland, CJGeo installed 500 linear feet of 48″ HDPE reline pipe through a 63″ CMP culvert and filled the annular space at a very low installation pressure. In this project, access was limited such that grouting could be installed at only one end of the pipe. For this application, CJGeo used highly flowable cellular concrete. The peak pressure for pumping the grout was 15 psi. They placed 30 pcf wet cast density cellular concrete with a compressive strength of 125 psi. The 24-hour penetration of the grout exceeded 50 psi, and the grout provided adequate strength and stability.

A.7.6.4 Capitol Tunneling

Capitol Tunneling uses a lightweight cellular grout for filling annular spaces that is significantly lighter than traditional sand grouts. For this reason, it can be pumped over longer distances. This grout has a unit weight that averages 35 pcf, which is 100 pcf less than traditional sand grouts. The 28-day compressive strength of this grout was 200 psi. Capitol Tunneling was awarded a contract by the City of Ontario, Ohio, to install a HDPE slip-liner pipe into a failing 42″ CMP culvert. The company successfully completed the installation of the liner and the grouting of the annulus voids.

A.7.7 Summary of Supplier Guidelines for Grout Materials

The guidelines for sliplining and recommended grout materials used by the suppliers were described in this section. It is observed that most suppliers are using cellular grouts for sliplining. ISCO Industries has its own guidelines and has recommended three different types of grouts (flowable fill, reduced density flowable fills, and cellular grouts) with its Snap-Tite® culvert lining system. These recommendations provided useful information about the properties of the available grout materials.

A.8 Research by State and Local Transportation Agencies

A.8.1 Introduction

Experimental and numerical studies have been conducted over the past 25 years to investigate the effect of grouts in sliplined culverts or pipes. This section provides a summary of the various research studies sponsored by different state and local transportation agencies.

A.8.2 Previous Studies on Sliplined Culverts

Ahmad et al. (1994) described the Danby pipe renovation system where an existing structure was lined with PVC liner using cementitious grout. The 7-day compressive strength of the grout was 5,000 psi and its density was 105 pcf. The soil test results and the results of D-load testing (ASTM C655) of the lined and unlined pipe demonstrated that the grout integrated the pipe wall into a composite of PVC, grout, and host pipe effectively. McAlpine (1997) studied the rehabilitation of reinforced concrete pipe (RCP), which conformed to ASTM F1698, with a spirally wound profiled PVC liner and a high-strength (5,000 psi) grout. The author proposed a design procedure for the rehabilitation of RCP pipes that involved computing the vertical loads and applying those loads to the culvert structure by assuming a uniform horizontal and vertical pressure distribution. Wall thickness and grout strength are two variables in the design. The structure is to be analyzed at both pre- and post-rehabilitation using the transformed section method. Using the iteration method in the analysis, the grout thickness and compressive strength should be calculated so that the rehabilitated pipe can achieve the required safety factor. This design method can be applied to other pipes such as circular brick pipe and non-circular pipe.

In a study funded by the City of Ottawa and the National Research Council Canada, Zhao and Daigle (2001) investigated the structural performance of a sliplined pressurized water main. A practical method was presented to determine the shared loads and the stresses along the circumference of the sliplined pressurized pipe. It was assumed that both the liner pipe and the existing (host) pipe are concentric, the host pipe has uniform deterioration along the pipe wall, and the liner pipe, host pipe, and grout are within their elastic range of behavior under the expected loading conditions. Moreover, the authors assumed there was no bond between the host pipe and the grout or between the grout and the liner pipe. In the composite pipe, they assumed that each ring acts like a thin-walled ring and there is no gap between the pipe rings. The authors conducted structural load tests to verify the theoretical method they proposed. An old cast iron pipe (an existing pipe with an outside diameter of 13.7 inches) was tested using the two-point loading method (Figure A.21) with or without a HDPE liner pipe (10.7-inch outside diameter). The annulus was filled with a grout made from a mixture of Type 20 cement and Type C fly ash. The water-to-cement ratio of the grout was 0.38, and the compressive strength was 5,018 psi. The grout thickness was ¾ inch. Both the theoretical and experimental results showed that the load-carrying capacity of the water main pipe increased after sliplining. Furthermore, the results showed that with an increase in the grout strength, the proportion of the load shared by the host pipe will decrease (Figure A.22). Eventually, the service life of the sliplined system would increase due to the reduced stress level in the host pipe (Figure A.23).

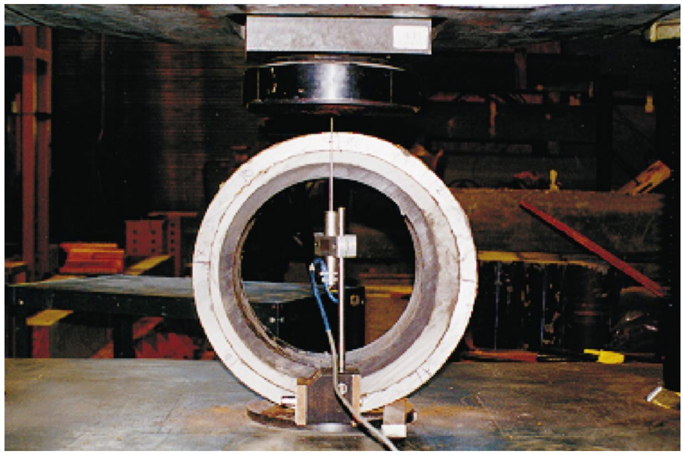


Figure A.21: Two-point loading test of a cast iron–grout–HDPE pipe with three rings (Zhao and Daigle 2001).

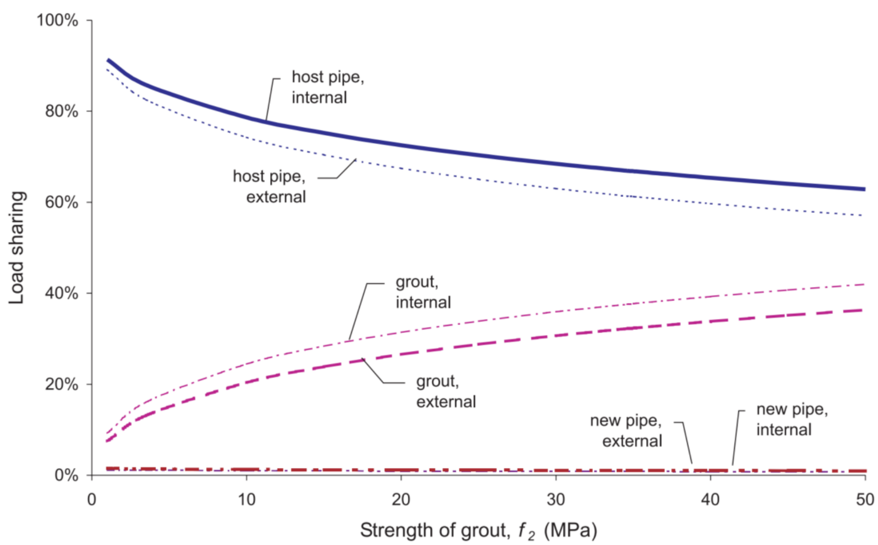


Figure A.22: Effect of grout strength on load sharing (Zhao and Daigle 2001). Unit conversion: 1 MPa = 145 psi.

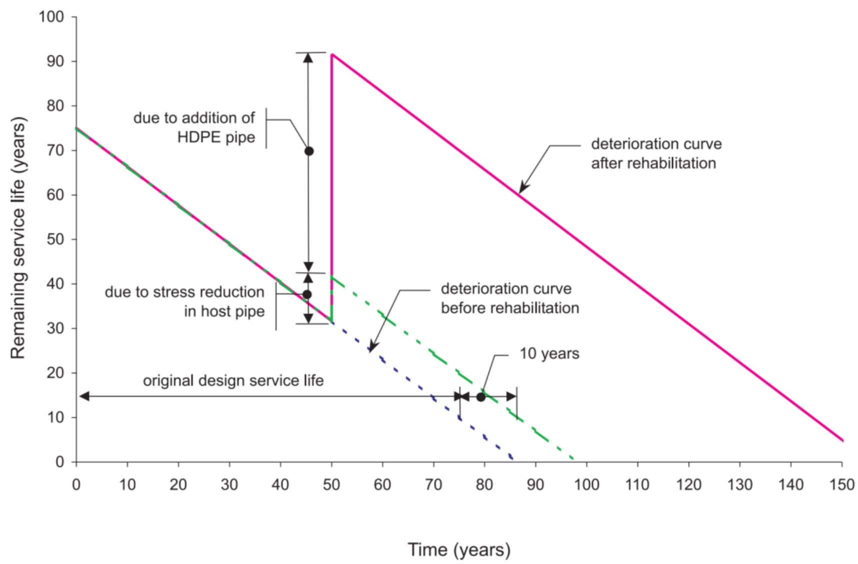


Figure A.23: Schematic deterioration curves of a water main with sliplining (Zhao and Daigle 2001).

In a subsequent study, Zhao et al. (2003) discussed a few more effects of grouts on the long-term and short-term performance of sliplined pipes. They suggested that the use of grouts can increase the buckling resistance of the sliplined pipe. In addition, an increase in grout strength would increase the rupture strength of a composite sliplined pipe (Figure A.24). In an ungrouted pipe, if the host pipe fails suddenly, the fractured pipe may create a point load on the liner pipe (Figure A.25). Annulus voids therefore need to be filled with grout to counter that possibility and to increase the durability of the liner pipe.

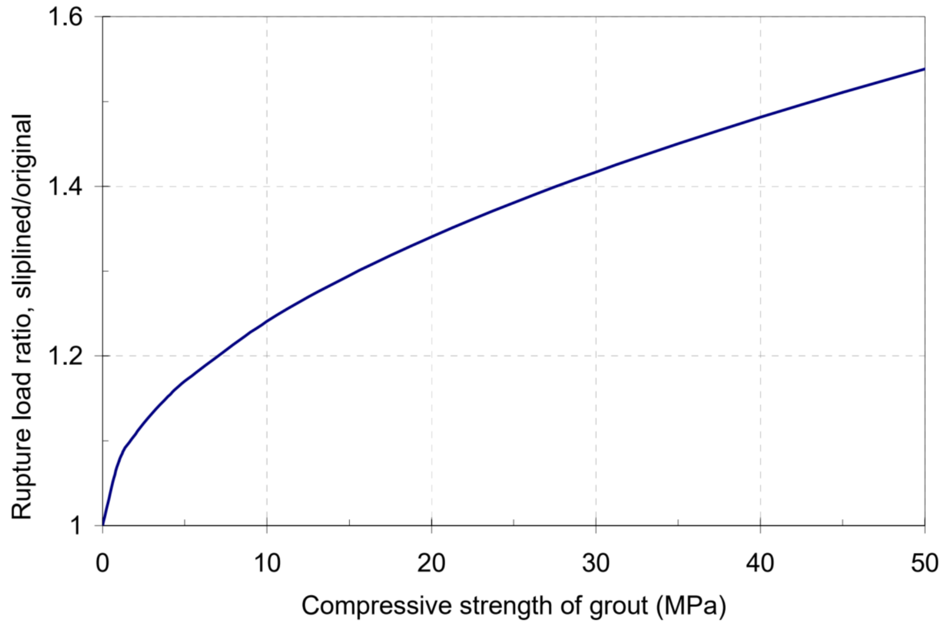


Figure A.24: Effect of grout strength on pipe rupture strength (Zhao and Daigle 2001, Zhao et al. 2003).

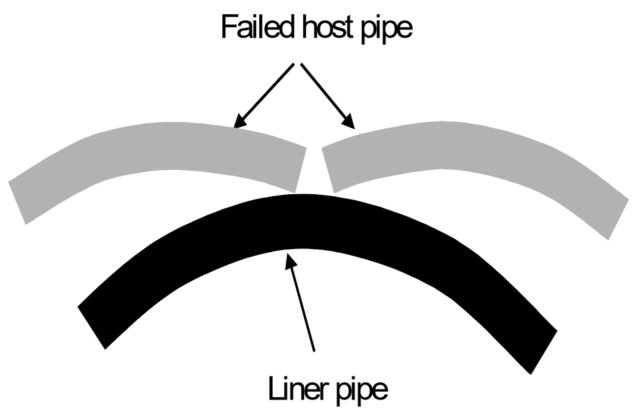
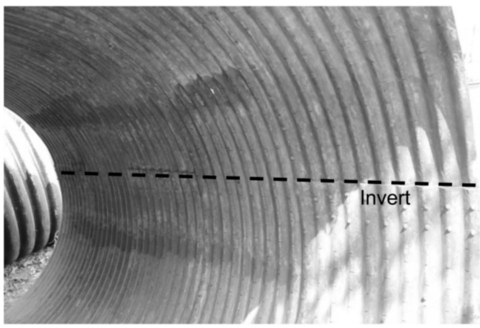


Figure A.25: Point loads of failed host pipe on liner pipe (Zhao et al. 2003).

In a study partially supported by the National Cooperative Highway Research Program (NCHRP) and the Natural Sciences and Engineering Research Council of Canada, Simpson et al. (2015) conducted a full-scale laboratory test on a deteriorated corrugated steel pipe (CSP) covered with soil. A deteriorated corrugated steel pipe (Figure A.26a) and a system rehabilitated by sliplining (RSP), in which the annulus void between the host conduit and a high-density polyethylene (HDPE) liner pipe (Figure A.26b) was grouted using a high-strength grout, were utilized as the specimens for the tests. As can be noticed from the test setup in Figure A.27, two undamaged extension culverts were placed at both ends of a deteriorated CSP pipe section to ensure that the soil cover would extend past the test specimen as well as to minimize the end effects of the embankment walls on the centrally located test specimen. Surface loading tests on the unrehabilitated and rehabilitated culvert and an ultimate limit state surface loading test on the rehabilitated culvert were conducted. The effect of vehicle loading on the pre- and post-rehabilitated culvert was investigated by applying surface loading using a single-wheel pair and single-axle load pads. Preliminary tests were performed on the deteriorated pipe specimen with 35.4″ (900 mm) and 23.6″ (600 mm) of soil cover. After the initial tests, the deteriorated corrugated steel pipe was rehabilitated using high-strength grout made using Type III Portland cement and having a water-to-cement ratio of between 0.50 and 0.55 and an average 28-day compressive strength of 4,480 psi (30.9 MPa). The grout was installed in five lifts so that the grout pressure and buoyant forces on the liner were reduced.



(a) deteriorated corrugated steel pipe

(b) HDPE liner pipe

Figure A.26: Pipe specimens (Simpson et al. 2015).

During the tests, the percentage of vertical diameter change was recorded with the applied load for a pre- and post-rehabilitated of a culvert, as shown in Figure A.28. It was found that the rehabilitation procedure increased the stiffness of the culvert, with the grout annulus providing nearly all of the increased stiffness. The reduction of the deflection was approximately 92%, and the load sharing between the pipe and surrounding soil had changed due to a reduction in the amount of transferred surface load. Figure A.29a and Figure A.29b show the strains at the outer (crest) location and the inner (valley) location, respectively, around the circumference of the corrugated steel pipe. These calculated strains were used to calculate the average strain and were used in subsequent analyses. Two plots from the analysis are presented in Figure A.30. These results indicate a 70% reduction in average strains after rehabilitation of the culvert; the curvature of the post-rehabilitated specimen showed an 83% reduction in strain at the crown and an 86% reduction in strain at shoulder locations. The behavior of the corrugated steel pipe as well as the load sharing between the pipe and the soil was delineated by a reduction in both the average strains and curvatures following rehabilitation.

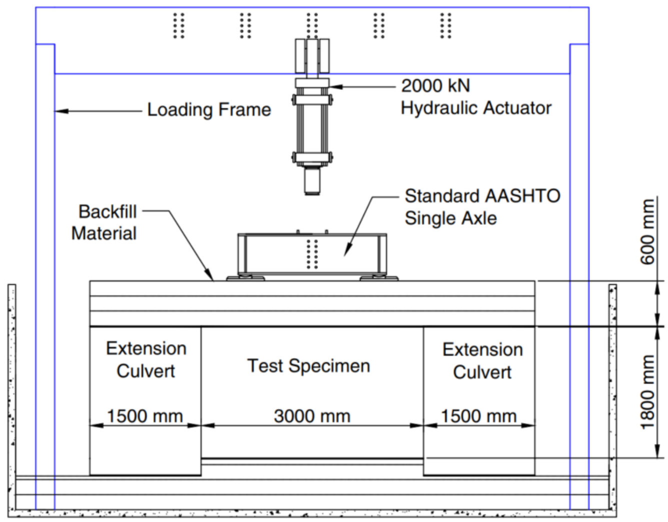


Figure A.27: Test setup from Simpson et al. (2015). Unit conversion: 1,000 mm = 39.37″.

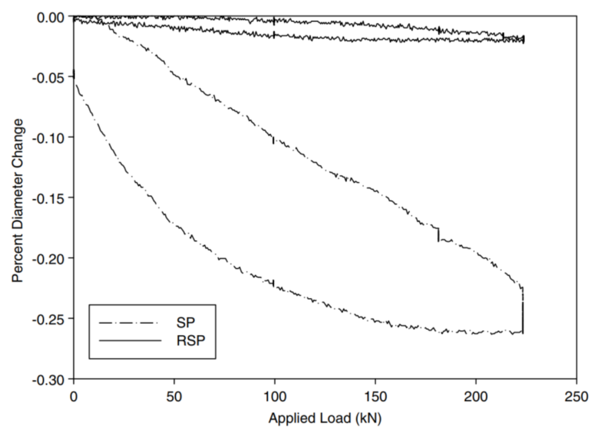
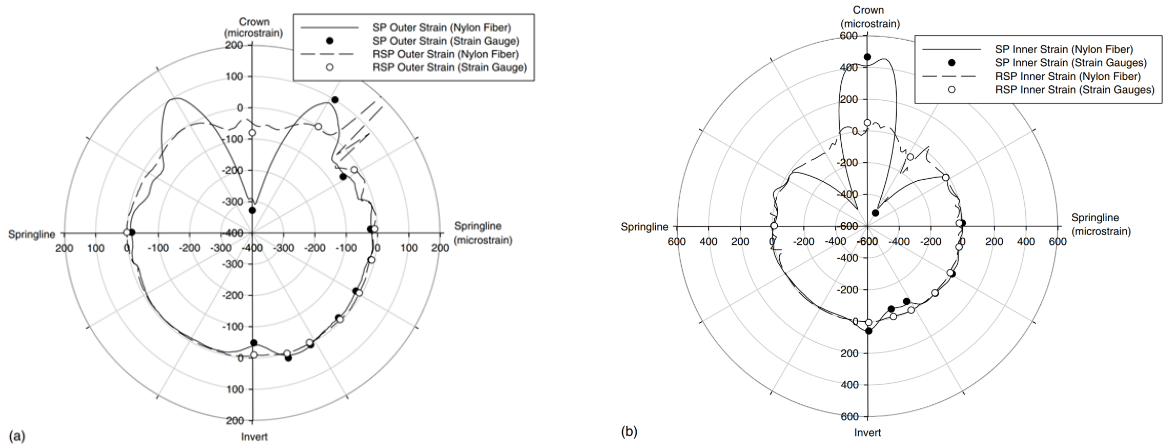


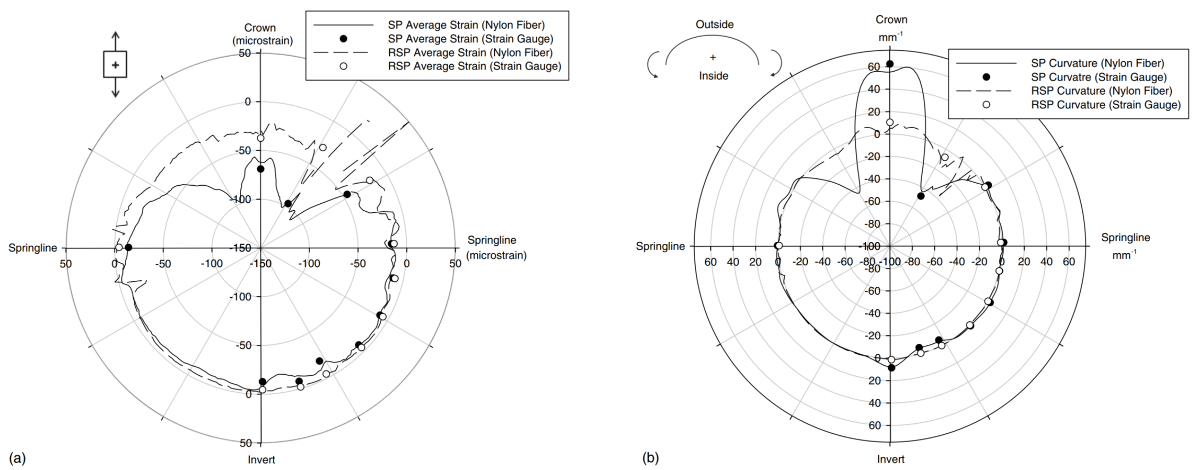
Figure A.28: Vertical diameter change with applied load for the single-axle load configuration pre- and post-rehabilitation (Simpson et al. 2015).
Unit conversion: 1 kN = 224.8 lb.



(a) Outer (crest) measured strains

(b) Inner (valley) measured strains

Figure A.29: Measured strain at the south location at 224 kN (50.4 kips) single-axle load pre- and post-rehabilitation (Simpson et al. 2015).

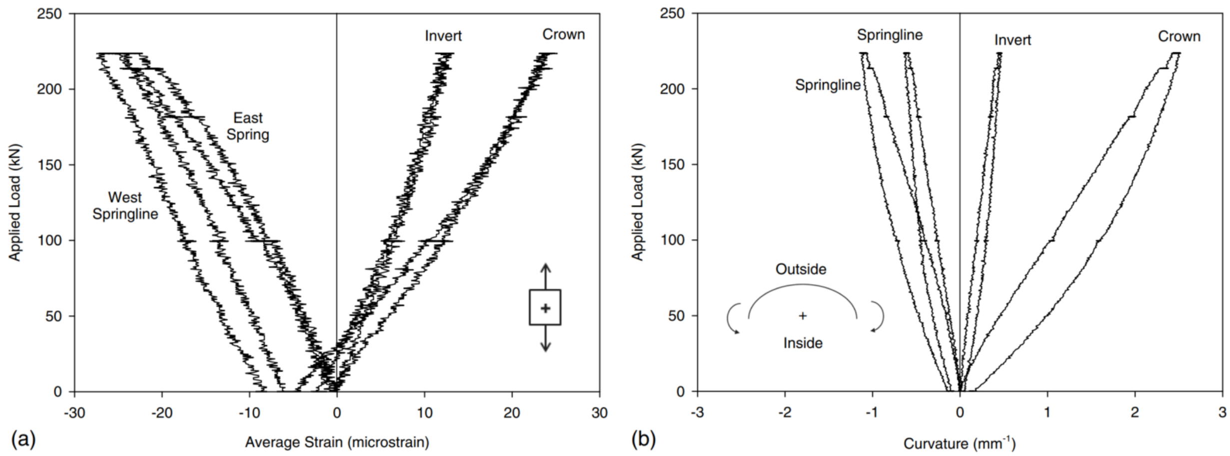


(a) Average strain at the south location during single-axle loading at 224 kN (50.4 kips)

(b) Curvature at the south location during single-axle loading at 224 kN

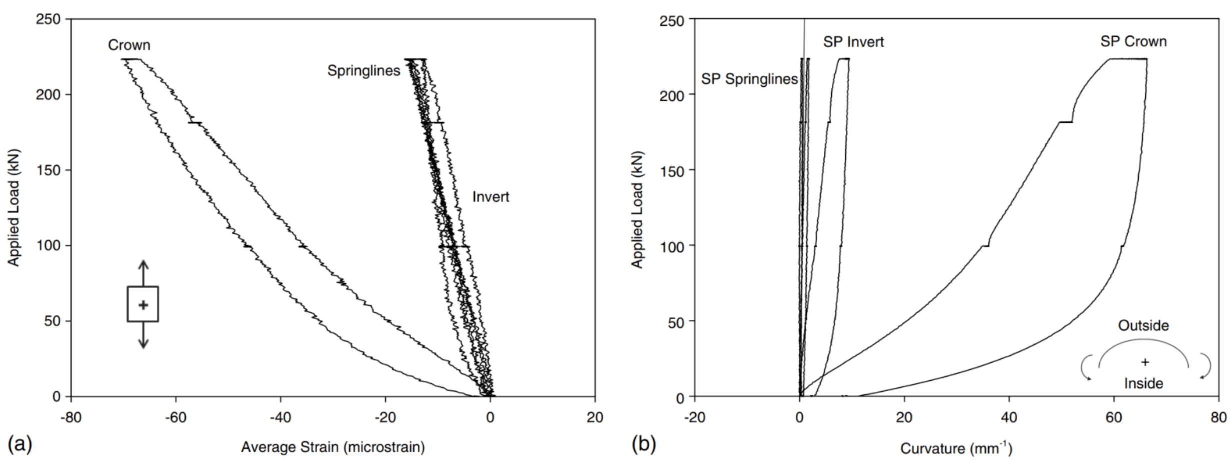
Figure A.30: Comparison of steel pipe response before and after rehabilitation (Simpson et al. 2015).

The authors also studied the overall pipe behavior to understand the load sharing characteristics. A liner pipe can contribute in several ways to the load-carrying capacity of a sliplined culvert system. By acting compositely with the host pipe and the grout, the liner can either carry the surface loads or carry most of the surface load by acting as flexible pipe, or the liner may not act compositely with the grout if the grout is very stiff. The average strain and curvature response for the liner as measured at the crown, spring lines, and invert of the liner pipe are shown in Figure A.31. The average strain and curvature response for the corrugated steel pipe prior to rehabilitation is shown in Figure A.32. A comparison reveals that the strains and curvature response of the liner were considerably lower than those for the host conduit prior to rehabilitation. It was observed that the liner did not act as a part of the composite system due to the use of high-strength grout in the rehabilitation. Additionally, the curvature response of the host pipe and liner were not identical at the crown and invert locations; thus, the bonding of the materials was not perfect. The liner pipe did not have any impact on the load sharing between the host pipe and the surrounding soil. It was concluded from the liner response that while the liner did not increase the structural capacity significantly, it contributed to the restoration of the hydraulic capacity of the rehabilitated culvert.



(a) Average strain (b) Curvature response

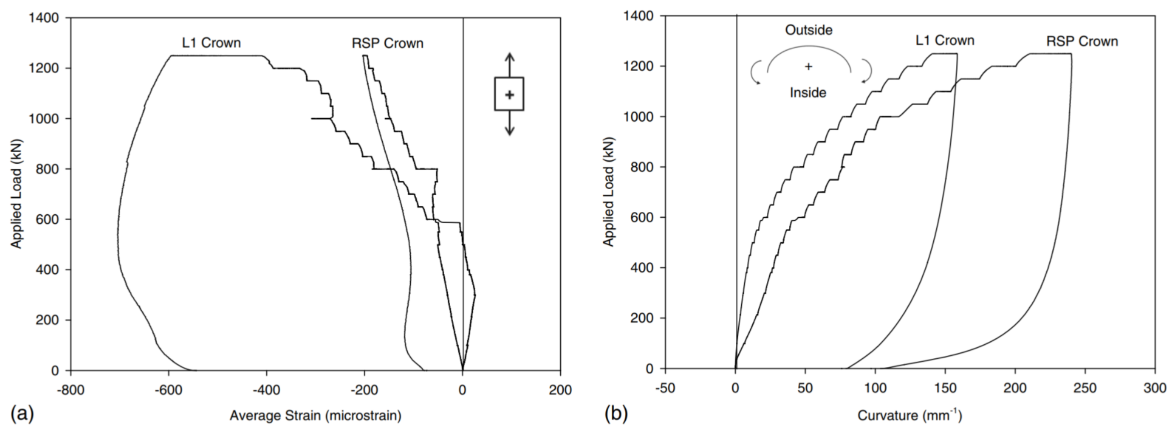
Figure A.31: Response of liner pipe under single-axle loading (Simpson et al. 2015). Conversion factors: 1 kN = 224.8 lb, 25.4 mm = 1 inch.



(a) Average strain response (b) Curvature response

Figure A.32: Response of host pipe (prior to rehabilitation) at the south location during single-axle loading at 0.6 m of cover (Simpson et al. 2015).

Figure A.33 illustrates the response of the rehabilitated steel pipe (RSP) and liner (L1) during the ultimate load test. It was reported that the steel culvert, the grouted annulus, and the liner did not have full interaction and, therefore, the average strains of the host pipe and liner recorded at the crown for the ultimate limit state were different. The figure indicates a significant bending moment in both the rehabilitated pipe and the liner. In the initial portion of the curve, the curvature of the steel host conduit increased in proportion to the liner curvature due to the presence of grout voids at the crown between the corrugations. The grout cracked when the applied load reached 134.9 kips (600 kN), and the curvature of both the liner and the steel culvert subsequently increased. Eventually, the load was distributed to the liner, and the surrounding soil and the bending stiffness at the crown decreased significantly.



(a) average strain (b) curvature response

Figure A.33: Response of rehabilitated steel pipe (RSP) and liner (L1) during ultimate load test (Simpson et al. 2015). Unit conversions: 1 kN = 224.8 lb, 25.4 mm = 1 inch.

The authors drew several conclusions from the research results. The bending across the upper region of the pipe and the thrust across the spring lines were the two dominant load-carrying mechanisms. For the sliplined culvert that was grouted using high-strength grout, the liner did not play much of a structural role. However, this conclusion may not be applicable for applications where low-strength grouts are used. In the design for slipline rehabilitation of a culvert using grout, designers should consider semi-rigid pipe theory instead of a rigid pipe moment. The predicted tensile bending stresses would be very conservative if a rigid pipe approach is used. One of the limitations of this research study was that the authors considered only one culvert rehabilitated using high-strength grout.

In another study supported by the Natural Science and Engineering Research Council of Canada, Smith et al. (2015) performed a series of parallel-plate load tests for evaluating the effect of grout strength on the stiffness and load-carrying capacity of sliplined corrugated steel pipes. Five different types of pipe specimens were tested to capture the behavior of the pipes with and without the grouted slip liner, as shown in the experimental design in Figure A.34. The liners were placed at the center of the existing steel pipes. Grout cylinder tests and two-point loading pipe tests were conducted in this study included two types of cellular grouts: a low-strength grout and a high-strength grout. The mix proportions of the grouts as well as the design compressive strengths are presented in Table A.42. The two-point loading tests were conducted on grouted specimens to negate the effect of a gap at the crown of the pipe due to shrinkage of the high-strength grout (Figure A.35). Figure A.36 shows the test setup that was used to conduct the two-point loading tests.

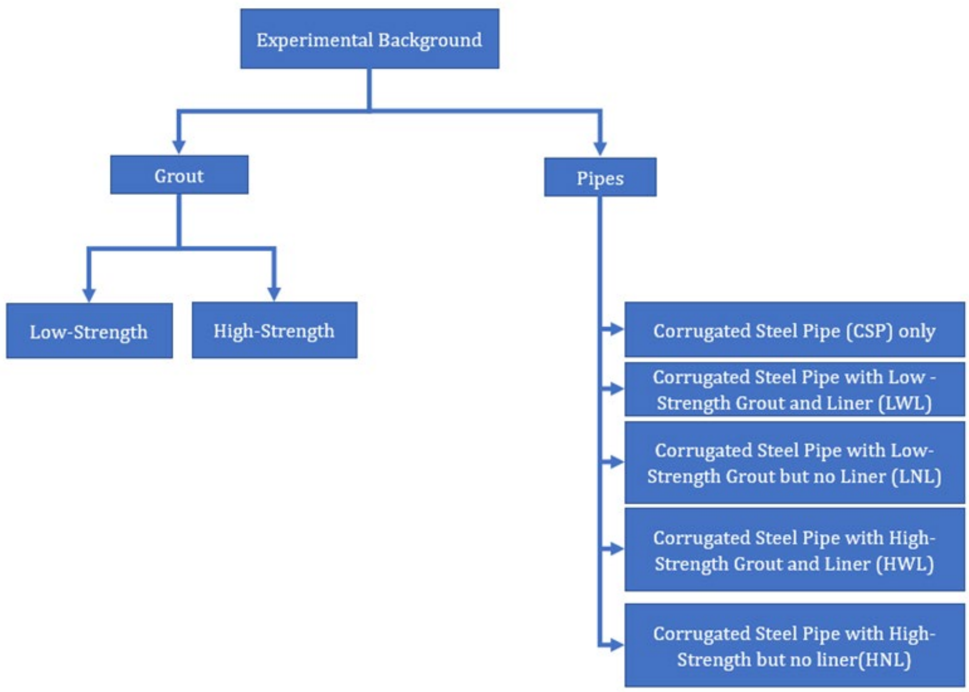


Figure A.34: Experimental Program of Smith et al. (2015).

(a) Shrinkage of the high-strength grout in the rehabilitated specimen.

(b) No apparent shrinkage in the low-strength grout specimen

Figure A.35: Difference in placement of high-strength and low-strength grouts (Smith et al. 2015).

Figure A.36: Two-point loading setup showing the low-strength grout specimen with the liner (Smith et al. 2015).

Table A.42: Cellular Grout Mix Design (Smith et al. 2015)

Mix Type	Cement lb/yd³ (kg/m³)	Sand lb/yd³ (kg/m³)	Water lb/yd³ (kg/m³)	Super-plasticizer oz/yd³ (liter/m³)	Foam (%)	Density lb/yd³ (kg/m³)	Avg. Compressive Strength psi (MPa)
Low-strength	372 (221)	--	622 (369)	--	66	944 (560)	188 (1.3)
High-strength	964 (572)	1,980 (1,175)	632 (372)	28 (1.18)	--	3,168 (1,880)	4,600 (31.7)

The plots for applied load versus diameter change for both the rehabilitated and unrehabilitated pipe are shown in Figure A.37 and Figure A.38, respectively. The results indicate that the change in the vertical diameter of the pipe with high-strength grout and liner (HWL) is larger than the change in the horizontal diameter. This was attributed to the failure mechanism of the grout specimen with the liner. The cracking and plastic hinges started to form at the shoulders, eventually resulting in large deflections at the crown of the pipe.

The rehabilitated pipes showed higher load-carrying capacity than the unrehabilitated pipe, with the rehabilitated steel pipe with the low-strength grout showing a load-carrying capacity that is three times higher than the corresponding unrehabilitated pipe. The use of high-strength grout resulted in a 10-fold increase in the load-carrying capacity of the rehabilitated pipe as compared to the unrehabilitated pipe. Figure A.39 also shows the difference in stiffness of the three different specimens. Initially, the pipe with low-strength grout but no liner (LWL) had higher stiffness than the CSP. However, after the cracking of the annular grout material, the stiffness of the pipe with low-strength grout decreased significantly and eventually became similar to that for the corrugated steel pipe. In contrast, the stiffness of the pipe with high-strength grout was 50 times larger than that for unrehabilitated CSP.

Figure A.40 illustrates the effect of the liner on the rehabilitated specimen based on the plot of the applied load versus the diameter change. The HDPE liner was found to increase the load-carrying capacity of the rehabilitated low-strength grout specimen (LWL) by approximately 60% as compared to the unrehabilitated CSP. Nonetheless, this increase in capacity was not achieved until the diameter change exceeded 8%. Moreover, the HDPE liner did not have any impact on the load-carrying capacity of the pipe with high-strength grout. However, it was able to increase the stiffness of the pipe specimen. Finally, it was concluded that the strength of the grout material has an important role in the behavior of the rehabilitated pipe. Further research work was identified to investigate the impact of lateral soil pressure on the pipe.

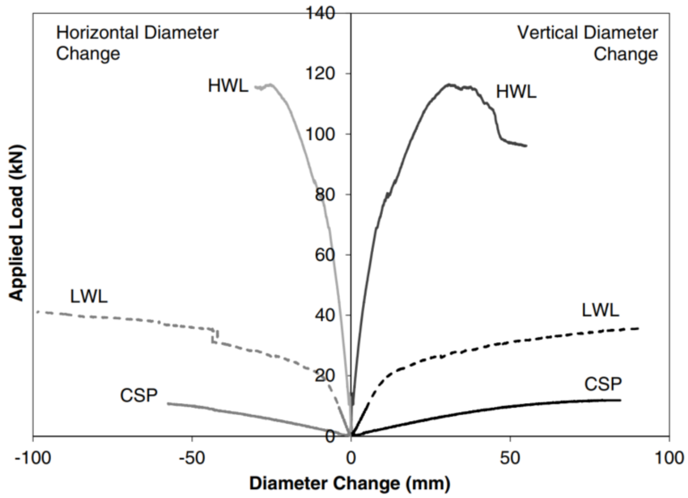


Figure A.37: Applied load versus diameter change for the CSP, LWL, and HWL (Smith et al. 2015)

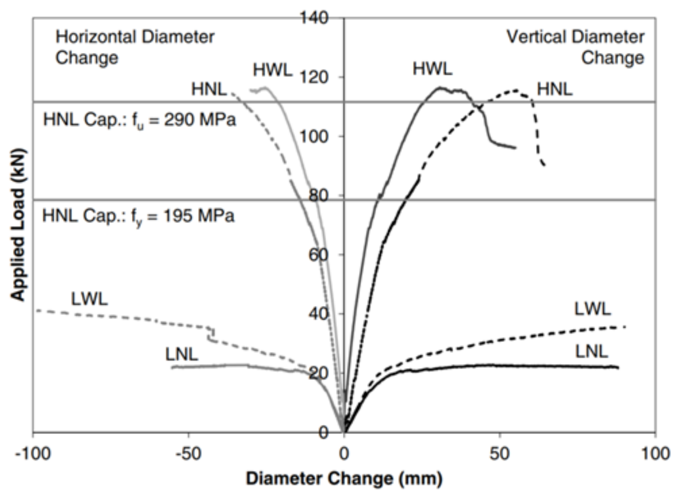


Figure A.38: Applied load versus diameter change for all the rehabilitated specimens (HWL—liner and HNL—without liner) (Smith et al. 2015)

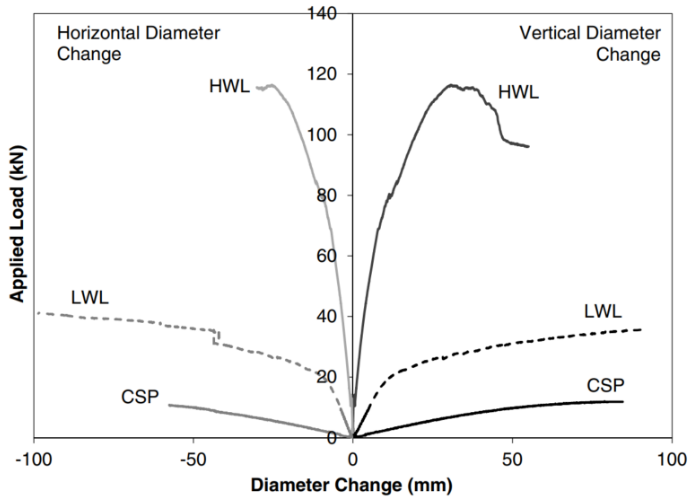


Figure A.39: Applied load versus diameter change for the CSP, LWL, and HWL (Smith et al. 2015). Unit conversion: 1 kN = 224.8 lb, 25.4 mm = 1 inch.

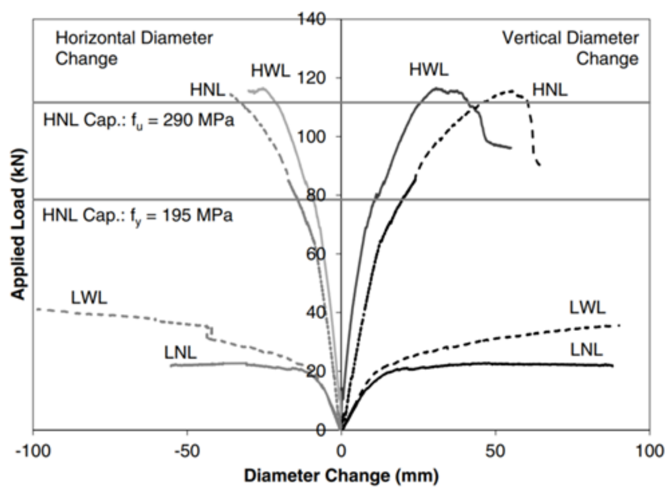
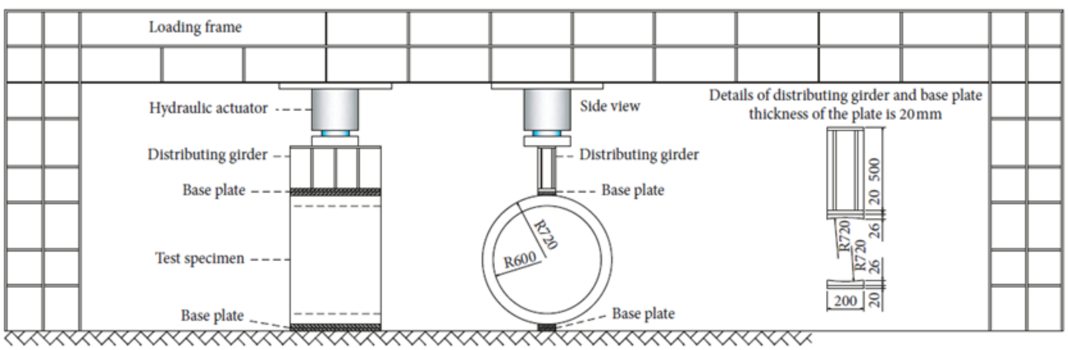
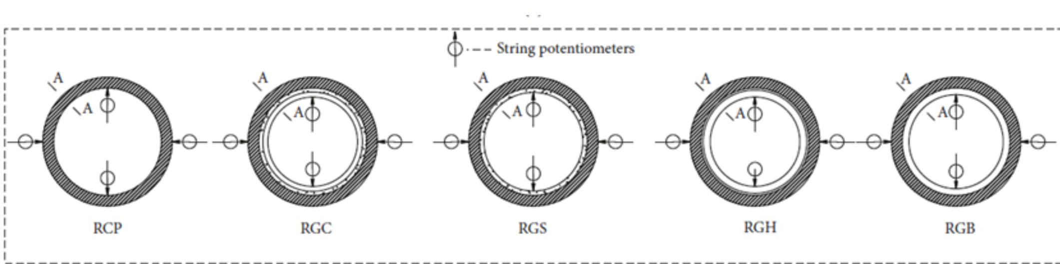


Figure A.40: Applied load versus diameter change for the CSP, LWL, and HWL (Smith et al. 2015). Unit conversion: 1 kN = 224.8 lb, 25.4 mm = 1 inch.

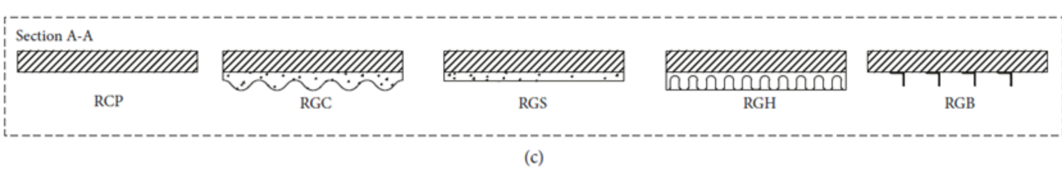
In a study funded by the Science and Technology Support Program of Hunan Province (China), Li et al. (2019) conducted laboratory tests on the load capacity of reinforced concrete pipes that were rehabilitated with different slip liners. The researchers tested five specimens: reinforced concrete pipe (RCP), RCP rehabilitated with corrugated steel pipe (RGC), RCP rehabilitated with a steel pipe (RGS), RCP rehabilitated with an HDPE pipe (RGH), and RCP rehabilitated with a shaped steel bracket (RGB). Two types of grouts were used in this study: C40 concrete with a compressive strength of 7,240 ± 580 psi (49.93 ± 4 MPa) and a modulus of elasticity of 4,710 ksi (32.5 GPa) for RGC and RGS, while a high-performance grouting material with a compressive strength of 12,620 ± 435 psi (87 ± 3 MPa) and an elastic modulus of 5,500 ksi (38 GPa) was used for the RGH pipes. No grout was used for RGB, and the shaped steel bracket was connected directly to the RCP. The loading conditions and section details of the test specimens are shown in Figure A.41. A two-point load was applied to each specimen, as shown in Figure A.42. The applied loads versus the diameter changes for both the unrehabilitated pipe (RCP) and the rehabilitated pipes (RGC, RGS, RGH, and RGB) are shown in Figure A.43. The RCP rehabilitated with CSP showed an increase in load-carrying capacity that was 3.46 times greater than that for RCP, whereas the RCP rehabilitated with steel pipe, HDPE pipe, and steel brackets exhibited increases in the load-carrying capacity that were 1.32, 1.50, and 1.31 times greater, respectively, than that for RCP. A load-sharing mechanism was also proposed in this study, and the results obtained from the theoretical approach matched reasonably well with the experimental results. A comparison between the experimental and theoretical results is shown in Table A.43. The authors reported a maximum difference of 13.4% and a minimum difference of 0.5% between the experimental results and the theoretical predictions.



(a) Longitudinal section



(b) Cross section



(c) Section A-A

Figure A.41: The loading conditions and the specimen details: (Li et al. 2019). Unit conversion: 1 inch = 25.4 mm.

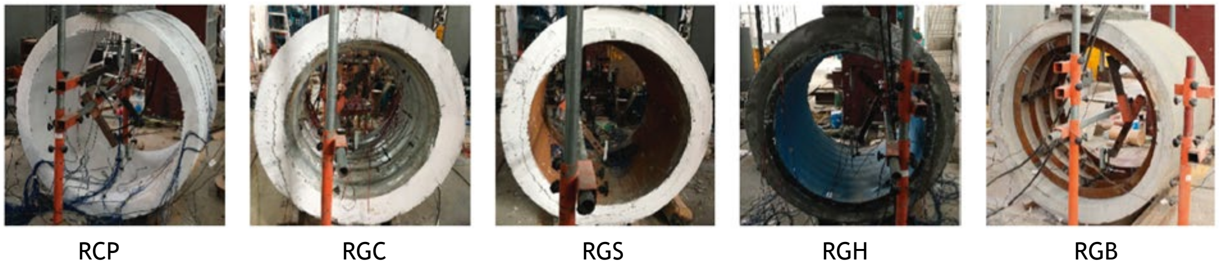


Figure A.42: Specimens used in the two-point loading setup of Li et al. (2019).

The proposed load-sharing theory was based on the compatibility of deformations in the vertical direction. Moreover, the author implied from the crack distributions of the specimens that the RCP, the grout, and the liners act independently. Nonetheless, this study did not consider the effects of the surrounding soil on the reinforced concrete pipe. They suggested that the stresses from the surrounding soil may be considered in future tests rather than the two-point loading stress considered in this study. In the theoretical analysis, it was assumed that cracked grouts cannot carry any load. However, in a practical situation, the friction or a bonding force between the three materials (host pipe, grout, and liner) used in sliplining can affect the load-sharing mechanism of the post-rehabilitated pipe.

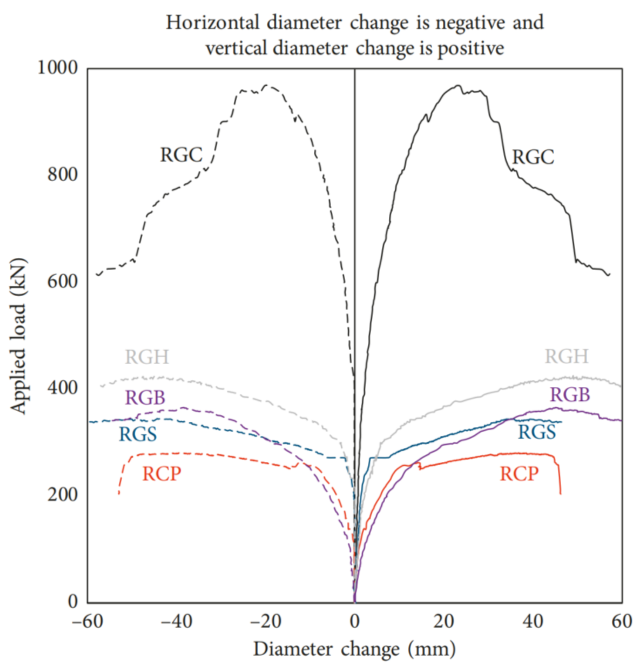
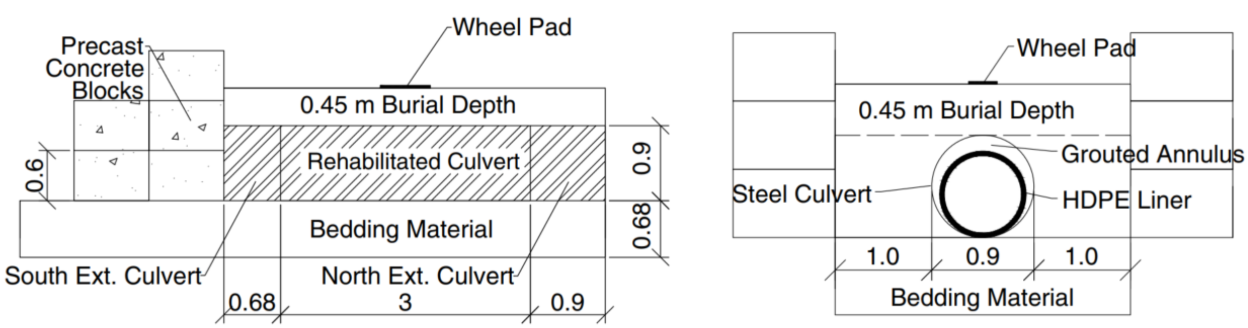


Figure A.43: Applied load versus diameter change (Li et al. 2019).
Unit conversion: 1 kN = 224.8 lb; 25.4 mm = 1 inch.

Table A.43: Comparison of Load-Carrying Capacities (Li et al. 2019)

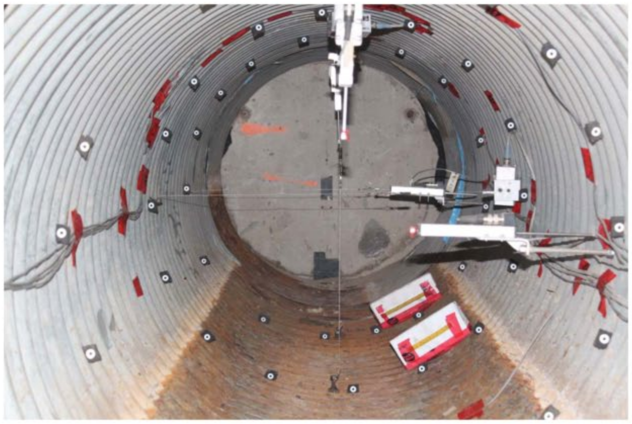
Pipe Ring Type	F_c (Theoretically calculated) kips (kN)	F_t (as Tested) kips (kN)	Percent Difference $\lvert(F_c-F_t)/F_t\rvert$ (%)
RCP	--	62.95 (280)	--
RGC	200.3 (891)	217.6 (968)	8
RGS	87.7 (390)	77.3 (344)	13.4
RGH	94.2 (419)	94.9 (422)	0.6
RGB	82.7 (368)	82.3 (366)	0.5

In a follow-up study sponsored by the Natural Sciences and Engineering Research Council of Canada, Tetreault et al. (2019) conducted laboratory tests to investigate the effect of sliplining on the performance of two corrugated steel pipes with a soil cover. The corrugated steel pipes were repaired using high-density polyethylene (HDPE) slipliners and low-density and high-density grouts. An uncorroded corrugated steel pipe was grouted with a low-density grout having a density of 43 lb/ft^3 (703 kg/m^3) and a compressive strength of 220 psi (1.5 MPa). The corroded corrugated steel pipe was grouted with a high-density grout material having a density of 130 lb/ft^3 (2,135 kg/m^3) and a compressive strength of 2,175 psi (15 MPa). The response of the rehabilitated pipes was measured under service loads, fully factored design loads, and even at a load level higher than the factored design load. The configuration of the test setup is shown in Figure A.44. Each test specimen had a diameter of 35.4″ (0.9 m), a length of 9′-10″ (3 m), and featured corrugations with an amplitude depth of ½″ (12.7 mm). Backfilling was undertaken with poorly graded sandy gravel classified as A1 by AASHTO (2009). A steel plate (wheel pad) measuring 9.84″ × 23.6″ (250 mm × 600 mm) was used to simulate the Canadian Highway Bridge Design Code axle (a pair of wheel loads).

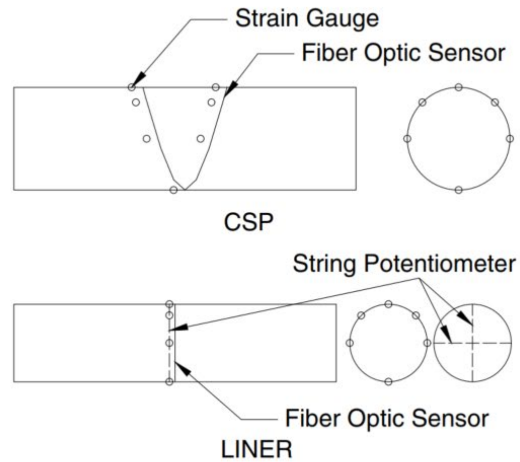


(a) West profile (b) North profile

Figure A.44: Experimental configuration and test instrumentation from Tetreault et al. (2019). Unit conversion: 1 m = 39.37”.



(c) Instrumentation used to examine the corroded pipe response before rehabilitation

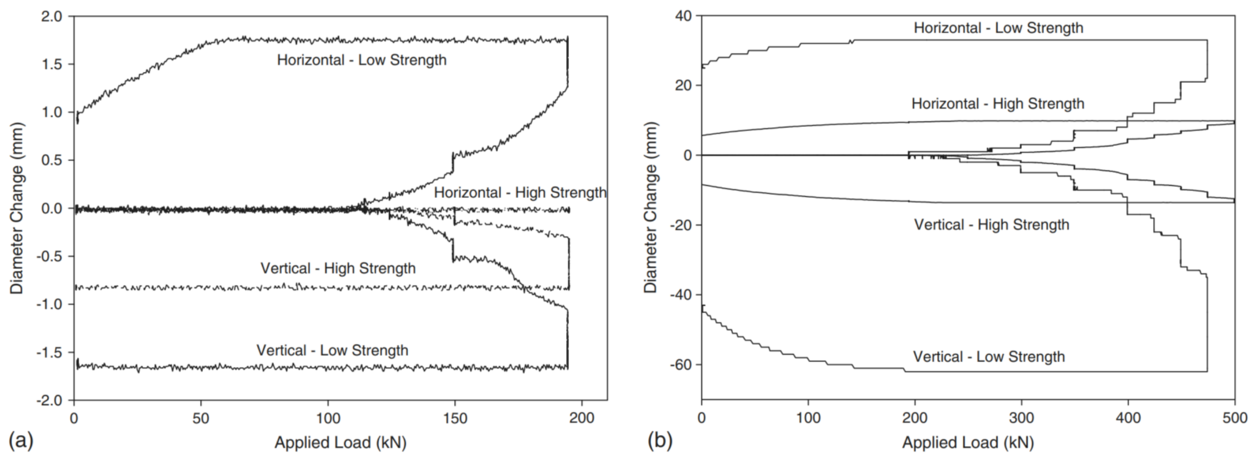


(d) Location of strain gauges and optical fibers in corrugated steel pipe and slipliner

Figure A.44 (continued): Experimental configuration and test instrumentation from Tetreault et al. (2019). Unit conversion: 1 m = 39.37”.

Figure A.45 illustrates the vertical and horizontal diameter change in pipes repaired with low-density and high-density grout with respect to the fully factored loads and the ultimate limit states. Tetreault et al. (2019) found the culverts had higher stiffness and provided better strength than the required load-carrying capacity after rehabilitation. Under full-service loads, both of the rehabilitated culverts experienced smaller deflections (with 0.21% and 0.11% decreases in the vertical diameter, respectively, for the culverts rehabilitated using low-density and high-density grout). Moreover, the curvatures of both culverts were reduced by approximately 90% and 100% after grouting with low-density and high-density grouts (Figure A.46). The strains at the crowns for both culverts were reduced by almost 65%.

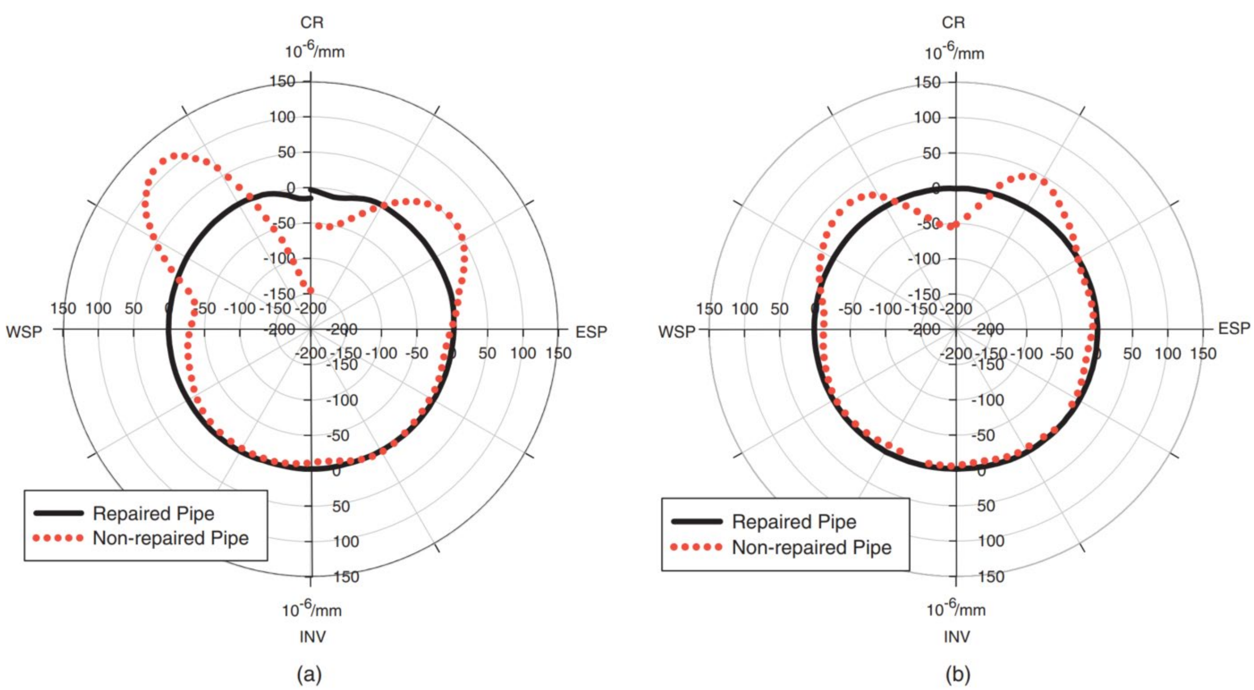
The authors made several conclusions based on the analysis of the strain and curvature of corrugated steel pipes under different loading conditions. When low-density grout is used, the liner material provides structural support to the system; however, when high-density grout is used, the liner response is dictated simply by the strains of the inner surface of the grout ring. The pipe sliplined using low-density grout behaved like a rigid body during service loading but behaved like a flexible pipe at higher loads. Filling the annulus void with low-density grout increased the bending stiffness; under service loads, it resulted in zero deflections. The pipe sliplined using high-density grout behaved like a rigid pipe during both the service load and ultimate load tests. The high-density grout also increased the bending stiffness, and the resulting deflections were negligible.



(a) Fully factored loads

(b) Ultimate limit states

Figure A.45: Vertical and horizontal diameter change in pipes repaired with low-density and high-density grout (Tetreault et al. 2019).



(a) Low-density grout

(b) High-density grout

Figure A.46: Curvature changes under a pair of 16-kip (71.2-kN) wheel loads around the steel pipes repaired with low-density grout and high-density grout (Tetreault et al. 2019). Unit conversion: 1 kN = 224.8 lb, 25.4 mm = 1 inch.

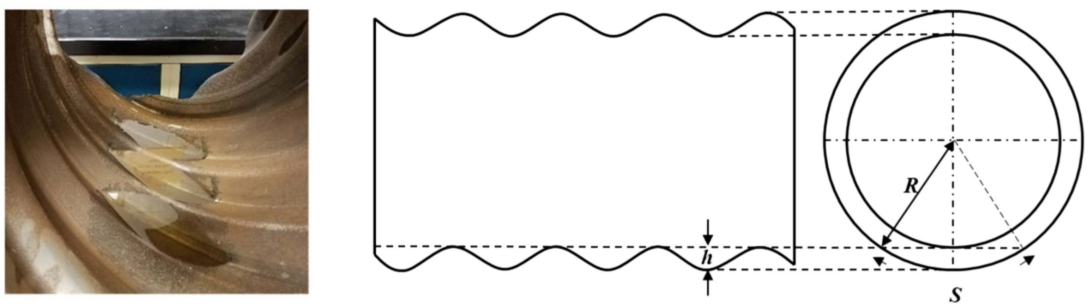
Figure A.47 shows cross sections of corrugated steel pipes that were repaired using low-density and high-density grouts in the annulus, after the pipes were cut into segments upon exhumation. Figure A.47a shows the extensive shear cracks that developed in the annulus filled with low-density grout. The low-density grout began to fail after significant deflections developed at loads much higher than the failure load. The authors observed shear failure and crushing due to the reduced stiffness and erratic strain distributions. Figure A.47b shows the failure mode of the high-density grout, where tensile fracture developed at the crown as well as at locations just above the springline.

The authors also investigated the distribution of hoop strain through the liner–grout–steel pipe system. The system repaired using high-density grout showed composite behavior in some sections, while the system repaired with low-density grout exhibited non-composite behavior. At full-service loads, the strain measurement in the low-density grout adjacent to the liner exhibited a loss of bonding between the liner and the grout. In contrast, the liner was able to bond well when high-density grout was used. The authors recommended that further research should be conducted to gain a better understanding of the strains, curvatures, and interactions between the three components (host conduit, grout, and liner) in the sliplining system.

(a) low-density grout (b) high-density grout

Figure A.47: Cross-sectional views after test to failure of sections of exhumed samples that were directly under the loading pad (Tetreault et al. 2019).

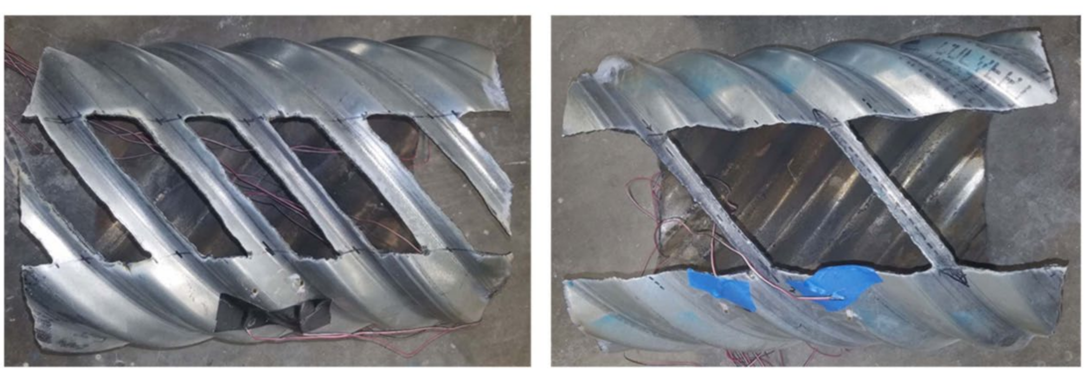
Rahmaninezhad et al. (2019) evaluated the effect of PVC liners on the behavior of rehabilitated corroded corrugated steel pipes for the Kansas Department of Transportation (KDOT). They examined the load-carrying capacity and stiffness, the vertical and horizontal diameter changes, and the average strains and curvatures of the pipes using a universal testing machine to perform a series of parallel plate loading tests. The pipe sections, which conformed to ASTM D2412, had a nominal inside diameter of 12″ (305 mm) and a length of 18.1″ (460 mm). In this investigation, different degrees of corrosion of the steel pipe were simulated (0%, 50%, and 90%). Because water is usually trapped between two consecutive crests on the inside of the pipe along the invert (Figure A.48), the trapped water can eventually cause an increase in the rate of steel corrosion. This simulation was performed by trimming the pipe along the invert (Figure A.49). Moreover, the authors used a low-strength grout with 36 psi (249 kPa) 7-day compressive strength as well as a normal-density grout with a density of 130 lb/ft^3 (2,126 kg/m^3). The mix proportions for the grout comprised 98 lb/yd^3 (59.3 kg/m^3) of cement, 293 lb/yd^3 (178 kg/m^3) of fly ash, 2,540 lb/yd^3 (1,543 kg/m^3) of sand, and 571 lb/yd^3 (347 kg/m^3) of water. The test setup used in this study is shown in Figure A.50 for three different series of tests. Series A tests included tests on steel pipes without a liner with 0%, 50%, and 90% cutouts; Series B tests included sliplined steel pipes with a liner on the invert and 0%, 50%, and 90% cutouts; and Series C tests comprised sliplined steel pipes in intact condition with 0% cutout and with a liner that was concentric with the host pipe). A larger load was carried by the grout when the liner was concentric to the host pipe than when the liner was placed off-center with its bottom in contact with the invert of the host pipe.



(a) Water remaining inside the corrugated pipe

(b) Schematic cross sections of corrugated steel pipe

Figure A.48: Possible corrosion area (Rahmaninezhad et al. 2019).



(a) 50% cutout

(b) 90% cutout

Figure A.49: Corrugated steel pipes with simulated corrosion (Rahmaninezhad et al. 2019).

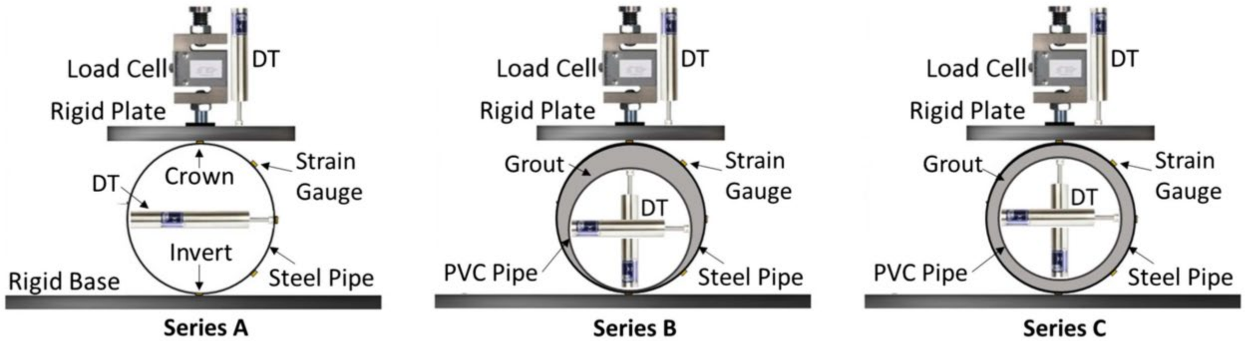


Figure A.50: Test configurations for the parallel plate loading tests (Rahmaninezhad et al. 2019).

The curves representing the applied load versus diameter change for the steel pipes in each series are presented in Figures A.51 and A.52. The results show that the sliplined steel pipe with the highest degree of cutout (90%) had a lower load-carrying capacity than the pipe with the lowest degree of cutoff (0%). Furthermore, the load-carrying capacity of the rehabilitated steel pipes with 0% and 50% cutouts were increased relative to the unlined pipes. However, in the pipe with the 90% cutout, the load-carrying capacity did not increase because the culvert acted as an arch structure. The placement of the liner did not have an impact on the load-carrying capacities or the diameter changes (vertically and horizontally) in the three series of tests. The authors concluded that drainage performance of the rehabilitated pipe may improve practically if the liner is placed so that that bottom of the liner is close to the host conduit invert rather than when it is placed so that it is concentric with the host pipe, as a larger load was carried by the culvert section when the liner was placed concentrically rather than eccentrically. Apart from that, grouted culvert sections carried higher loads when the steel pipe was sliplined with a 0% cutout rather than a 50% cutout.

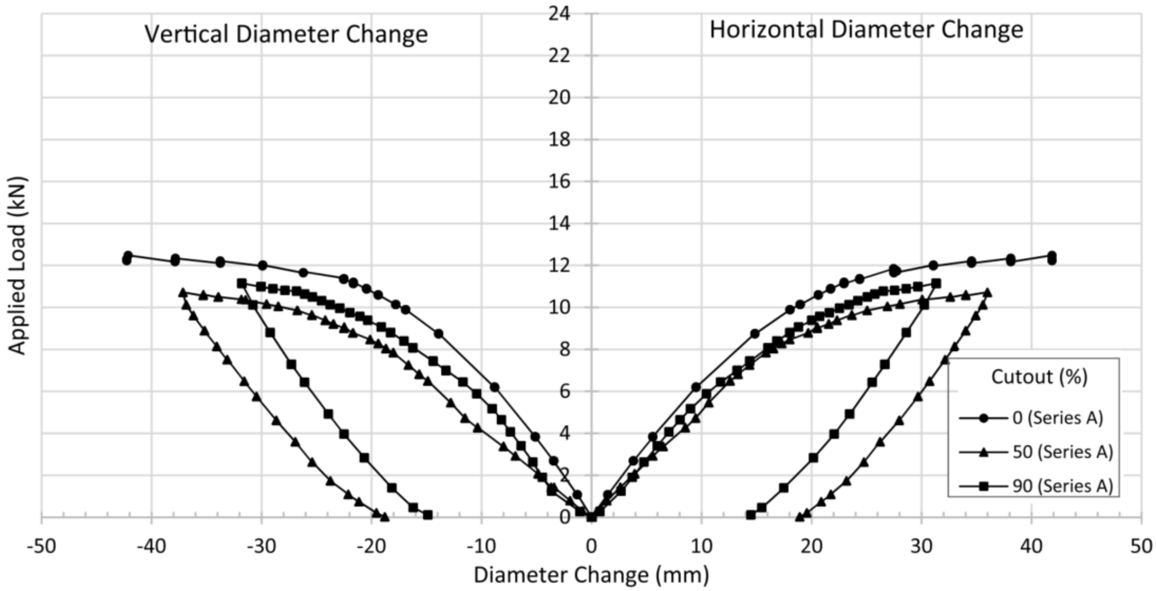


Figure A.51: Applied load versus vertical and horizontal diameter changes in Series A (Rahmaninezhad et al. 2019).

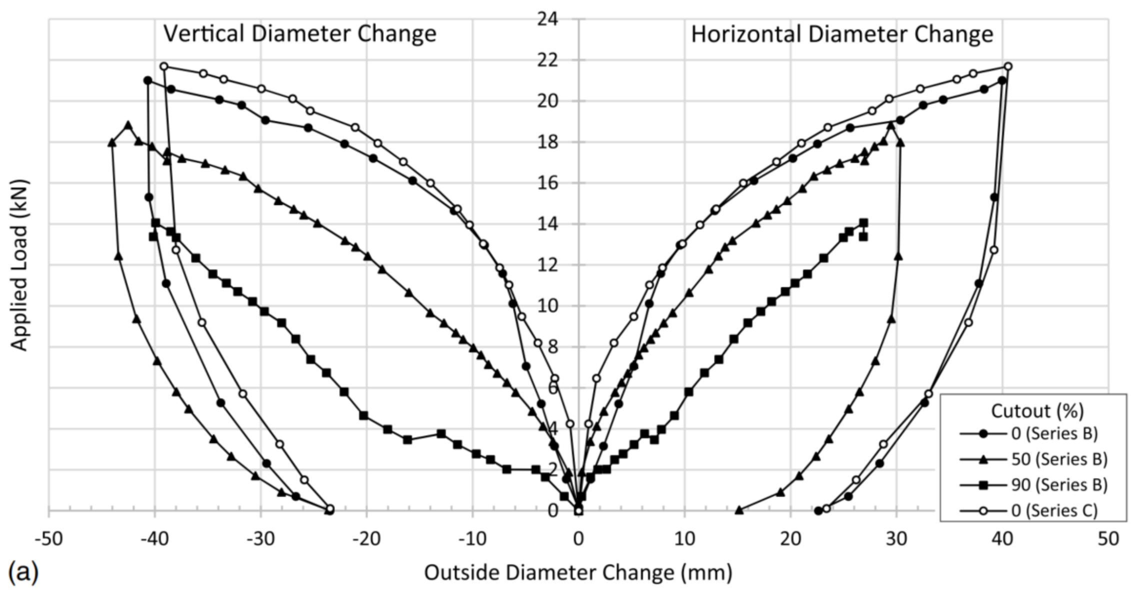


Figure A.52: Applied load versus vertical and horizontal outside diameter changes in Series B and Series C (Rahmaninezhad et al. 2019).

Strain gauges were attached to the valleys and crests of corrugations in the steel pipe to measure the strains in the test specimens. Large bending moments were developed in the springline region and at the crown of unlined steel pipes having 0% and 50% cutouts. Nevertheless, the authors did not observe significant bending moments for unlined steel pipes having 90% cutouts because of the arch effect of the pipe. Further studies were suggested in order to examine the behavior of corrugated steel pipes in soil.

In a subsequent investigation sponsored by the Kansas Department of Transportation (KDOT), Rahmaninezhad et al. (2020) conducted a field study to investigate the performance of a highly corroded corrugated steel pipe after it was rehabilitated by sliplining. The objective of this study was to perform a series of truck loading and plate loading tests on a steel conduit before and after rehabilitation. The study included an investigation of the load-carrying behavior and stiffness, vertical and horizontal diameter changes, average strain and curvature of pipes, and displacement of the pavement surface.

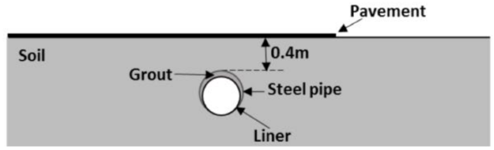
The authors selected a corroded corrugated steel pipe located at a T-intersection on the North 482 Road and East 1250 Road (Old 59 Highway) in Douglas County, Kansas. The entire wall thickness along the invert of the pipe was disintegrated due to corrosion (Figure A.53a). After complete removal of the pipe from the soil, the corroded pipe was placed at a shallow depth of 15.75″ (400 mm) under an asphalt pavement. A high-density polyethylene pipe (HDPE) was used as the liner pipe (Figure A.53b), and the annulus void was filled with a low-viscosity grout. The mix proportions of the grout were 418 lb/yd^3 (254 kg/m^3) of cement, 632 lb/yd^3 (384 kg/m^3) of fly ash, and 810 lb/yd^3 (492 kg/m^3) of water. The grout exhibited average 7-day and 28-day compressive strengths of 390 psi (2.7 MPa) and 740 psi (5.1 MPa), respectively. The annular space between the liner and host pipes was grouted in a single lift by using a gravity grouting process (Figure A.53c). Wooden blocks were placed as spacers above the liner at both ends of the corrugated steel pipe to prevent uplift of the liner pipe resulting from buoyancy due to grouting. An insulating foam sealant was used to prevent the grout from flowing out of the pipe. Figure A.54 presents a schematic diagram of the cross sections of North 482 Road.

(a) Corroded corrugated steel pipe

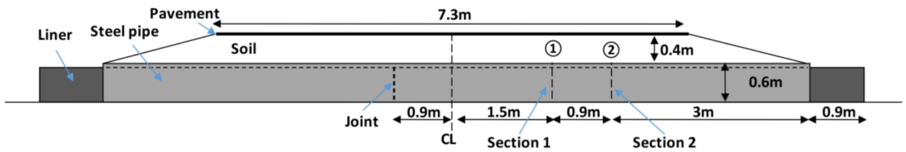
(b) Installing the HDPE liner

(c) Grouting the annulus space between the HDPE liner and the host pipe

Figure A.53: Sliplining procedure used in Rahmaninezhad et al. (2020).



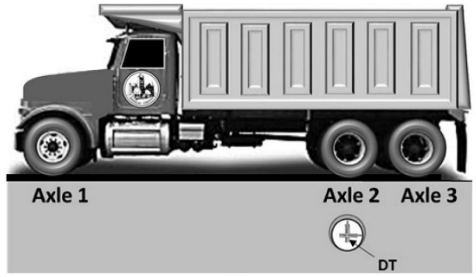
(a) Across the length



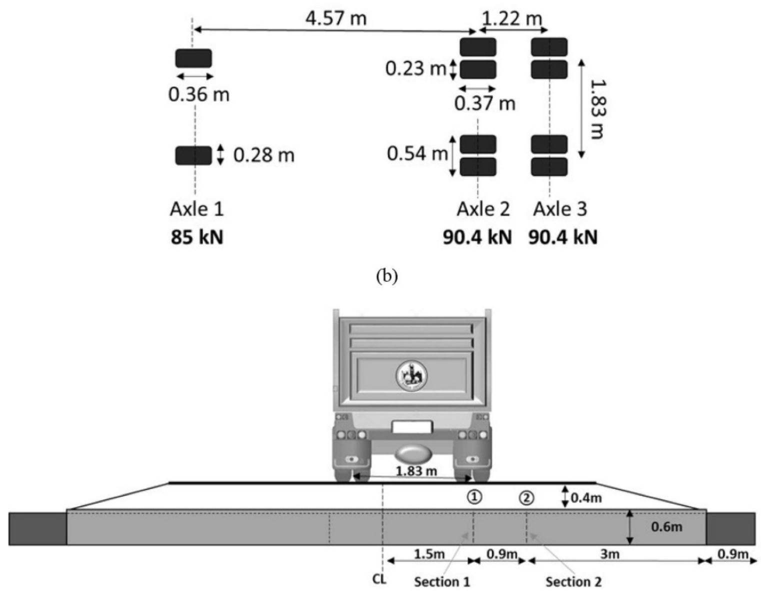
(b) Across the width

Figure A.54: Schematic view of the cross sections of the North 482 Road, Douglas County, Kansas, USA (Rahmaninezhad et al. 2020).

Figure A.55 and Figure A.56 show the test setup for the truck loading test and the plate loading test, respectively. The authors assumed that the measured vertical diameter changes in the liner would be the same as the vertical diameter changes of the steel pipe after rehabilitation based on the results of their previous study (Rahmaninezhad et al. 2019). The results (Figure A.57) demonstrated that the vertical diameter changes of the corroded steel pipe were reduced by approximately 78% and 82% after 7 and 28 days of grouting, respectively. The strains measured on the liner were smaller than 0.02%, which indicated that most of the distributed vertical load was carried by the steel pipe and the grout.



(a) Dump truck and axles



(b) Axle configuration and load

Figure A.55: Truck loading test setup (not to scale) (Rahmaninezhad et al. 2020).

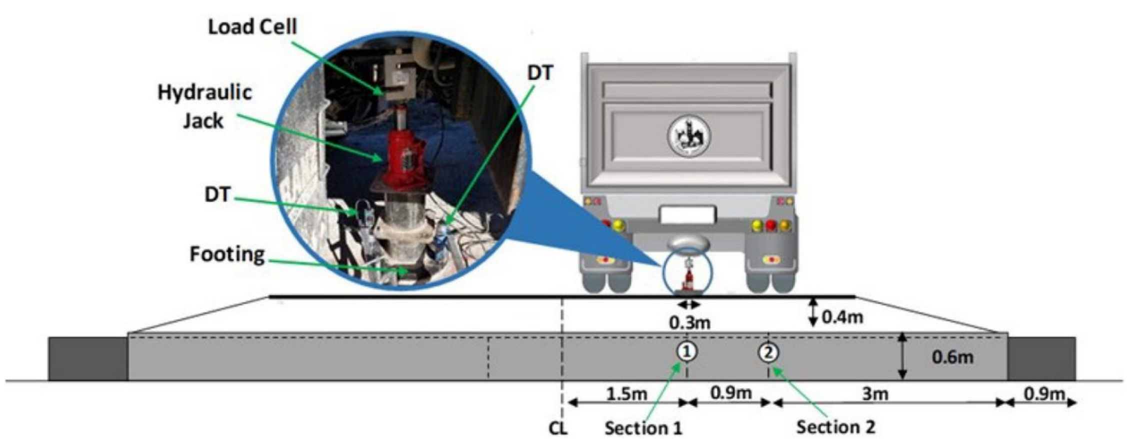


Figure A.56: Plate loading test setup (not to scale) (Rahmaninezhad et al. 2020).

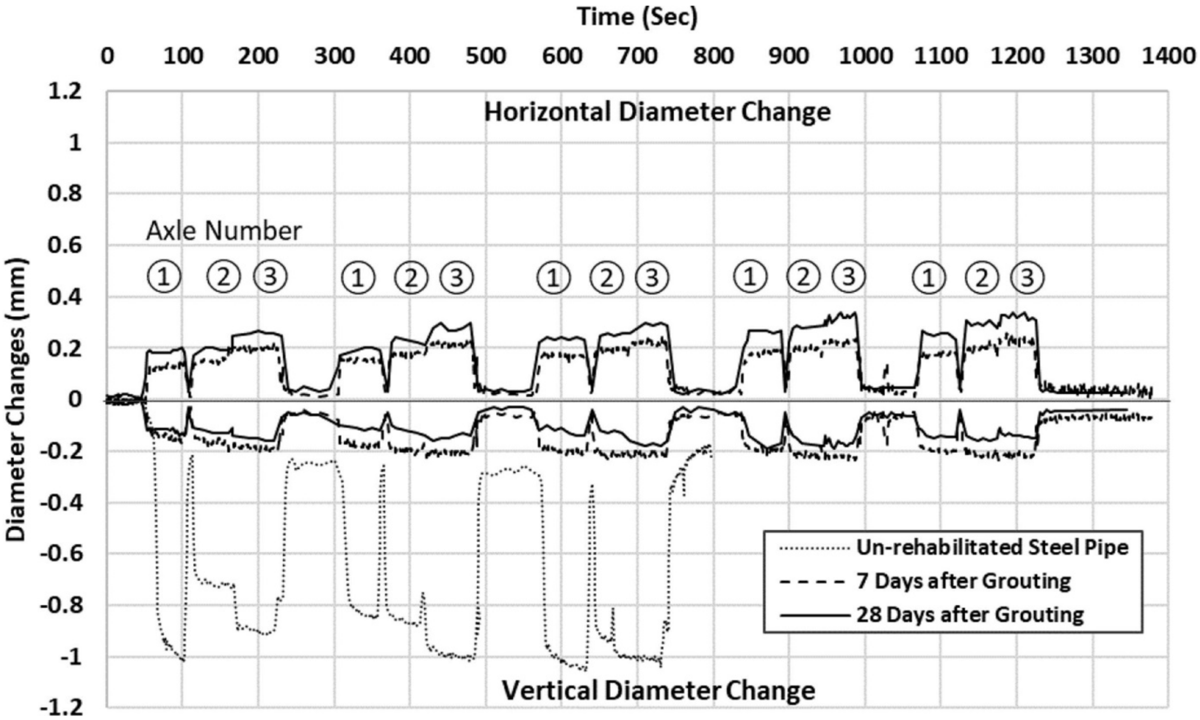


Figure A.57: Vertical and horizontal diameter changes versus time for Section 1. (Rahmaninezhad et al. 2020).

The results of the plate load test (presented in Figures A.58 and A.59) reveal that the displacement of the pavement was reduced by 6% and 31%, respectively, after 7 and 28 days of grouting compared the displacements before rehabilitation. Moreover, the figure indicates that after the rehabilitation by sliplining, the steel pipe showed stiffer behavior than before rehabilitation. The vertical diameter changes were reduced by 87% and 90%, respectively, at 7 and 28 days after sliplining rehabilitation. In addition, the load-carrying capacity of the corroded corrugated steel pipe was increased by 300% due to the sliplining rehabilitation.

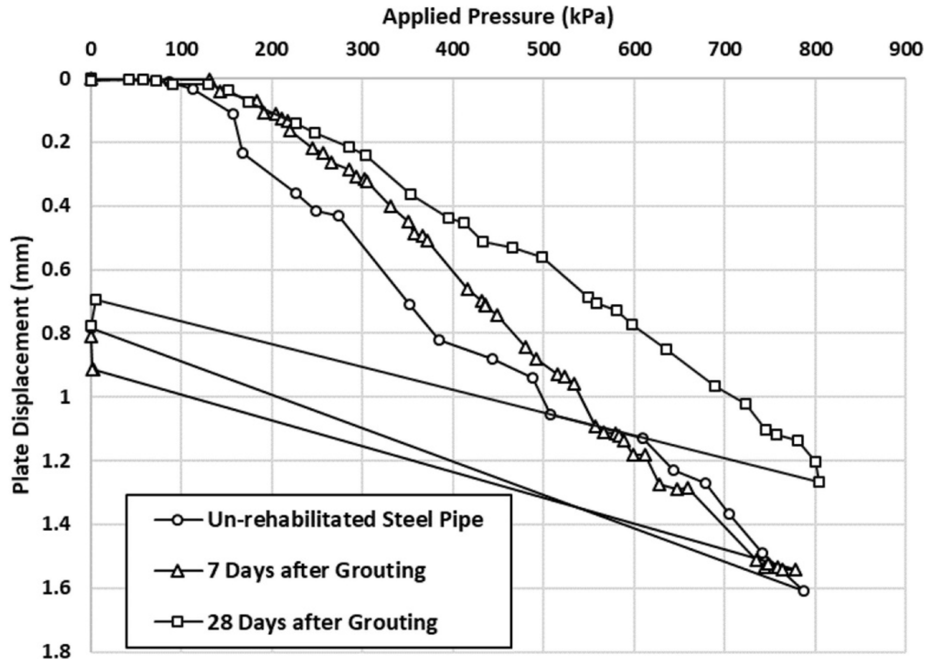


Figure A.58: Pressure–displacement curves in plate tests (Rahmaninezhad et al. 2020).

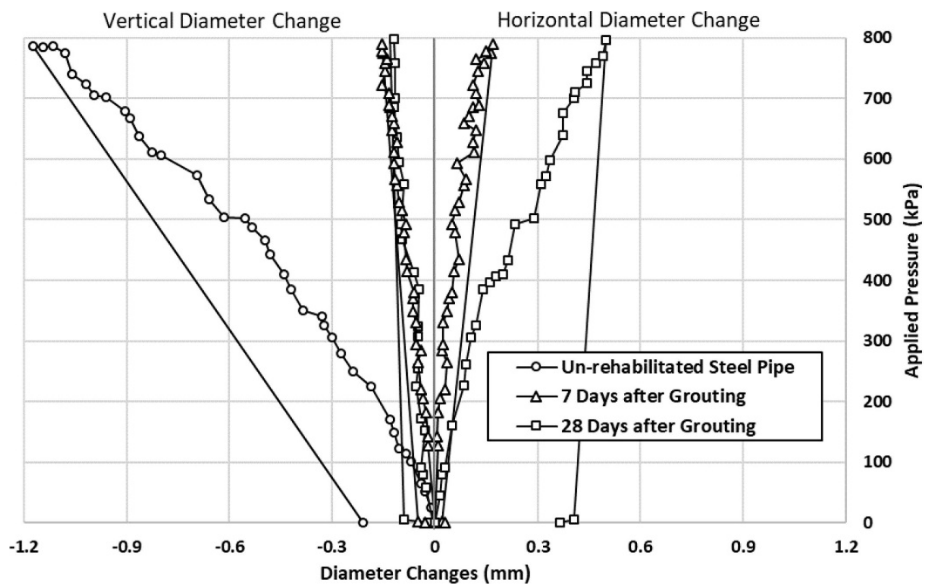


Figure A.59: Applied pressure versus vertical and horizontal pipe diameter changes (Rahmaninezhad et al. 2020).

A.8.3 Summary of Research by State and Local Agencies

This section summarized research studies on the effect grout materials on a sliplined pipe. Several recent studies, such as Simpson et al. (2015), Smith et al. (2019), and Rahmaninezhad et al. (2019, 2020), examined the effect of grouts on the load-carrying capacity of rehabilitated pipes. Future research work based on these studies needs to be conducted.

A.9 Verification Methods to Confirm Grout Filling and Effectiveness

A.9.1 Introduction

In the culvert industry, a simple sounding test using a hammer is the most commonly used and universally accepted verification method for detecting voids in the annular space of a culvert. While this method is not sophisticated, it is a rapid and inexpensive method that can be used to detect voids by unskilled or semi-skilled personnel. However, it has frequently been reported that this method gives a false assessment and is dependent on several factors that are outside the control of the inspector. This section provides detailed information on a few sophisticated methods reported in the literature that may be specifically applied to detect voids and verify the complete filling of grout in the annular space.

A.9.2 Verification Methods

The presence of voids within grout has traditionally been detected by drilling holes along the crown of the lined tunnels at locations where voids in the grout are most likely to occur. While such probe holes can readily locate unfilled voids in the vicinity of the holes, they do not reveal the extent of the voids or the distribution of voids at other locations. Another traditional way to detect voids is by cutting cores at locations where voids are suspected. This method is destructive and, similar to probe holes, the voids detected through coring are not representative of the larger extent or distribution of voids at other locations (Karlovšek et al. 2012).

Anderson and Bowles (2012) evaluated the potential of using backscatter computed tomography (BCT) to measure the extent of voids and the culvert's structural condition before decisions are made on whether or not the culvert needs to be rehabilitated, repaired, or replaced. In their pilot study, three culverts were selected by the City of Toronto for performing BCT inspections.

The authors found that BCT can be used to examine a structure by employing a beam of gamma rays and measuring the backscatter radiation. They reported that the BCT technique can be applied to inspect buried infrastructure from only one side for almost any culvert material. Snapshots through the culvert wall into the surrounding backing material can be provided by implementing a BCT probe, and the resulting images can reveal voids in the annular space. In their study, the researchers employed a three-part inspection methodology consisting of visual inspection, acoustic inspection, and BCT imaging. An inspection map for a culvert is presented in Figure A.60.

A total of 11 features can be assessed by visual inspection. Some of the features identified by Anderson and Bowles are the pavement, embankment, abutment, and deterioration. The knock test or acoustic inspection can determine the extent of the voids suspected within the pipes in a subjective manner. In this manner, the suspected voids can be rapidly and inexpensively identified. After performing visual and acoustic inspection, the authors selected an area for diagnosis using BCT imaging based on the information from previous two inspections (visual and acoustic). The BCT scanner can be positioned against the culvert wall, and an area of up to 12” of per position can be imaged and assessed in real time. The resulting BCT images provide a cross-sectional view behind the culvert wall.

Figure A.61 shows a sample BCT image where the front side or the accessible side of the culvert wall is indicated along the y-axis, and the x-axis represents the width of the cross-sectional BCT image. The example shown in Figure A.62 represents an image that was captured at a visible void section at the inlet end of the culvert on the south wall. The bottom of the image indicates the visible corrugated steel wall, the dark gray regions in the image indicate voids of approximately 5” to 9” in width, and the gray regions with a width of approximately 9” to 12” represent the soil.

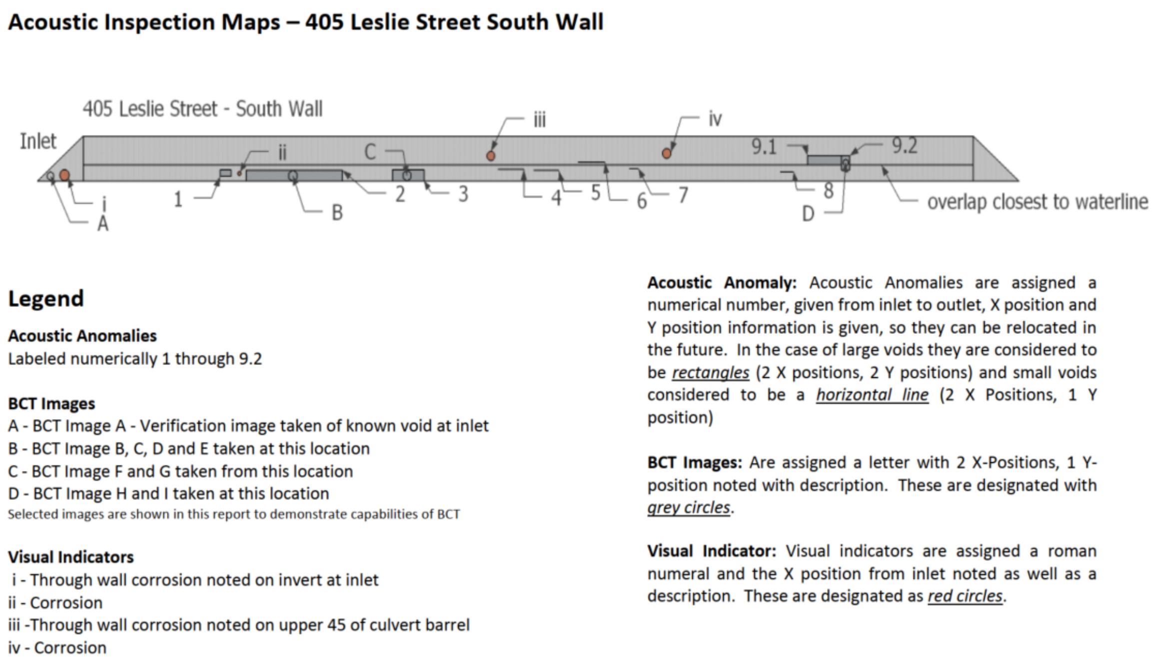


Figure A.60: Inspection Maps – 405 Leslie Street South Wall (Anderson and Bowles 2012).

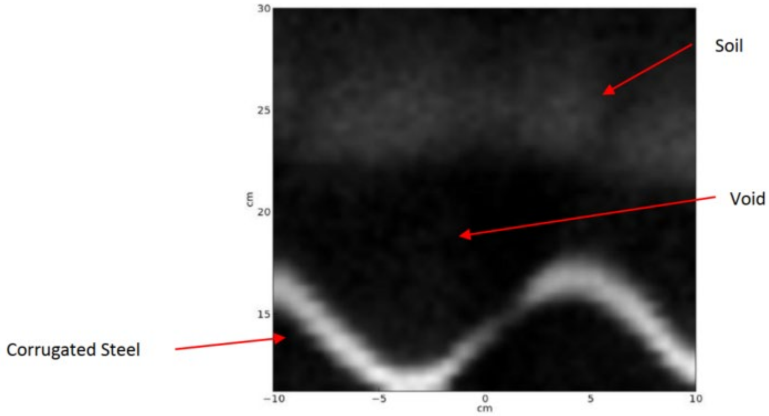


Figure A.61: A sample BCT Diagnostic Image (Anderson and Bowles 2012).

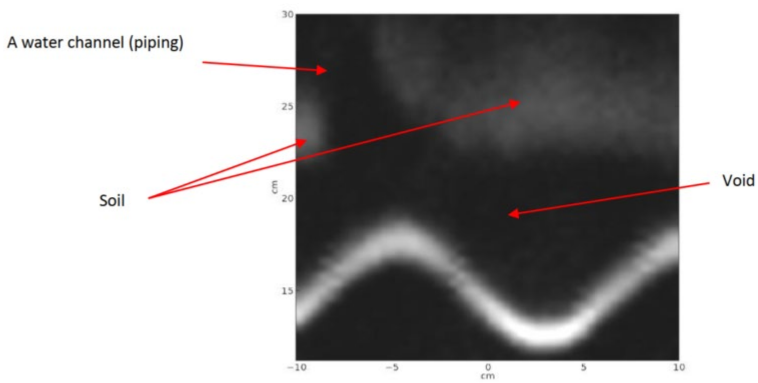


Figure A.62: BCT inspection showing a large void behind the culvert wall
(Anderson and Bowles 2012).

In their study, Anderson and Bowles found that acoustic mapping cannot consistently identify the voids behind the conduit wall. In order to measure the undermining conclusively, BCT imaging was needed. According to the pipe inspection protocol demonstrated in this study, the implementation of BCT can provide the necessary information to quantify the necessary repairs, determine the repairs needed for voids prior to sliplining, identify trends in the deterioration, select the repair approach, and other information to support decisions on culvert repairs and maintenance.

A company called Inversa Systems in New Brunswick, Canada (https://www.inversasystems.com/civil/trenchless-rehabilitation) claims that they have been doing post-construction quality control/quality assurance for grouting of sliplined culverts since 2009 (Palmer, 2016). Their clients for the exact service included the U.S. Army Corps of Engineers as well as transportation agencies in Canada and the United States. The following information was provided by the company's President/Chief Executive Officer, John Bowles (personal communication 2020).

Inversa Systems provides in-field condition assessment services with a suite of tools, including their own instruments, to locate and quantify voids behind pipe walls in both soils and annular spaces (post-rehabilitation). These tools can locate and map voids in the tunnel plate or pipes lined with HDPE liners, plastic-based liners, or FRP/GRP liners. Inversa uses two main tools to accomplish this: “Insight Lite” and “Insight.” Both tools, which are based on backscatter CT, are patented and are proprietary to Inversa Systems. The “Insight Lite” tool is a fast screening tool that provides a heat map view of all low-density regions, while “Insight” is a BCT system that provides a detailed image of the void itself. This allows a culvert to be quickly screened, and follow-up investigations can be conducted as needed. Some examples of BCT images obtained by “Insight” in a tunnel made from a plated pipe and HDPE are shown in Figure A.63.

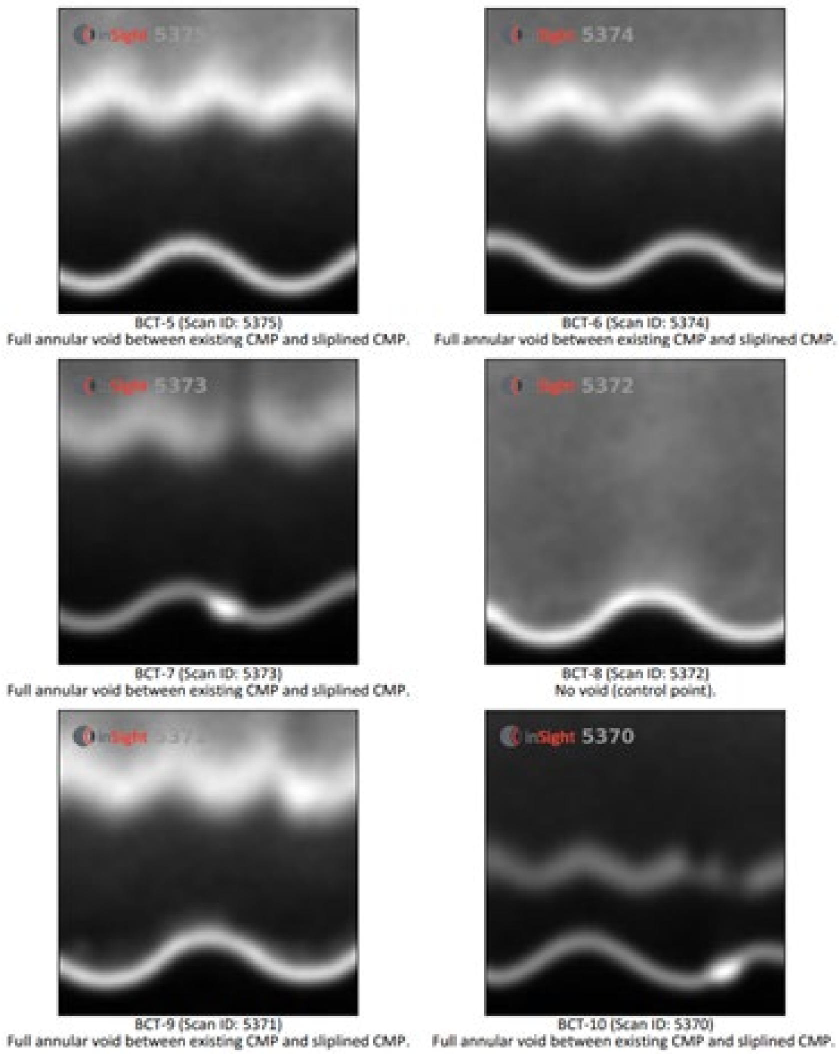


Figure A.63: Examples of Inversa System BCT images (Provided by John Bowles, 2020).

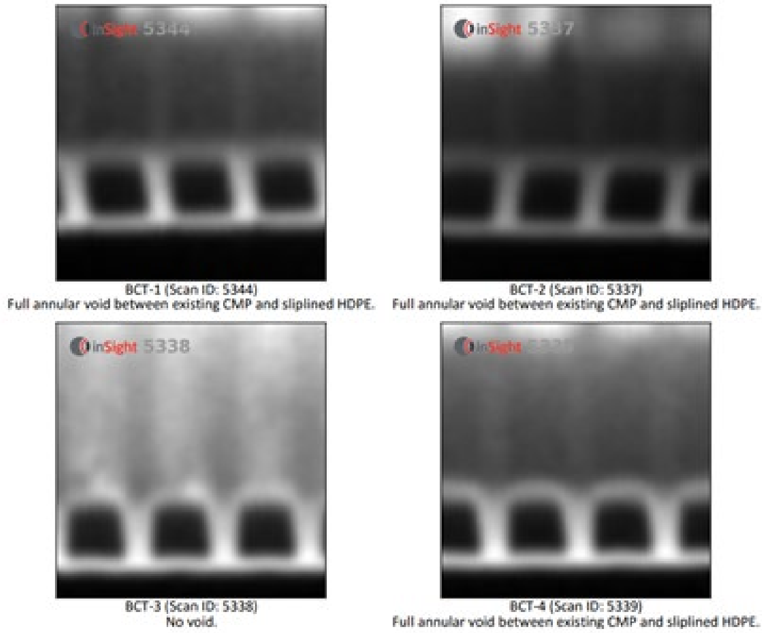


Figure A.63 (Continued): Examples of Inversa System BCT images (Provided by John Bowles, 2020).

Figure A.64 shows a very small heat map that was captured for screening. This map is set to a predefined scale and is associated with detailed measurements, which are then used to map the deterioration.

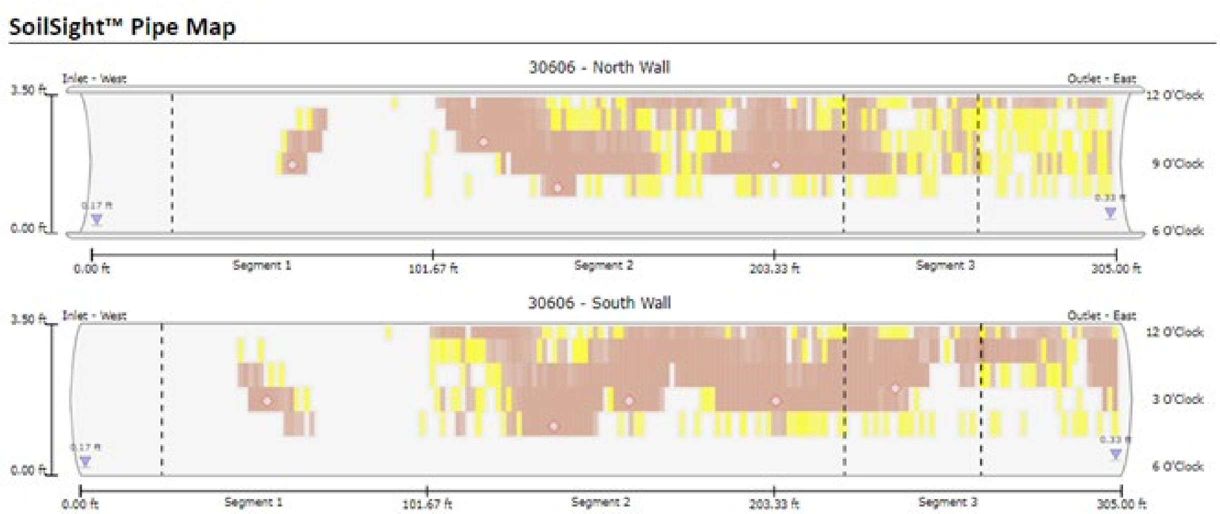
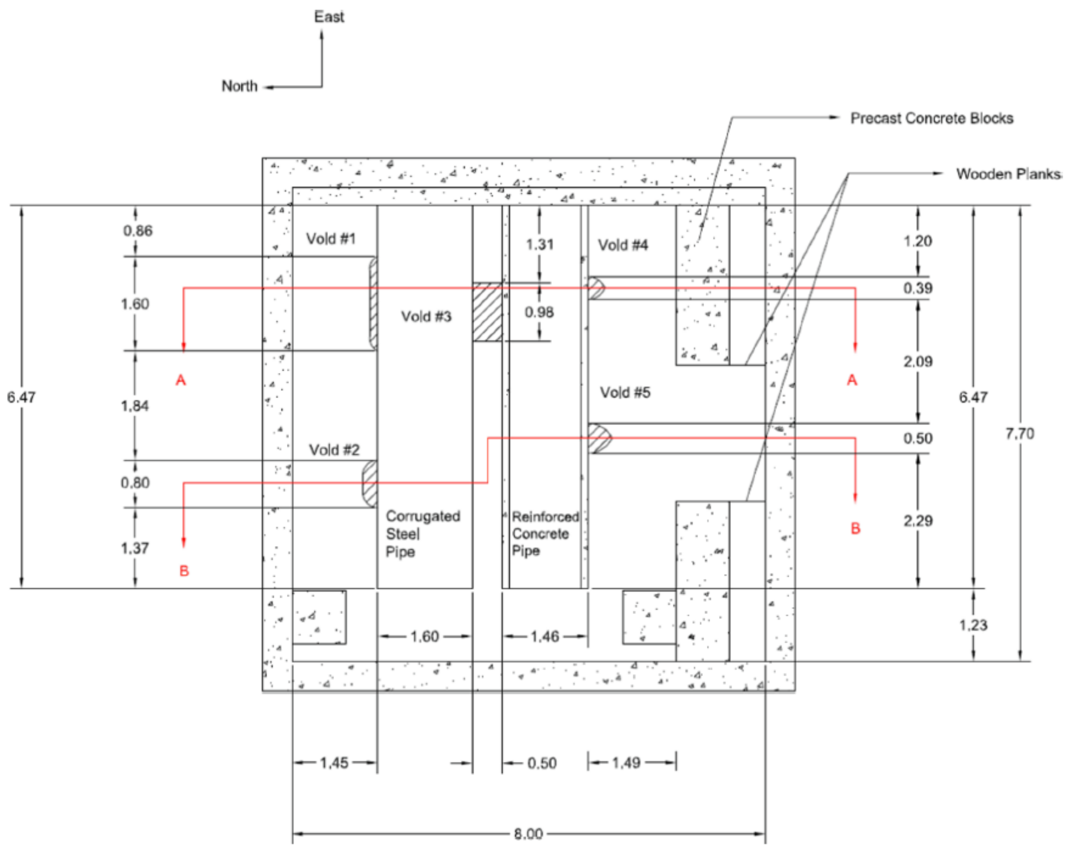


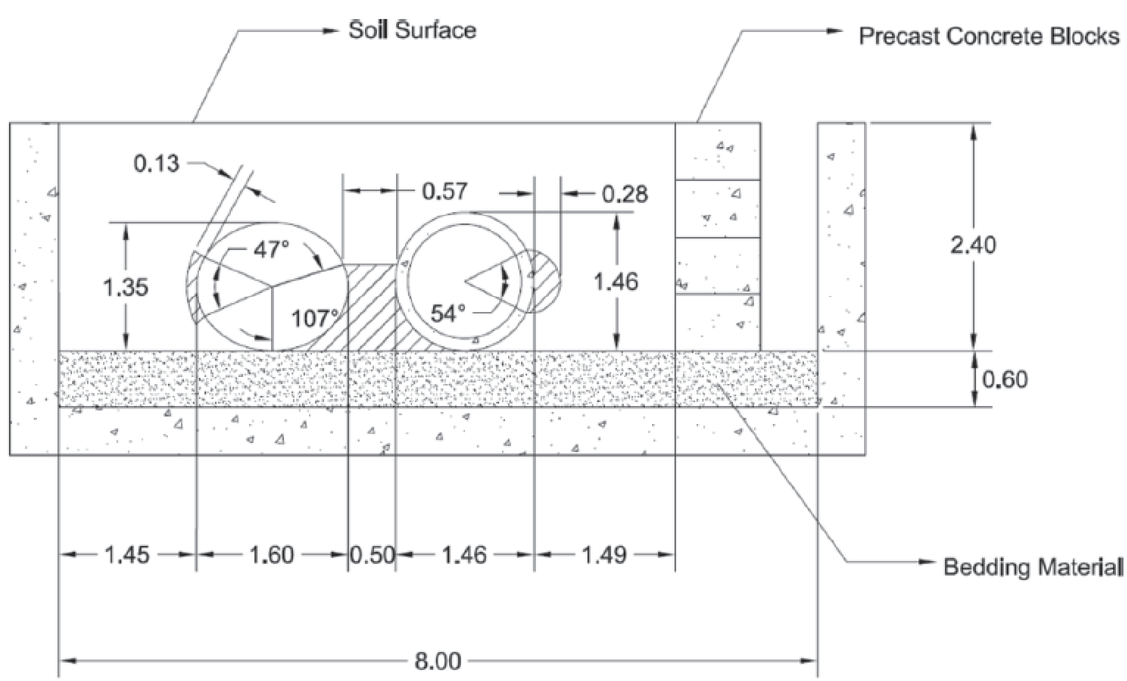
Figure A.64: Examples of scaled heat map images (Provided by John Bowles, 2020).

Another research study that included BCT was conducted by Wang et al. (2012), in which various technologies for locating voids around buried pipes were examined. Five empty spaces were created in the areas next to the pipes; the arrangement of these spaces is shown in Figure A.65. In certain areas, the voids have a different shape than in others. As an example, in Figure A.66 (a), polymer air mattresses were utilized to simulate prismatic voids adjacent to the steel pipe. These mattresses were placed in Voids 1 and 2. In another example, Figure A.66 (b) shows inflated exercise balls that have been placed in Voids 4 and 5 to simulate a pseudospherical shape. In addition, a large void was created in the space between two pipes by constructing a water retention structure as a rectangle and using wooden boards to represent the void. This space was designated as Void 3. The purpose of using voids with varying dimensions and contours was to test the capacity of various technologies to locate specific types of voids.

Once the simulated voids were created, Wang et al. examined and compared the effectiveness of five different void detection systems that are currently available for purchase: conventional backscatter computed tomography (BCT), portable backscatter computed tomography, ground penetrating radar (GPR), pipe penetrating radar (PPR), and infrared thermography (IRT). The results of the study led the authors to conclude that portable BCT and IRT were the most effective technologies for the preliminary detection of voids in the areas surrounding corrugated steel pipes. It was advised that inspections of corrugated steel pipes employ ordinary BCT and inspections of concrete pipes employ PPR to attain better accuracy and detailed geometry. It was found that ground penetrating radar could be used to detect a sizeable gap that had been artificially created between the two test pipes.

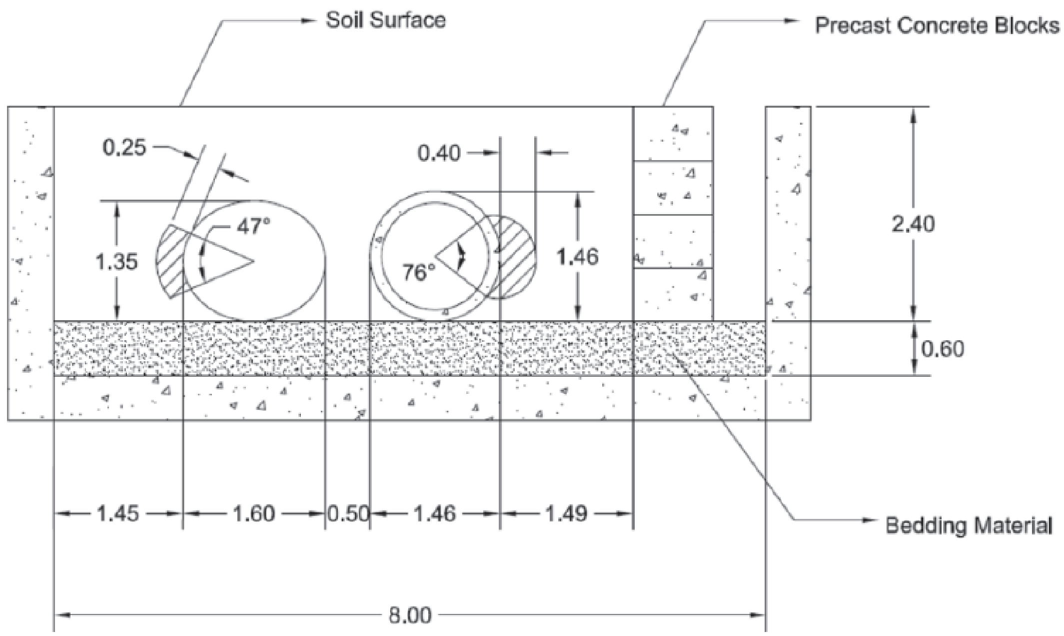


(a) Top view



(b) Side view for Section A-A

Figure A.65: Pipes and voids in the pit configuration (Wang et al. 2012).



(c) Side view for Section B-B

Figure A.65 (Continued): Pipes and voids in the pit configuration (Wang et al. 2012).

(a) Voids 1 and 2

(b) Voids 4 and 5

Figure A.66: Air mattresses and exercise balls used to create voids (Wang et al. 2012).

A.9.3 Summary of Methods used to Verify Grout Filling

Few sophisticated methods are available to confirm the complete filling of grout in the annulus. Of these methods, backscatter computed tomography (BCT) is the most effective method that was presented in this section. BCT can be used to scan through the culvert structure and provide an accurate indicator of actual culvert conditions and can provide the locations and dimensions of any voids in the grout.

A.10 Inspection Methods and New Technologies

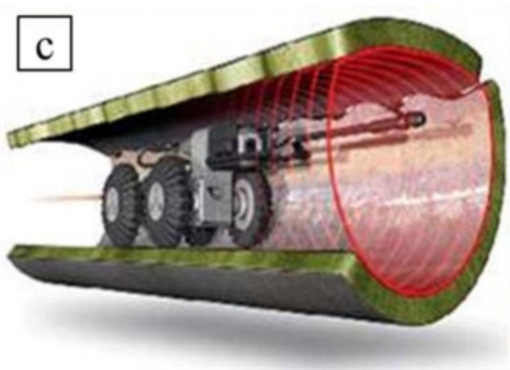
A.10.1 Introduction

The actual condition of a pipe or culvert can be understood only through an accurate condition assessment, which is a major component of any culvert rehabilitation program. A condition assessment assists the engineer in estimating the ability of a culvert to remain in service. This section provides details about several available inspection techniques and highlights their advantages and disadvantages. It also provides detailed explanations of the principles behind two specific inspection technologies: ground-penetrating radar (GPR) and a new technology for inspection called pipe penetrating radar (PPR). A summary of several research studies on the use of inspection techniques for culverts and tunnels will also be presented.

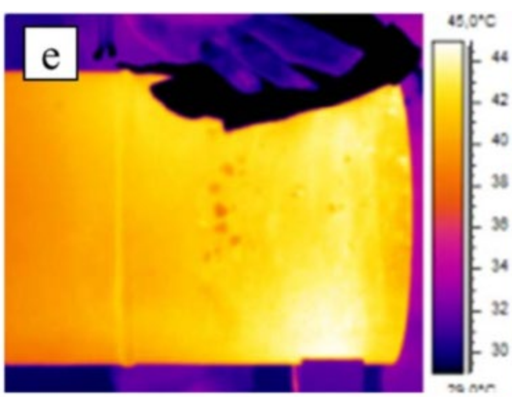
A.10.2 Available Techniques for the Inspection of Culverts

Selvakumar et al. (2014) evaluated the performance and project costs of five condition assessment techniques and compared those with conventional closed-circuit television (CCTV). The results revealed that digital scanning, zoom camera, CCTV, and laser scanning can accurately assess the pipe condition above the waterline, whereas the sonar technique can provide satisfactory performance below the waterline. Electro-scanning is able to reveal leakage-related defects all along the pipe circumference. The six inspection techniques are illustrated in Figure A.67, and the advantages and limitations of each are highlighted in Table A.44.

a) CCTV (b) Sonar scanning



(c) Laser profiling (d) Ultrasonic inspection



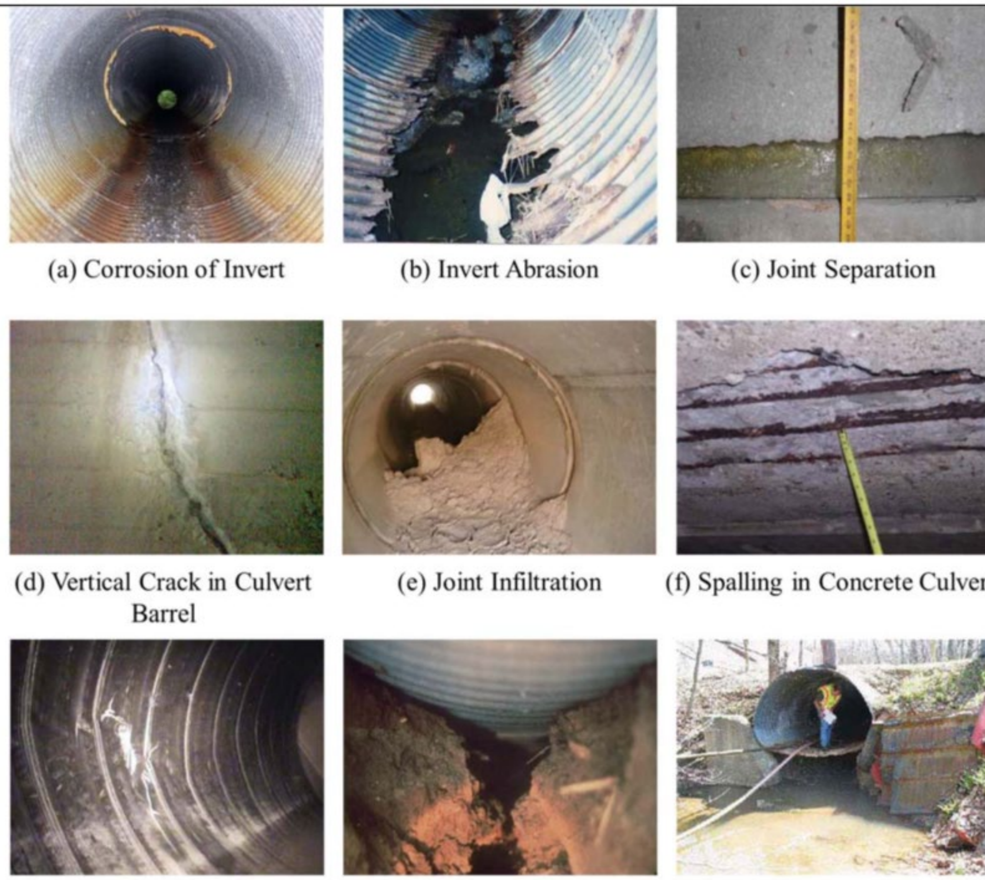
(e) Infrared thermography (f) GPR

Figure A.67: Illustrations of six pipe inspection methods (Piratla et al. 2017).

Table A.44: Advantages and limitations of culvert inspection methods (Piratla et al. 2017)

Technique	Advantages	Limitations
CCTV	▪ Provides direct illuminated image of pipe defects ▪ Can be viewed at different angles ▪ Real-time assessment	▪ Provides only qualitative information ▪ Pre-cleaning of the culvert is required ▪ Only useful above the waterline
Sonar scanning	▪ Can measure loss in wall thickness ▪ Works in live flow conditions ▪ Complements laser profiling by providing additional information	▪ Requires a specially trained workforce ▪ Works in air or underwater, but not at the same time ▪ Cannot be used for inspection of brick pipes
Laser profiling	▪ Produces a 3D model for better quality control/quality assurance ▪ Real-time recording and analysis ▪ Complements CCTV by providing additional Information	▪ Only useful above the waterline ▪ Pre-cleaning and drying of the culvert is required ▪ Requires skilled data analysts
Ultrasonic scanning	▪ Produces results in 2D or 3D formats ▪ Can detect invisible defects within the culvert wall ▪ Non-invasive	▪ Pre-cleaning of the culvert is required (internal ultrasonic) ▪ Dewatering is required (internal ultrasonic) ▪ Excavation is required to access the pipe surface
Infrared thermography	▪ Non-invasive ▪ Typically economical ▪ Highly productive	▪ Wind speed and ground surface influence results ▪ Affected by soil properties ▪ Need to clearly differentiate color shades to obtain accurate results
Ground-penetrating radar	▪ Produces immediate results ▪ Available for internal and above-ground inspection ▪ Cleaning of the pipe is not required	▪ Difficult to move the equipment on uneven ground ▪ Requires skilled operators ▪ Difficult in certain groundwater conditions

Cracks, invert deterioration, joint misalignment, joint infiltration or exfiltration, corrosion, shape distortion, debris, loss of wall thickness, and bedding voids are commonly observed defects in culverts (Figure A.68). Tables A.45 and A.46 present information about several inspection techniques used to detect defects in culverts that can aid in the selection of an appropriate method (Yang and Song 2009, Agarwal 2010, Allouche et al. 2010, Tuccillo et al. 2010).



(a) Corrosion of Invert (b) Invert Abrasion (c) Joint Separation
(d) Vertical Crack in Culvert Barrel (e) Joint Infiltration (f) Spalling in Concrete Culvert
(g) Wall Damage in Plastic Culverts (h) Piping Beneath a Culvert (i) Outlet Scour

Figure A.68: Common defects observed in culverts (Piratla et al. 2017).

Table A.45: Inspection Techniques for Defect Mapping
(Yang et al. 2009, Agarwal 2010).

Defects	Materials	Techniques
Debris	RCP, CMP, HDPE	CCTV, Sonar, Laser
Crack	RCP, HDPE	CCTV, Sonar
Invert deterioration	RCP, CMP	CCTV, Laser, Sonar
Joint misalignment	RCP, CMP, HDPE	CCTV, Laser
Joint in/exfiltration	RCP, CMP	CCTV, Laser
Wall thinning	RCP, CMP	Sonar, Ultrasonic, Laser
Bedding voids	RCP, CMP, HDPE	IT, GPR (Not reliable)
Corrosion	CMP	CCTV, Laser, Sonar, Ultrasonic
Shape distortion	CMP	Laser, Sonar

CCTV = closed-circuit television, GPR = ground-penetrating radar, IT = infrared thermography, CMP = corrugated metal pipe, HD/PE = high-density polyethylene, RCP = reinforced concrete pipe.

Table A.46: Methods of Culvert Inspections (Allouche et al. 2010)

Technique	Culvert Type	Flow in Pipe	The inspection will find
Visual inspection of man entry culverts	Any culvert type	No	Visible surface defects and defective joints; pipe misalignment, shape, or uniformity of curvature with additional field measurements
Pigs	Any culvert type	Not important	Pipe-shape deformations over allowed tolerances
CCTV	Any culvert type	No	Visible surface cracks, deformation, defective joints, stains from corrosion, shape distortion
Optical scanning	Any culvert type (preferably not corrugated)	No	Visible surface cracks, deformation, defective joints, stains from corrosion, shape distortion
Laser profiling	Any culvert type	No	Ovality, alignment, diameter; defects such as surface cracks, corrosion of pipe inner surface, deposits
Impact-echo	Concrete culvert	No	Pipe wall thickness, delamination conditions within reinforced concrete pipe
Spectral analysis of surface waves	Concrete culvert	No	Conditions inside the concrete pipe; soil conditions (density, voids) outside of the pipe
Mechanical impedance	Any culvert type	No	Soil conditions outside of the pipe (voids or over-compaction in the soil around the culvert)
Natural frequency		No	Changes in overall pipe condition over time
Microdeflection	Concrete culvert	Yes	Damaged areas in pipe wall
Ultrasonic, pipes empty	Any culvert type	No	
Ultrasonic, pipes full	Any culvert type	Yes	Pipe surface conditions and anomalies, deposits
Infrared	Any culvert type	Not important	Soil conditions outside of the pipe (voids, leakage from pipes)
Ground-penetrating radar from surface	Any culvert type	Not important	Soil conditions outside of the pipe (location, depth of voids)
Ground-penetrating radar from pipe	Any nonconductive culvert type	No	Defects behind liners

A.10.3 Ground-Penetrating Radar

Ground-penetrating radar (GPR) is similar to infrared thermography in that it is typically employed for detecting bedding issues. In this technique, high-frequency electromagnetic waves are transmitted into the ground through an antenna from the ground level, and the reflected electromagnetic waves from various underground materials are collected and analyzed. GPR works by measuring the time lag between the transmitted wave and the reflected wave, which correspond to the depth or the distance of the reflecting material (Agarwal 2010, Yang and Song 2009). GPR is popularly known to identify bedding voids in both RCP and CMP culverts (Yang and Song 2009, Tuccillo et al. 2010).

GPR or surface penetrating radar is a wave propagation technique that transmits electromagnetic (EM) waves through an antenna and collects signals reflected from a visually opaque substance or earth material (Figure A.69). A typical GPR generates short impulses of electromagnetic energy (signals with a central frequency that is typically between 50 MHz and 1.0 GHz), which are launched into the transmission medium (e.g., soil, concrete) via the transmission antenna. Energy reflected from interfaces between materials (discontinuities in impedance) is received by the receiving antenna and is processed and displayed by a radar receiver and display unit.

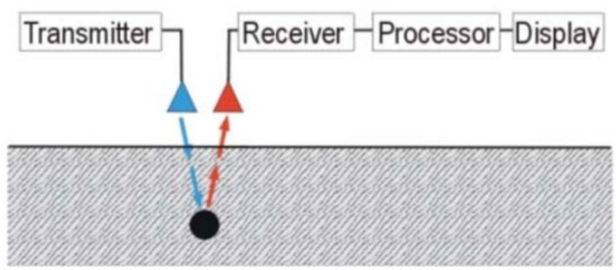


Figure A.69: Block diagram of generic radar system (Allouche et al. 2010).

GPR systems at the surface can be used to determine the position of voids and anomalies below the surface and to measure the thickness of various layers in the soil. Provided that several antennas are used and the velocity of propagation can be calibrated, it is possible to obtain an accurate measurement of layer depths.

GPR systems can be used on the inside of the pipe to assess the condition of the material surrounding a nonmetallic pipe wall. The radar image in Figure A.70 shows the signal reflection from a 6-in. pipe as well as from 8-in. and 4-in. voids in the soil. The reflection from the interface between the soil and the air void is presented as an inverted in the radar image. Table A.47 presents an example of an application of GPR for tunnel liners.

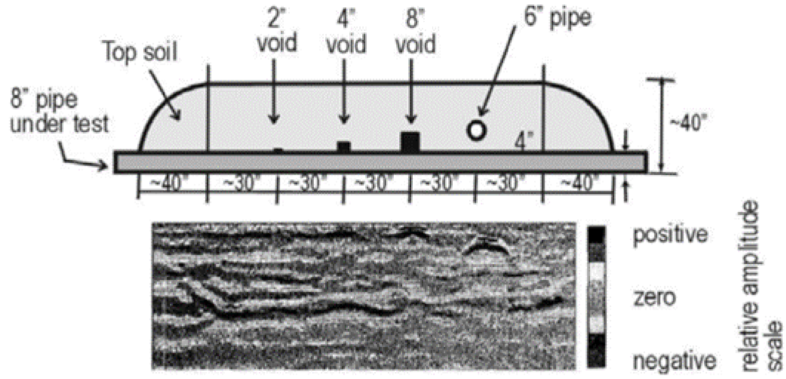


Figure A.70: Test rig for GPR testing from within the pipe and radar image of defects adjacent to the pipe (i.e., voids in the soil) in Allouche et al. (2010).

Table A.47: Examples of applications of GPR on Tunnel Liners (Lai et al. 2018)

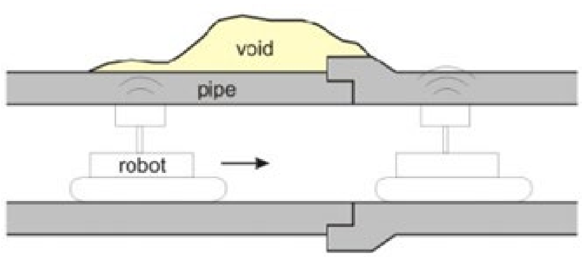
Source	Antenna frequency	Locale	Tunnel type	Subject of study	3D	Major findings/ Remarks
Lalagüe et al. (2016)	400 MHz; 1.5, 2.6, 1, and 2 GHz; 100 MHz–3 GHz	Vestfold, Norway	Cave-in penetrated the concrete lining	Void behind inner lining; rockfall from tunnel roof	Yes	Step frequency GPR is suitable for measuring the distance between inside and rock surfaces. Ground-coupled GPR is best for detecting loose rocks. Tunnel liner should be scanned immediately after tunnel construction.

A.10.4 Pipe Penetrating Radar

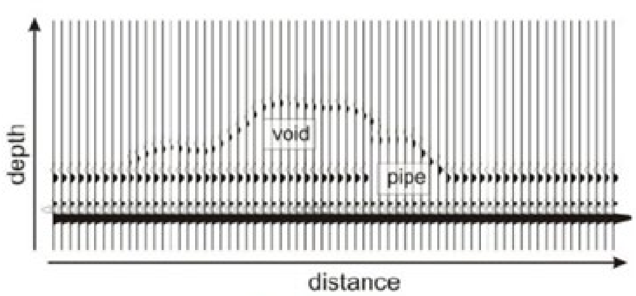
Pipe penetrating radar (PPR) is the underground in-pipe application of ground-penetrating radar. The PPR pulse travels through a pipe material as a function of its electrical properties, which are in turn a function of the material's chemical and physical composition. A portion of this pulse will be reflected and refracted by any sharp change in material properties, such as those at the interface between pipe the material and air or water. The greater the difference in the material properties, the greater is the amount of energy reflected. The reflected waves are detected by a receiving antenna and are recorded as a single trace (A-scan). This process is repeated continuously as the antenna is moved along a survey line to build up an entire profile (B-scan) along the survey line (Figure A.71). The radargram image is a display of transit time versus the distance traveled, with amplitude displayed either as a wiggle trace or as a color scale. The recorded reflections can then be analyzed in terms of their shape, travel time, signal amplitude, and phase.

The penetration depth is dependent on (1) the dielectric properties of the pipe and the host material and (2) the antenna frequency. The penetration depth of high-frequency antennas (2.6 GHz – 500 MHz), which are most suitable for pipe investigations, is on the order of 2 ft to 9 ft (60 cm to 3 m) beyond the pipe wall. PPR resolution is defined as the smallest size feature that can be distinguished. Resolution is primarily determined by the wavelength but is also affected by other factors such as polarization, dielectric contrast, signal attenuation, background noise, target geometry, and target surface texture, all of which will influence the reflected wave (Donazzolo and Yelf 2010). As a general rule, the thinnest layer that can be resolved is ¼ of the wavelength used. For a 2.6-GHz pulse traveling through a concrete pipe, this equates to a thickness of approximately 0.354" to 0.6" (9 to 15 mm). Once a layer is resolved, its thickness can be measured to a precision that is dependent on the time base sample rate and the signal jitter of the GPR system used. For a depth range of 8 inches (200 mm), this can be as small as ⅛ inch (4 mm) (Donazzolo and Yelf 2010).

PPR can be used to detect pipe wall fractures, changes in material, reinforcing location and placement, and pipe wall thickness. When used in conjunction with pipe rehabilitation technology, PPR can identify grout placement between pipe renewal systems and host pipes, liner bonding, and host pipe in-situ conditions including exterior repair clamps and soil variations for pipe-bursting replacement operations. PPR's primary use is to detect variation in pipe bedding conditions to identify the location and extent of voids that are outside the pipe walls (Najafi, 2010).

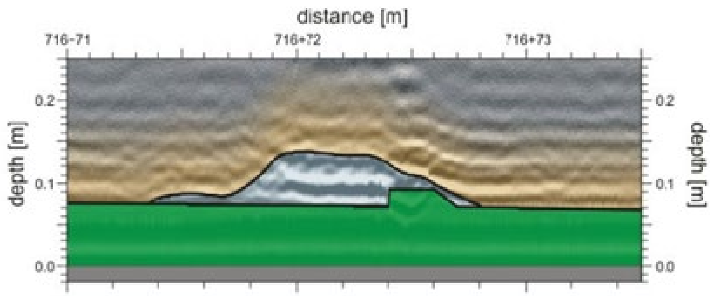


(a) Robot-mounted antennas continually emitting and recording pulsed GPR signals



(b) Signals recorded as a series of A scans making up a corresponding radar "wiggle" trace (B scan)

Figure A.71: Principles of inspection using PPR (Ékes et al. 2011).



(c) Interpretation is superimposed on the processed radar plot

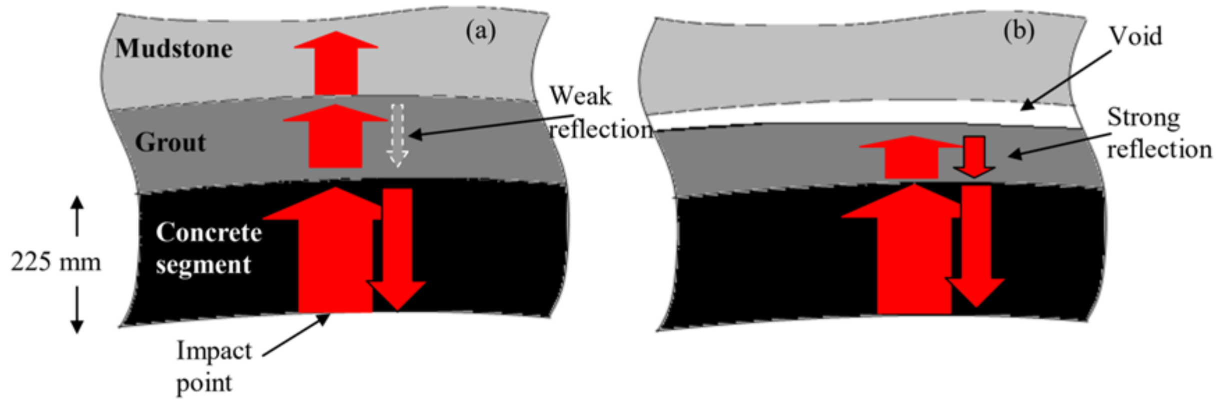
Figure A.71 (Continued): Principles of inspection using PPR (Ékes et al. 2011).

A.10.5 Research on inspection methods

Aggelis et al. (2008) discuss a case where impact-echo was used for the evaluation of grouting in a tunnel lining. This non-destructive and time-effective evaluation technique was applied successfully and helped to assess the presence of voids in the grout. In this case, an impact hammer (Figure A.72) was used to create excitation on the concrete surface and an accelerometer was employed to acquire the reflection. The impact hammer was used repeatedly for 10 s and resulted in 20 individual signals. In general, after the application of low-frequency excitation, the spectral analysis of the response of the member can be employed by impact-echo. The frequency of the recorded reflection can give useful information on the member thickness, depth of the defects, and material properties.

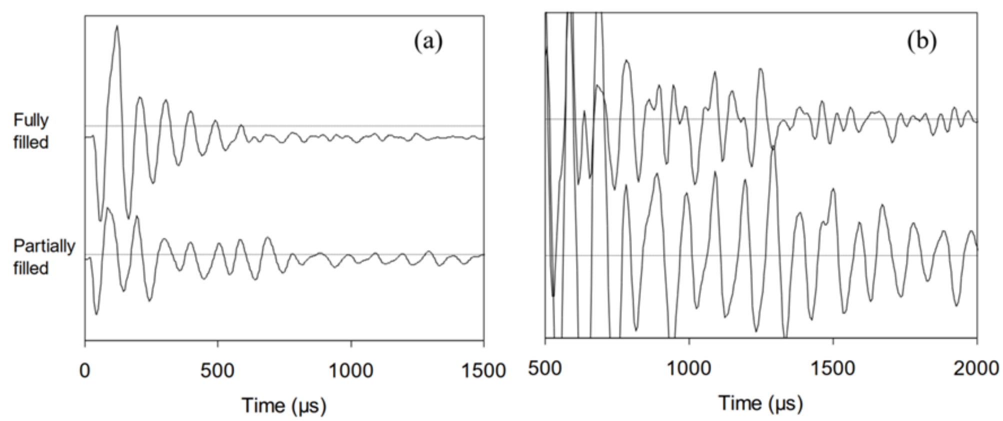
Figure A.72: Excitation using a 1-inch (25-mm) impact hammer near the accelerometer (Aggelis et al. 2008).

For the layered test bed in a fully grouted condition, only one major frequency peak will appear in the trace due to the propagation of almost all the energy through the mudstone (Figure A.73a). In contrast, two peak frequencies will appear in the trace due to the void between the grout and mudstone (Figure A.73b). The traces shown in Figure A.74 can explain the typical waveforms obtained for both fully and partially filled positions. In the case of a fully grouted position, the wave (Figure A.74a) had a single burst that decayed smoothly. However, in the case of a partially filled position (Figure 74b), the decay was not smooth due to the late arrival of the reflection. This time domain characteristic helped to distinguish clearly between fully and partially filled cases. Fast-Fourier transforms (presented in Figure A.75) showed similar peaks for the two cases.



(a) fully filled annulus (b) partially filled annulus

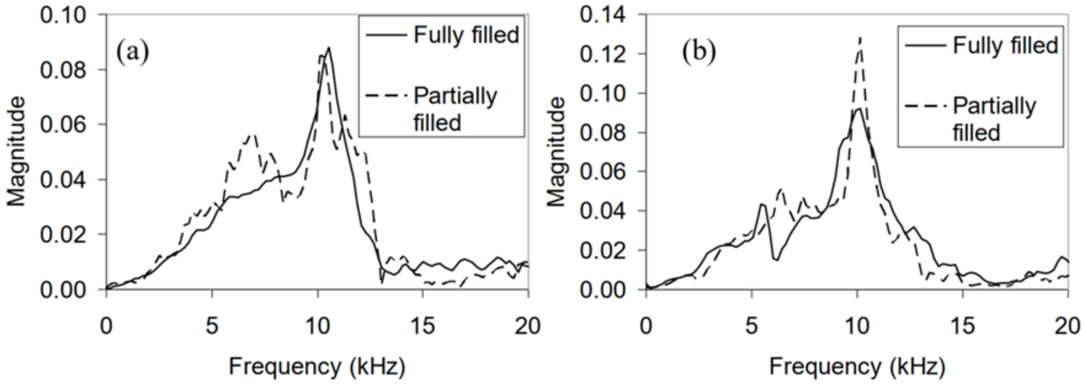
Figure A.73: Reflections from sounding tests according to the internal geometry (Aggelis et al. 2008).



(a) Waveforms from different filling cases with a threshold 10% of the maximum

(b) The waveforms magnified after 500 μs, with a threshold 0.1%

Figure A.74: Waveforms from different filling cases (Aggelis et al. 2008).



(a) Distinguishable cases

(b) The waveforms magnified after 500 μs, with a threshold 0.1%

Figure A.75: FFT of different filling cases (Aggelis et al. 2008).

The authors concluded that the impact-echo technique is an effective non-destructive evaluation technique due to its time- and cost-effectiveness and that it can also be used in unlimited positions for evaluation purposes. Nonetheless, the expected frequency peak was valid only for this specific case, and it can only be used in a similar case. The values would need to be modified based on the geometry, material properties, and the type of application if used for other cases.

Parkinson and Ékes (2008) discussed a case history of a concrete-lined tunnel inspection using GPR (Figure A.76), in which a 1,000-MHz optimum antenna frequency was used for the mapping of liner conditions in tunnels. By using GPR, the authors were able to map the concrete liner thickness, detect the presence of reinforcement, and delineate zones where mesh roof supports and construction support timbers were embedded in the liner. Moreover, they could map the locations and orientations of faults that intersected the tunnel. Minor voids, honeycomb sections, and areas of rock–liner separation were also detected. Radar response was slightly different in voids, zones of slight liner–rock separation, sharp rock pinnacles or hollows under the liner, and locations where wood was embedded. However, these responses were not always uniquely distinguishable from each other.

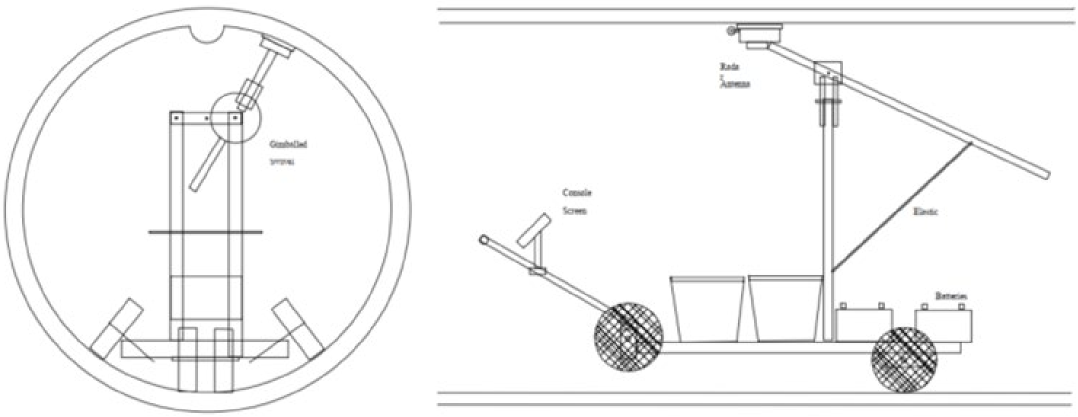


Figure A.76: Basic design of GPR survey methodology (Parkinson et al. 2008).

A.10.6 Summary of Inspection Method and New technologies

Based on the information summarized in this section, PPR is useful methodology that can be applied by contractors for culvert inspections. It is recommended that additional research work be conducted on this newly available inspection technique to verify its suitability for this purpose.

A.11 Conclusions Based on the Literature Review

The following conclusions were based on the findings from the literature review:

- Sliplining in most cases is the simplest, most economical method that is currently available for trenchless culvert rehabilitation, and it is widely used by many agencies. As reported in different sources, most pipes in sliplined culverts are round. Corrugated metal pipe (CMP) is the most common host conduit pipe; but for liners, high-density polyethylene (HDPE) is most commonly used in culvert rehabilitation.
- Grout material can increase the buckling resistance of the liner pipe and host pipe and expand the service life of the culvert. For practical purposes, a compressive strength of 100 psi was reported to be adequate. High-density grout (> 70 pcf) is recommended if water is present during the grouting operation.
- Many manufacturers prefer to use Elastizell PS 120 (120 psi) as the standard fill for annulus voids. Cement-based grouts are less costly than chemical grouts, but the installation of cement grouts can be time-consuming (installation time for a polymer grout was reported to be less than one hour, while a cement-based grout required a much longer time). Some newly available grouts have comparable properties and show promise as a fill material for annular voids, but they are not yet widely used. Some of these new grouts available in recent times are described and discussed in sections A.3.5.1 to A.3.5.7. Cellular grouts are gaining recognition as a viable and effective alternative to mortar grouts that use cementitious material, but their higher cost may not be justified for many projects. A two-component grout such as sodium silicate can gain high early strength and can act as a structural element to support the liner. Another grout used for annulus voids for tunnels, tunneling annulus grout, has higher compressive strength than low-strength mortar (LSM grout) and can achieve 14.5 psi compressive strength in just one hour.
- ODOT C&MS specifies mix designs for common LSM grouts but allows a strength in the range of 50 to 100 psi for alternative mixes. Most DOTs recommend a compressive strength of 100 psi at 28 days. ASTM D6103 is the standard test method for flow consistency of controlled low-strength material (CLSM). The compressive strengths of non-shrink mortar (NSM) grouts specified in C&MS are comparable to specifications of other DOTs. No separate guidelines exist for cellular grouts in ODOT SS 837 aside from a reference to ASTM C869.
- A few sliplining contractors and grout manufacturers have their own detailed specifications for sliplining methods. ISCO Industries has a specification for grout materials and the types of grouts to use with its Snap-Tite® system. They recommend two types of grouts: flowable fills and cellular grouts. The compressive strength of these grouts varies is based on the density, and three mix proportions for cellular grouts are suggested. Cellular grouts are readily available, but they are known to be more expensive than mortar grouts. The average 28-day compressive strength of cellular grouts supplied by different manufacturers ranges from 30 psi to 300 psi based on the density of the grout.

- The load-carrying capacity of a rehabilitated pipe culvert is generally greater than that of the corresponding unlined pipe. Several studies have reported that grout strength can affect the load-carrying capacity and the response of the rehabilitated pipe.
- Inspections of culverts and the verification of the complete grout filling in the annulus voids have traditionally been performed by manual sounding. Refined methods are unavailable for immediate implementation.

Table A.48: LSM Grout Compressive Strength

Agency	Properties: LSM grout compressive strength
PennDOT	Type B (125 max.), Type C (800 min.), Type D (90-400)
FDOT	Excavatable (max. 100 psi), non-excavatable (min. 125 psi)
MaineDOT	28 days (30–110 psi) and 90 days max. 200 psi
NYSDOT	Unconfined 28-day compressive strength: 40 psi ≤ *qu* ≤ 150 psi
WYDOT	Min. 28-day compressive strength 290 psi
WSDOT	28-day strength (min. 50 psi, max. 300 psi)
WVDOT	Min. 50 psi
NCDOT	Min. 3-day strength (Type 4 = 600 psi; Type 5 = 100 psi)
KDOT	Low-strength mix = 28 days @ 100psi (max.) High-strength mix = 28 days @ 200 psi (min.) Undersealing mix = 7 days @ 600 psi
TxDOT	Excavatable (80–200 psi), non-excavatable (> 200 psi)
VDOT	30–200 psi
IDOT	≥ 30 psi to < 150 psi (at 28 and 180 days)
UDOT	100–400 psi
Caltrans	Min. 300 psi @ 28 days
Delaware DOT	50–200 psi @ 28 days
Louisiana DOTD	Excavatable (max. 100 psi); non-excavatable (Min 125 psi) @ 28 days
USACE (with UFGS)	Structural (ASTM C942) Nonstructural grout (min. 350 psi @ 28 days)
USDA	Max. 200 psi @ 28 days
Galveston	200 psi (min.) @ 28 days
Palo Alto	≥300 psi @ 28 days (ASTM C495 or C109)
Hampton Roads (Virginia)	300 psi @ 28 days

Table A.49: LSM Grout Density

Agency	Properties: LSM grout density
PennDOT	30–70 pcf (Type D)
FDOT	Excavatable (110 pcf), non-excavatable (100–125 pcf)
WVDOT	$80 < \rho < 130$ pcf
KDOT	92 pcf (high-strength)
TxDOT	Excavatable (90–125 pcf), non-excavatable (100–145 pcf)
TDOT	80–120 pcf
Caltrans	53 to 68 pcf
Arkansas DOT	minimum of 110 pcf
Louisiana DOTD	Excavatable (90–110 pcf), non-excavatable (100–125 pcf)
USDA	40–70 pcf
INDOT Report	80–120 pcf
Galveston	55 pcf ± 5 pcf
Hampton Roads (Virginia)	Min. 55 pcf, max. 61 pcf

Table A.50: LSM Fluidity

Agency	Properties: LSM Fluidity
IOWADOT	Efflux time 10 to 16 sec
NCDOT	Flow 10–26 sec (Type 4)
KDOT	10–16 sec (undersealing)
Caltrans	Must not exceed 20 sec (ASTM C939)
INDOT Report	May be gravity flowed
Palo Alto	Shall not exceed 20 sec (ASTM C939)
Hampton Roads (Virginia)	< 18 sec (ASTM C939)

Table A.51: LSM Slump

Agency	Properties: LSM Slump
PennDOT	3 inches (min.)
MaineDOT	A spread of 9 to 14 inches is considered flowable (modified slump test)
NYSDOT	a minimum diameter spread of 8 inches
WYDOT	8 inches
WSDOT	3 to 10 inches
NCDOT	less than 2 inches (Type 5)
VDOT	8 inches
IDOT	≥ 7 inches
Arkansas DOT	Minimum flow of the mixture shall be 8” (200 mm). The flow test shall consist of filling a 3” (75 mm) diameter × 6” (150 mm) high open-ended cylinder to the top with the flowable material mixture. The cylinder will then be pulled straight up, and the flow will be measured by the approximate diameter of the mixture. There shall be no evidence of segregation in the mixture.

Table A.52: Water Required in LSM Mix

Agency	Properties: Water Required in LSM Mix
IOWADOT	70 gallons of water
Arkansas DOT	Approx. 65 gallons of water
Louisiana DOTD	Mix designs shall produce a consistency that will result in a flowable self-leveling product at the time of placement.

Table A.53: Penetration Resistance of LSM

Agency	Properties: Penetration resistance of LSM
USACE (with UFGS)	after 24 hr 100 psi, ASTM C403
Galveston	after 24 hr 100 psi, ASTM C403
Hampton Roads (Virginia)	min 100 psi

Table A.54: LSM Air content

Agency	Properties: LSM Air content
FDOT	5–35% (excavatable), 5–15% (non-excavatable)
MaineDOT	5–15%
WYDOT	20%
TxDOT	10–30% (excavatable), 5–15% (non-excavatable)
IDOT	0–25 %
Louisiana DOTD	10–35% (excavatable), 5–20% (non-excavatable)

Table A.55: LSM Shrinkage

Agency	Properties: LSM Shrinkage
WYDOT	Max. 1% by volume
UDOT	not to exceed 1% by volume
USACE (with UFGS)	1% shrinkage by volume
Galveston	Max. 1% by volume
Hampton Roads (Virginia)	< 1% by volume

Table A.56: LSM Initial Set Time

Agency	Properties: LSM Initial set time
WYDOT	2 hours
Hampton Roads (Virginia)	3 hrs

Table A.57: Minimum Temperature of LSM

Agency	Properties: Minimum Temperature of LSM
FDOT	50 °F at the point of delivery
Maine DOT	40 °F min. concrete temperature, as placed
IDOT	Min. of 35 °F (2 °C)
Delaware DOT	Place flowable fill only when: A. The ambient temperature is a minimum of 40 °F and rising; B. The temperature of the flowable fill is a minimum of 50° F
USACE (with UFGS)	60 °F or higher at the time of pumping (cold weather)
USDA	Cold weather min. 40 °F, Hot weather max. 90 °F. Pump the mix within 45 min of adding the cement to the mix in hot weather

Table A.58: Non-Shrink Grout Min./Max. Compressive Strength

Agency	Properties: Non-shrink grout min./max. compressive strength
ODOT	Min. 28-day compressive strength 5000 psi
IOWADOT	Not mentioned
FDOT	Min. 3-day strength of 5000 psi
WSDOT	Min. strength of 4,000 psi at 7 days
NCDOT	Min. 3-day strength of 5000 psi (Type 2 and Type 3)
TxDOT	5800 psi at 28 days
VDOT	4000 psi at 7 days

Table A.59: Non-Shrink Grout Fluidity

Agency	Properties: Non-shrink grout Fluidity
ODOT	Min. flow is 125 @ 5 drops of the flow table in 3 sec
TxDOT	Efflux time 20–30 sec

Table A.60: Non-Shrink Height Change

Agency	Properties: Non-shrink height change
ODOT	Max 4%
FDOT	0.0% to 0.3%

Table A.61: Non-Shrink Grout Volume Change

Agency	Properties: Non-shrink grout volume change
TxDOT	0.0–0.3% @ 24 hr and 28 days
Palo Alto	Less than 1% shrinkage by volume

Table A.62: Non-shrink Grout Water-to-cement Ratio

Agency	Properties: Non-shrink Grout Water-to-Cement Ratio
WSDOT	0.45
IDOT	0.6

Table A.63: Non-shrink Air Content

Agency	Properties: Non-shrink air content
PennDOT	3% to 7%
IDOT	6–9%

Table A.64: Cellular Grout Minimum/Maximum Compressive Strength

Agency	**Properties: Cellular Grout Min./max Compressive Strength**
IOWADOT	Min. 100 psi
INDOT	28-day 150 psi (min)
FDOT	Min. 80 psi
NYSDOT	Min. 28 days Type A (40 psi) and Type B (100 psi)
MnDOT	75–400 psi (low-density and high-density)
INDOT Report	75–500 psi

Table A.65: Cellular Grout Density

Agency	**Properties: Cellular grout density**	
	High	**Low**
IOWADOT	Min. 70 pcf, cannot be dewatered	Min. 30 pcf, no water is present
FDOT	20-80 lbs/ft^3	
NYSDOT	Type B (42 pcf)	Type A (30 pcf)
MnDOT	70 lbs ±3 pcf	30 lbs ±3 pcf
TxDOT	40–80 pcf	
INDOT Report	20–80 pcf	

Table A.66: Cellular Grout Foam

Agency	**Properties: Cellular grout foam**
MnDOT	20 ft^3 (low-density mix), 13.5 ft^3 (high-density mix)

Table A.67: Cellular Grout Slump

Agency	Properties: Cellular grout slump
MnDOT	10 in ± 1 inches (high-density and low-density mix)

Table A.68: Cellular Grout Water-to-Cement Ratio

Agency	Properties: Cellular Grout Water-to-Cement Ratio
MnDOT	0.5 (for both high-density and low-density mixes)

Table A.69: Bulkhead Requirement

Agency	Properties: Bulkhead requirement
INDOT	From the end of the existing pipe inward, a min. depth of 18 inches
USACE (with UFGS)	Bulkhead concrete shall be above 4° C /40° F during placement, Min. length measured along the long axis of the pipe of 300 mm (1 ft) or the thickness of the headwall, whichever is greater
INDOT Report	At least 1 foot thick. May require special blocking at the outlet end if the flotation of liner for over 5 ft

Table A.70: Grout/Cellular Concrete Pumping Method

Agency	Grout/Cellular concrete pumping method
IDOT	Intermittent pumping method, bracing method, or water fill method
INDOT Report	Gravity flow: used on short runs of liners, generally 80 feet or shorter, Pressure grouting: used when the length of the liner exceeds 80 feet
San Diego	Grout shall be pumped until a grout is within 0.3 lbs per gallon of proposed grout injection density discharges from the end opposite the injection point

Table A.71: Existing Pipe Preparation

Agency	Properties: Existing Pipe Preparation
NYSDOT	Fill all voids within 12 inches of the existing pipe's circumference if less than 48 inches in diameter; preliminary filling of voids in the periphery of the existing pipe is not required.

Table A.72: Grouting Pressure

Agency	Properties: Grouting pressure
WYDOT	Max. allowable gages grouting pressure shall not exceed 5 psi
WVDOT	Pressure on the annular void shall not exceed 2 psi
Caltrans	Pipe liner stiffness < 29 psi: grouting pressure must not exceed 5 psi, Pipe liner stiffness ≥ 29 psi: grouting pressure must not exceed 7.25 psi
USACE (with UFGS)	5 psi
San Diego	Grout shall be pumpable through a 2-inch diameter hose for a distance of 1000 feet with a maximum pressure of 12 psi at the point of placement. Grouting pressure shall not exceed 5 psi.
Galveston	To be pumpable through a 2-inch-diameter hose for a distance of 1,000 feet with a maximum allowable pressure at point of placement of 5 psi

Table A.73: Initial Curing Temperature

Agency	Properties: Initial Curing Temperature
INDOT	70°F ± 10°F

Table A.74: Liner Pipe Deflection

Agency	Properties: Liner pipe deflection
TDOT	The annular void shall be completely grout filled without deflecting the insertion pipe greater than 1.5%
Caltrans	Pipe liners greater than 36 inches in nominal diameter: 5% greater than the actual dimension of the pipe liner or 6.5% of the nominal pipe liner dimension. If more than 8% of the nominal pipe liner dimension is over-deflected, the pipe liner is rejected.
Galveston	Annular space shall be completely filled without deflecting the pipe greater than 1.5%

Table A.75: Minimum Annular Space

Agency	Properties: Minimum Annular space
NYSDOT	1 inch for fill material between the new and existing pipes
NCDOT	1 inch
USACE (with UFGS)	1 inch min. average annular space

Table A.76: Requirement for Length of Liner Pipe

Agency	Properties: Requirement for length of liner pipe
INDOT	8 inch outside the end of the existing pipe

Table A.77: Special Requirements

Agency	Special Requirement
NYSDOT	Prior to relining, install skids or place a concrete or grout bed in the invert.
IDOT	Upon completion of the pumping operation, all remaining unfilled vent holes including those at both the upstream and downstream ends shall be filled with nonshrink grout.
TDOT	For pipe 12”–36” when justified by structural design factors the use of grout is not required.
Caltrans	For each batch of grout, perform density and viscosity tests under ASTM C138 and ASTM C939. Add the foaming agent at the job site.
Delaware DOT	Do not place flowable fill against frozen surfaces. Make relief holes wherever necessary to ensure that all voids are filled. Ensure that all interior items are capable of withstanding the lateral hydraulic pressures of the flowable fill. Do not exceed 5 feet in lift thickness unless otherwise directed by the Engineer.
Louisiana DOTD	The requirements for percent air, compressive strength and unit weight are for laboratory designs only and are not intended for jobsite acceptance requirements unless otherwise directed by the project engineer.
USDA	The grout mix container must have a minimum volume of 0.2 cubic feet and minimum dimension of 6 inches.
INDOT Report (Thomas 1991)	Flotation is generally not a problem if the difference in the size of the liner and the size of the original pipe is less than 4 inches. To place the grout tube a hole is cut, a little smaller than the diameter of the grout tube, in the top of the existing pipe and a 6-inch piece of PVC pipe is placed over the hole.
Galveston	During placement of the grout, the density shall be measured in accordance with ASTM C138 a minimum of twice per hour. Grout shall be pumped until a grout of within 0.3 lbs per gallon of specified grout injection density discharges from the end opposite the injection point.
Hampton roads (Virginia)	This specification is to rehabilitate sewer lines greater than 24 inches in diameter. The grouting equipment shall be capable of mixing and pumping at least 40 cubic yards per hour. On-site test equipment density for each batch shall be verified by ASTM C138.

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Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX B

Survey Report

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Prepared for:
The Ohio Department of Transportation,
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APPENDIX B
SURVEY REPORT

B.1 Introduction

An online survey was developed to collect information on practices regarding annulus void fill material for rehabilitated sliplined culverts. The survey was developed using the Qualtrics survey platform and was administered online between February 23 and June 23, 2020 (allowing adequate time for a response). A link to the survey was initially distributed through email to people in five different groups: conduit manufacturers, ODOT districts, county/local public agencies, ODOT designers, and ODOT contractors. In order to increase the response rate, a follow-up email was also sent two weeks prior to the close date of the survey. After collecting basic contact information, the online survey posed questions to gather information about sliplined culverts.

B.2 Conduit Manufacturers

The 15-question survey that was issued to conduit manufacturers focused on sliplining components and specifications. Questions concerned conduits and the materials used for grouting of the annulus of sliplined culverts with a grout included in ODOT SS 837 as well as other grouts. Nine conduit manufacturers responded, and these manufacturers provided information on several types of conduits used in sliplined culverts. The questions and responses from conduit manufacturers are discussed in the following sections and are summarized in Tables B.1 to B.28.

B.2.1 Conduit types used

Q.2.1.1 Identify the conduit type(s) you manufacture/supply for sliplining?

Table B.1: Conduit Types Supplied by Conduit Manufacturers

Company Name	Conduit Types Installed and Item/Spec. Numbers	Other Conduit Types
Haviland Drainage	Corrugated steel pipe (707.01 or 707.02), Corrugated polyethylene smooth lined pipe (707.33) Polyethylene profile wall pipe (707.35)	
ADS	Corrugated polyethylene smooth lined pipe (707.33)	Polypropylene (PP) 707.65, 707.69
Springfield Plastics, Inc	Corrugated polyethylene smooth lined pipe (707.33)	
St Regis Culvert, Inc.	Corrugated steel pipe (707.01 or 707.02) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12,) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated aluminum alloy pipe (707.21 or 707.22) Corrugated aluminum spiral rib pipe (707.24)	Max Flow Double Wall Polymer-Coated Corrugated Steel Pipe

Table B.1: Conduit Types Supplied by Conduit Manufacturers (continued)

Company Name	Conduit Types Installed and Item/Spec. Numbers	Other Conduit Types
Contech Engineered Solutions	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated aluminum alloy pipe (707.21 or 707.22) Aluminum alloy structural plate conduit (707.23) Corrugated aluminum spiral rib pipe (707.24) Polyvinyl chloride corrugated smooth interior pipe (707.42) Polyvinyl chloride profile wall pipe (707.43) Steel reinforced thermoplastic ribbed pipe (SS 938)	
Lane Enterprises, Inc.	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated aluminum alloy pipe (707.21 or 707.22) Aluminum alloy structural plate conduit (707.23) Corrugated aluminum spiral rib pipe (707.24) Corrugated polyethylene smooth lined pipe (707.33)	
D A Van Dam & Associates LLC	Corrugated steel spiral rib pipe (707.12) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34), Polyethylene profile wall pipe (707.35) Polyvinyl chloride corrugated smooth interior pipe (707.42) Polyvinyl chloride profile wall pipe (707.43), Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938)	large diameter HDPE pipe up to 17 feet in diameter
American Concrete Pipe Association	Reinforced concrete circular pipe (706.02)	
ISCO Industries Inc.	Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Glass-fiber-reinforced polymer mortar pipe (707.75)	

Q.2.1.2 What conditions promote or limit the use for these conduit types for sliplining? For example, culvert dimensions/diameters, spans, shapes, lengths, cost, construction speed, access, available space, etc.

Table B.2: Conditions Promoting or Limiting Conduit Use for Culvert Sliplining

Company Name	Limitation of Conduit
Haviland Drainage	Costs, access, depths are always a factor in determining the most cost-effective method. We have very limited experience with this process.
ADS	Culvert dimensions, lengths, cost, access
Springfield Plastics, Inc	Corrugated polyethylene pipe is lightweight with a high strength to weight ratio. It is easily handled and comes in long lengths allowing rapid installation. It is one of the most economical pipes on the market.
St Regis Culvert, Inc.	That promotes use: Diameters can be fabricated to fit almost any diameter. Large diameters and arched pipes. The total length is 60 feet or less so that a single piece can be utilized. That limits use: The available space in the ditch and in front of the host pipe to insert slip liner. If there is an area in the host pipe that is collapsed or damaged so that an appropriate diameter liner cannot slip through.
Contech Engineered Solutions	Only limitation would be if the already installed pipe/structure does not allow for proper clearance of any possible options. Possible loading conditions due to excessive cover. Any application where the pipe fits the host are the "conditions" that promote their use.
Lane Enterprises, Inc.	The versatility of CMP products is the chief benefit in sliplining applications, primarily the ability to produce custom sizes and lengths. Another benefit includes the various coating options. Applications that involve a high level of abrasive flows should opt for polymer coated spiral rib pipe.
	Applications using aluminum alloy pipe should specify a non-acidic grout with no chlorides for the annular space. In the absence of a grout specification the aluminum alloy pipe should be painted to form a barrier between the pipe and the grout. Aluminized steel does not require this precaution.
D A Van Dam & Associates LLC	The depth of cover and ability to push the pipe might need to push shorter lengths depending on stream conditions...we would like to push 50-foot lengths when possible. We have done culverts that are over 1900 feet in length and one that was over 1,000 in length and 11 foot in diameter with several laterals over 72 inches coming into it. Sharp bends can cause some issues and then you need to look at a structural coating like a UV CIPP (up to 60 inches). We do not like the CIPP due to leaching into the streams and the high temperatures needed to cure the material hurting the stream basins. UVCIPP does not do that and does not have the higher mobilization cost like CIPP does. NY has banned the use of CIPP for culverts and will only allow UVCIPP.
ISCO Industries Inc.	We are limited to diameters of 8" or greater and 10 ft in diameter or less for the liner. We have lined host culvert structures in many different geometric shapes from round to box including archways and oval structures. We offer round and oval products as liners. Often times the liner will match or exceed the flow conditions of the existing host, but it becomes more difficult to match existing flow in box-shaped conveyance systems.

Q.2.2.3 Provide links to technical datasheet(s) that has (have) the outside and inside dimensions for each span and for each conduit type.

Table B.3**:** Conduit Dimensions Mentioned by Conduit Manufacturers

Company Name	**Links or Datasheets**
Springfield Plastics, Inc	18": ID = 17.856, OD = 21.125 21": ID = 20.832, OD = 24.550 24": ID = 23.798, OD = 27.500 30": ID = 29.759, OD = 34.625 36": ID = 35.711, OD = 41.800 48": ID = 47.615, OD = 54.900
Contech Engineered Solutions	Go to Conteches.com. All this information can be found on this website under the "reline" section.
Lane Enterprises, Inc.	We suggest using the applicable ASTM/AASHTO standards for this information as certain tolerances may be applicable, while also noting that custom dimensions are quickly becoming common for sliplining applications.
ISCO Industries Inc.	www.culvert-rehab.com

B.2.2 Annulus filling

Q.2.2.1: How critical is complete filling of grout in the annulus void to the successful functioning and longevity of your conduit type(s)? Please respond only for conduit type(s) that are relevant to you.

Table B.4: Conduit Types Used by Conduit Manufacturers for Culvert Sliplining

Conduit Type	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**St Regis Culvert, Inc.**	**Contech Engineered Solutions**	**Lane Enterprises, Inc.**	**D A Van Dam & Associates LLC**	**American Concrete Pipe Association**	**ISCO Industries Inc.**
Corrugated steel pipe	VC			SC	SC	U	VC		VC
Structural plate corrugated steel structure	U				SC	U	VC		VC
Precoated galvanized steel culvert	VC			SC	SC	U	VC		VC
Polymer-precoated corrugated steel spiral rib pipe	U			SC	SC	U	VC		VC
Corrugated steel spiral rib pipe	U			SC	SC	U	VC		VC
Polymer precoated, galvanized steel conduit	VC			SC	SC	U	VC		VC
Aluminum coated steel conduit	VC			SC	SC	U	VC		VC
Galvanized coated steel conduits	VC			SC	SC	U	VC		VC
Corrugated aluminum alloy pipe	U			VC	SC	U	VC		VC
Aluminum alloy structural plate conduit	U				SC	U	VC		VC
Corrugated aluminum spiral rib pipe	U				SC	U	VC		VC
Corrugated polyethylene smooth lined pipe	VC	VC	SC		SC	U	VC		VC
Polyethylene plastic pipe based on outside diameter (OD)	VC						VC		VC
Polyethylene profile wall pipe	VC				SC		VC		VC
Polyvinyl chloride corrugated smooth interior pipe	VC				SC		VC		VC
Polyvinyl chloride profile wall pipe	VC				SC		VC		VC

Table B.4: Conduit Types Used by Conduit Manufacturers for Culvert Sliplining (continued)

Conduit Type	Haviland Drainage	ADS	Springfield Plastics, Inc	St Regis Culvert, Inc.	Contech Engineered Solutions	Lane Enterprises, Inc.	D A Van Dam & Associates LLC	American Concrete Pipe. Association	ISCO Industries Inc.
Steel casing pipe	VC						VC		VC
Steel reinforced thermoplastic ribbed pipe	VC				SC		VC		VC
Glass-fiber-reinforced polymer mortar pipe	U						VC		VC
Reinforced concrete circular pipe	VC						VC		VC

*** NCA: Not Critical at All, NC: Not Critical, U: Unknown, SC: Somewhat Critical, VC: Very Critical*

Table B.5: Other Conduit Types Used by Conduit Manufacturers for Culvert Sliplining

	ADS	D A Van Dam & Associates LLC	American Concrete Pipe Association
Other Materials/ Additional responses	PP Pipe per 707.65, 707.69 (Very Critical)	Grouting must be done in uniformed lifts and slowly as to not to produce excessive heat on HDPE material (Very Critical)	Beyond stabilizing the liner and holding it in place, the grout has little impact on the life expectancy of the installed liner. A 100 year life span or longer can be anticipated for the liner pipe is anticipated based on 3rd party studies by JANA Labs – AWWA – TRB and other resources. The most critical role that the grout plays in the SnapTite approach is its ability to fill existing voids beyond the host pipe to stabilize the fill materials used to support and maintain the road surface. That is what is of primary importance. (Very Critical)

Q.2.2.2 Indicate which grout you recommend for annulus voids with each type of conduit for culvert lengths less than or equal to 100 feet. Please respond only for conduit type(s) that are relevant to you.

Table B.6: Controlled Low Strength Mortar (ODOT Item 613) Recommended by Conduit Manufacturers (Up to 100 feet)

Controlled Low Strength Mortar (ODOT Item 613)	**Haviland Drainage**	**ADS**	**Lane Enterprises, Inc.**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S		S		S
Structural plate corrugated steel structure			S		S
Precoated galvanized steel culvert			S		S
Polymer-precoated corrugated steel spiral rib pipe			S		S
Corrugated steel spiral rib pipe			S		S
Polymer precoated, galvanized steel conduit			S		S
Aluminum coated steel conduit			S		S
Galvanized coated steel conduits			S		S
Corrugated aluminum alloy pipe			S		S
Aluminum alloy structural plate conduit			S		S
Corrugated aluminum spiral rib pipe			S		S
Corrugated polyethylene smooth lined pipe	S	A	S		S
Polyethylene plastic pipe based on outside diameter	S				S
Polyethylene profile wall pipe					S
Polyvinyl chloride corrugated smooth interior pipe				N	S
Polyvinyl chloride profile wall pipe				N	S

**A: Always, S: Sometimes, N: Never*

Table B.6: Controlled Low Strength Mortar (ODOT Item 613) Recommended by Conduit Manufacturers (Up to 100 feet) (continued)

Controlled Low Strength Mortar (ODOT Item 613)	**Haviland Drainage**	**ADS**	**Lane Enterprises, Inc.**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Steel casing pipe				S	S
Steel reinforced thermoplastic ribbed pipe				S	S
Glass-fiber-reinforced polymer mortar pipe				S	S
Reinforced concrete circular pipe				S	S
Other		A (PP Pipe per 707.65, 707.69)			S (We always recommend Cellular Grouts but will some-times use CLSM if required by the owner or necessary to meet loading demands)

**A: Always, S: Sometimes, N: Never*

Table B.7: Low-Shrinkage Mortar Recommended by Conduit Manufacturers
(Up to 100 feet)

Low-Shrinkage Mortar (ODOT Item 602)	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S			S	N
Structural plate corrugated steel structure				S	N
Precoated galvanized steel culvert				S	N
Polymer-precoated corrugated steel spiral rib pipe				S	N
Corrugated steel spiral rib pipe				S	N
Polymer precoated, galvanized steel conduit				A	N
Aluminum coated steel conduit				S	N
Galvanized coated steel conduits				S	N
Corrugated aluminum alloy pipe				S	N
Aluminum alloy structural plate conduit				S	N
Corrugated aluminum spiral rib pipe				S	N
Corrugated polyethylene smooth lined pipe	S		S	S	N
Polyethylene plastic pipe based on outside diameter	S			S	N
Polyethylene profile wall pipe				S	N
Polyvinyl chloride corrugated smooth interior pipe				N	N
Polyvinyl chloride profile wall pipe				N	N
Polyethylene profile wall pipe				S	N
Polyvinyl chloride corrugated smooth interior pipe				N	N
Polyvinyl chloride profile wall pipe				N	N
Steel casing pipe				S	N
Steel reinforced thermoplastic ribbed pipe					N
Glass-fiber-reinforced polymer mortar pipe				S	N
Reinforced concrete circular pipe				S	N

** A: Always, S: Sometimes, N: Never*

Table B.8: Low-Shrinkage Mortar Recommended by Conduit Manufacturers (Up to 100 feet) – Other Materials

	ADS	**ISCO Industries Inc.**
Other materials	Polypropylene Pipe per 707.65, 707.69	N (We always recommend Cellular Grouts but will sometimes use CLSM if required by the owner or necessary to meet loading demands)

** N: Never*

Table B.9: Cellular Concrete Grout Recommended by Conduit Manufacturers
(Up to 100 feet)

Cellular Concrete Grout (ASTM C869)	Haviland Drainage	ADS	Springfield Plastics, Inc	D A Van Dam & Associates LLC	ISCO Industries Inc.
Corrugated steel pipe	S			A	A
Structural plate corrugated steel structure				A	A
Precoated galvanized steel culvert				A	A
Polymer-precoated corrugated steel spiral rib pipe				A	A
Corrugated steel spiral rib pipe				A	A
Polymer precoated, galvanized steel conduit				A	A
Aluminum coated steel conduit				A	A
Galvanized coated steel conduits				A	A
Corrugated aluminum alloy pipe				A	A
Aluminum alloy structural plate conduit				A	A
Corrugated aluminum spiral rib pipe				A	A
Corrugated polyethylene smooth lined pipe	S		S	A	A
Polyethylene plastic pipe based on outside diameter	S			A	A
Polyethylene profile wall pipe				A	A
Polyvinyl chloride corrugated smooth interior pipe				N	A
Polyvinyl chloride profile wall pipe				N	A
Steel casing pipe				A	A
Steel reinforced thermoplastic ribbed pipe					A
Glass-fiber-reinforced polymer mortar pipe				A	A
Reinforced concrete circular pipe				A	A

** A: Always, S: Sometimes, N: Never*

Table B.10: Cellular Concrete Grout Recommended by Conduit Manufacturers (Up to 100 feet) (Other Materials)

Cellular Concrete Grout (ASTM C869)	**ADS**	**ISCO Industries Inc.**
Other materials	Polypropylene Pipe per 707.65, 707.69	A (We always recommend Cellular Grouts but will sometimes use CLSM if required by the owner or necessary to meet loading demands)

** A: Always, S: Sometimes, N: Never*

Q.2.2.3 Indicate which grout you recommend for annulus voids with each type of conduit for culvert lengths greater than 100 feet, but less than or equal to 200 feet. Please respond only for conduit type(s) that are relevant to you.

Table B.11: Controlled Low Strength Mortar Recommended by Conduit Manufacturers (100 feet – 200 feet)

Controlled Low Strength Mortar (ODOT Item 613)	**Haviland Drainage**	**ADS**	**Lane Enterprises, Inc.**	**ISCO Industries Inc.**
Corrugated steel pipe	S		S	S
Structural plate corrugated steel structure			S	S
Precoated galvanized steel culvert			S	S
Polymer-precoated corrugated steel spiral rib pipe			S	S
Corrugated steel spiral rib pipe			S	S
Polymer precoated, galvanized steel conduit			S	S
Aluminum coated steel conduit			S	S
Galvanized coated steel conduits			S	S
Corrugated aluminum alloy pipe			S	S
Aluminum alloy structural plate conduit			S	S
Corrugated aluminum spiral rib pipe			S	S
Corrugated polyethylene smooth lined pipe	S	A	S	S
Polyethylene plastic pipe based on outside diameter				S
Polyethylene profile wall pipe	S			S
Polyvinyl chloride corrugated smooth interior pipe				S
Polyvinyl chloride profile wall pipe				S
Steel casing pipe				S
Steel reinforced thermoplastic ribbed pipe				S
Glass-fiber-reinforced polymer mortar pipe				S
Reinforced concrete circular pipe				S

** A: Always, S: Sometimes, N: Never*

Table B.12: Controlled Low Strength Mortar Recommended by Conduit Manufacturers (100 feet – 200 feet) (Other Materials)

Controlled Low Strength Mortar (ODOT Item 613)	**ADS**	**ISCO Industries Inc.**
Other materials	A (Polypropylene Pipe per 707.65, 707.69	S (We always recommend Cellular Grouts but we will use CLSM when required by owner or deemed necessary to meet loading demand. From our experience lighter density grouts create less risk as length increases.)

* *A: Always, S: Sometimes, N: Never*

Table B.13: Low-Shrinkage Mortar (ODOT Item 602) Recommended by Conduit Manufacturers (100 feet – 200 feet)

Low-Shrinkage Mortar (ODOT Item 602)	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S			S	N
Structural plate corrugated steel structure				S	N
Precoated galvanized steel culvert				S	N
Polymer-precoated corrugated steel spiral rib pipe				S	N
Corrugated steel spiral rib pipe				S	N
Polymer precoated, galvanized steel conduit				S	N
Aluminum coated steel conduit				S	N
Galvanized coated steel conduits				S	N
Corrugated aluminum alloy pipe				S	N
Aluminum alloy structural plate conduit				S	N
Corrugated aluminum spiral rib pipe				S	N
Corrugated polyethylene smooth lined pipe	S		S	S	N
Polyethylene plastic pipe based on outside diameter				A	N
Polyethylene profile wall pipe	S			S	N
Polyvinyl chloride profile wall pipe				N	N
Steel casing pipe				S	N
Steel reinforced thermoplastic ribbed pipe				S	N
Glass-fiber-reinforced polymer mortar pipe				S	N
Reinforced concrete circular pipe				A	N

**A: Always, S: Sometimes, N: Never*

Table B.14: Low-Shrinkage Mortar (ODOT Item 602) Recommended by Conduit Manufacturers (100 feet – 200 feet) - Other Materials

Low-Shrinkage Mortar (ODOT Item 602)	**ADS**	**ISCO Industries Inc.**
Other materials	Polypropylene Pipe 707.65, 707.69	N (We always recommend Cellular Grouts but we will use CLSM when required by owner or deemed necessary to meet loading demand. From our experience lighter density grouts create less risk as length increases.)

** A: Always, S: Sometimes, N: Never*

Table B.15: Cellular Concrete Grout (ASTM C869)
Recommended by Conduit Manufacturers (100 feet – 200 feet)

Cellular Concrete Grout (ASTM C869)	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S			A	A
Structural plate corrugated steel structure				A	A
Precoated galvanized steel culvert				A	A
Polymer-precoated corrugated steel spiral rib pipe				A	A
Corrugated steel spiral rib pipe				A	A
Polymer precoated, galvanized steel conduit				A	A
Aluminum coated steel conduit				A	A
Galvanized coated steel conduits				A	A
Corrugated aluminum alloy pipe				A	A
Aluminum alloy structural plate conduit				A	A
Corrugated aluminum spiral rib pipe				A	A
Corrugated polyethylene smooth lined pipe	S		S	A	A
Polyethylene plastic pipe based on outside diameter				A	A
Polyethylene profile wall pipe	S			A	A
Polyvinyl chloride corrugated smooth interior pipe				N	A
Polyvinyl chloride profile wall pipe				N	A
Steel casing pipe				A	A
Steel reinforced thermoplastic ribbed pipe				A	A
Glass-fiber-reinforced polymer mortar pipe				A	A
Reinforced concrete circular pipe				A	A

**A: Always, S: Sometimes, N: Never*

Table B.16: Cellular Concrete Grout (ASTM C869) Recommended by Conduit Manufacturers (100 feet – 200 feet) - Other Materials

Cellular Concrete Grout (ASTM C869)	**ADS**	**ISCO Industries Inc.**
Other materials	Polypropylene Pipe 707.65, 707.69	A (We always recommend Cellular Grouts but we will use CLSM when required by owner or deemed necessary to meet loading demand. From our experience lighter density grouts create less risk as length increases.)

** A: Always, S: Sometimes, N: Never*

Q.2.2.4 Indicate which grout you recommend for annulus voids with each type of conduit for culvert lengths greater than 200 feet, but less than or equal to 300 feet. Please respond only for conduit type(s) that are relevant to you.

Table B.17**:** Controlled Low Strength Mortar (ODOT Item 613) Recommended by Conduit Manufacturers (200 feet – 300 feet)

Controlled Low Strength Mortar (ODOT Item 613)	**Haviland Drainage**	**ADS**	**Lane Enterprises, Inc.**	**ISCO Industries Inc.**
Corrugated steel pipe	S		S	S
Structural plate corrugated steel structure			S	S
Precoated galvanized steel culvert			S	S
Polymer-precoated corrugated steel spiral rib pipe			S	S
Corrugated steel spiral rib pipe			S	S
Polymer precoated, galvanized steel conduit			S	S
Aluminum coated steel conduit			S	S
Galvanized coated steel conduits			S	S
Corrugated aluminum alloy pipe			S	S
Aluminum alloy structural plate conduit			S	S
Corrugated polyethylene smooth lined pipe	S	A	S	S
Polyethylene plastic pipe based on outside diameter			S	S
Polyethylene profile wall pipe	S			S
Polyvinyl chloride corrugated smooth interior pipe				S
Polyvinyl chloride profile wall pipe				S
Steel casing pipe				S
Steel reinforced thermoplastic ribbed pipe				S
Glass-fiber-reinforced polymer mortar pipe				S
Reinforced concrete circular pipe				S
Other		A (PP 707.65, 707.69)		S (See Q 4.3)

** A: Always, S: Sometimes, N: Never*

Table B.18: Low-Shrinkage Mortar (ODOT Item 602) Recommended by Conduit Manufacturers (200 feet – 300 feet)

Low-Shrinkage Mortar (ODOT Item 602)	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S			S	N
Structural plate corrugated steel structure				S	N
Precoated galvanized steel culvert				S	N
Polymer-precoated corrugated steel spiral rib pipe				S	N
Corrugated steel spiral rib pipe				S	N
Polymer precoated, galvanized steel conduit				S	N
Aluminum coated steel conduit				S	N
Galvanized coated steel conduits				S	N
Corrugated aluminum alloy pipe				S	N
Aluminum alloy structural plate conduit				S	N
Corrugated aluminum spiral rib pipe				S	N
Corrugated polyethylene smooth lined pipe	S		S	S	N
Polyethylene plastic pipe based on outside diameter				S	N
Polyethylene profile wall pipe	S			S	N
Polyvinyl chloride corrugated smooth interior pipe				N	N
Polyvinyl chloride profile wall pipe				N	N
Steel casing pipe				S	N
Steel reinforced thermoplastic ribbed pipe				S	N
Glass-fiber-reinforced polymer mortar pipe				S	N
Reinforced concrete circular pipe				S	N
Other		PP 707.65, 707.69			N (See Q 4.3)

**A: Always, S: Sometimes, N: Never*

Table B.19: Cellular Concrete Grout (ASTM C869) Recommended by Conduit Manufacturers (200 feet – 300 feet)

Cellular Concrete Grout (ASTM C869)	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	S			A	A
Structural plate corrugated steel structure				A	A
Precoated galvanized steel culvert				A	A
Polymer-precoated corrugated steel spiral rib pipe				A	A
Corrugated steel spiral rib pipe				A	A
Polymer precoated, galvanized steel conduit				A	A
Aluminum coated steel conduit				A	A
Galvanized coated steel conduits				A	A
Corrugated aluminum alloy pipe				A	A
Aluminum alloy structural plate conduit				A	A
Corrugated aluminum spiral rib pipe				A	A
Corrugated polyethylene smooth lined pipe	S		S	A	A
Polyethylene plastic pipe based on outside diameter				A	A
Polyethylene profile wall pipe	S			A	A
Polyvinyl chloride corrugated smooth interior pipe				N	A
Polyvinyl chloride profile wall pipe				N	A
Steel casing pipe				A	A
Steel reinforced thermoplastic ribbed pipe				A	A
Glass-fiber-reinforced polymer mortar pipe				A	A
Reinforced concrete circular pipe				A	A
Other		PP 707.65, 707.69			A (See Q 4.3)

**A: Always, S: Sometimes, N: Never*

Q.2.2.5 What is the minimum and maximum grout thicknesses in inches you recommend for your conduit type(s) for sliplining applications? Please respond only for conduit type(s) that are relevant to you.

Table B.20: Grout Thicknesses Recommended by Conduit Manufacturers

Conduit Type	**Haviland Drainage**	**ADS**	**Springfield Plastics, Inc**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Corrugated steel pipe	6”-8”				1” (min)
Structural plate corrugated steel structure					1” (min)
Precoated galvanized steel culvert					1” (min)
Polymer-precoated corrugated steel spiral rib pipe					1” (min)
Corrugated steel spiral rib pipe					1” (min)
Polymer precoated, galvanized steel conduit					1” (min)
Aluminum coated steel conduit					1” (min)
Galvanized coated steel conduits					1” (min)
Corrugated aluminum alloy pipe					1” (min)
Aluminum alloy structural plate conduit					1” (min)
Corrugated aluminum spiral rib pipe					1” (min)
Corrugated polyethylene smooth lined pipe	6”-8”	Varies	0.25”-1.5”		1” (min)
Polyethylene plastic pipe based on outside diameter					1” (min)
Polyethylene profile wall pipe	6”-8”				1” (min)
Polyvinyl chloride corrugated smooth interior pipe					1” (min)
Polyvinyl chloride profile wall pipe					1” (min)
Steel casing pipe					1” (min)
Steel reinforced thermoplastic ribbed pipe					1” (min)
Glass-fiber-reinforced polymer mortar pipe					1” (min)
Reinforced concrete circular pipe					1” (min)

Table B.21: Grout Thicknesses Recommended by Conduit Manufacturers - Other Materials

Conduit Type	ADS	D A Van Dam & Associates LLC	ISCO Industries Inc.
Other	(Varies) Polypropylene 707.65,707.69	This is relevant to the amount of deflection in the pipe and what will be needed to hang the grout tubes and install running boards this determines what size pipe we can install therefore determining the amount of grout.	1" (min) (We recommend minimum of 1 inch around liner but have no maximum. That is determined by host pipe and existing conditions.)

Q.2.2.6 What procedures do you recommend for complete filling of annulus voids? Please respond only for conduit type(s) that are relevant to you.

Table B.22: Procedures of Annulus Filling Recommended by Conduit Manufacturers

	Haviland Drainage	ADS	D A Van Dam & Associates LLC	ISCO Industries Inc.
Response	grout, soil	See attached ADS literature regarding slip lining. ADS publishes recommendations on maximum grouting pressure, alignment, flotation, etc.	we like to run grout tubes and fill from the grout tubes. We have found when we fill from grout ports in the pipe we do not get as even of a fill	Use of a cellular grout that has low viscosity with fluidity properties rather than a high viscosity grout that is stiff and hard to flow. Use of vent ports to monitor grout fill levels. Guide and support rails that allow for free flow of grout in the annulus. Monitor the total volume placed (generally actual placement volumes will be 30% more or greater than annulus volume.

Q.2.2.7 How do you determine if the annulus void is fully filled with grout for your conduit type(s)?

Table B.23: Verification of Grout Filling Recommendation by Conduit Manufacturers

	Haviland Drainage	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Response	visual	we always have a person in the pipe sounding as we fill, we know what we calculated and we should be very close to that amount or over. We are over when we have voids behind the culvert that we fill with the grout. This is why you need to go slow and not try and do it in one shot. Slow and steady sounding and placing the grout tubes correctly and filling them correctly is the key.	See 4.6 above. Also studies have been conducted on past installations using pipeline assessment tools including soundings, ground penetrating radar, and backscatter chromatography using radioactive isotopes, along with physical dig-ups. All show not only is the annulus between the host pipe and the liner completely filled, but that the grout also efficiently fills voids in the surrounding embedment materials.

Q2.2.8 What coupling and/or jointing methods do you use for your conduit type(s)?

Table B.24: Coupling or Jointing Methods Recommended by Conduit Manufacturers

	Haviland Drainage	**ADS**	**D A Van Dam & Associates LLC**	**ISCO Industries Inc.**
Response	integrated bell/spigot	Standard pipe joints	we use plumbers glue on joints to insure a tight joint.	For solid wall pipe installations, we use a mechanical SnapTite joining system. For profile wall products a threaded connection or a bell and spigot connection is necessary. The allowable tensile load and compression load for the joining system is usually assumed to be 1/3 of the strength of the parent pipe material (actual ratings change with diameters). The joining methods meet the sealing requirements of AASHTO M326. Thermal extrusion welding has been utilized for additional mechanical reinforcement in limited cases.

B.2.3 Projects

Q.2.3.1 Do you have details of any successful past projects that you can share? Please also share any lessons learned and improvements made from these projects. What would you do differently to improve the effectiveness of sliplining culvert rehabilitation?

Table B.25: Successful Recommended Projected by Conduit Manufacturers

	Haviland Drainage	D A Van Dam & Associates LLC	ISCO Industries Inc.
Response	limited experience, just a local steel culvert lined and grouted	I will send some projects we have done over the years to your attention. We are finishing a project in Green Ohio if you want to go to a job site. Contact my foreman. I think they are grouting today and tomorrow. This was complicated because from the time we quoted the twin culverts another utility company come and punched a large hole in one of the culverts causing us to make a repair before we could even start the lining. Steve can give you directions. We are about to start a project in North Royalton within the next month also and we have one on the books for the fall after they close for a non profit at the Wilds in Cumberland, Ohio.	City of Huber Heights, OH Various locations and sizes throughout city limits. Used 40 lb wet cast density grout. No issues on grout installations. We learned that proper bulkhead building is key to successful grout projects City of Oak Hill TN Various location and sizes throughout city limits. Used 40 lb wet cast density grout 6 sites KYTC Maintenance Grout Contract 40 lb wet cast density grout Multiple sites throughout the state

Q.2.3.2 Do you have any material/installation/inspection specifications, standards or guidelines for your conduit type(s) when used in sliplining applications? If so, please provide links. You may also email files to: Patnaik@uakron.edu

Table B.26: Specification or Guidelines used by Conduit Manufacturers

	D A Van Dam & Associates LLC	ISCO Industries Inc.
Response	I will send them over	www.culvert- rehab.com

B.2.4 Non-Destructive Evaluation

Q.2.4.1 Are you aware of any non-destructive evaluation techniques suitable for the evaluation of annulus void grout when liners are made from your conduit type(s)?

Table B.27: Non-Destructive Evaluation Recommended by Conduit Manufacturers

	Haviland Drainage	D A Van Dam & Associates LLC	ISCO Industries Inc.
Response	not aware	no I don't know how you could do a parallel plate test since it is in the ground. I will ask some of my vendors.	There are many pipelines assessment tools available on the market. Pipe soundings can be used to quickly gain knowledge of any significant voids between the host pipe and the liner. Ground Penetrating Radar can be used investigate voids that may be present in the fill beyond the host pipe. But the presence of clays or salts (often used for snow and ice removal) can influence the electromagnetics used by the GPR systems. Backscatter Chromatography has also been utilized to evaluate how the low-density grouts can fill and mitigate voids beyond the host pipe, but the necessary radioactive isotopes used and obtained from the DOE make that evaluation very expensive to conduct.

B.2.5 New Technology or Materials

Q.2.5.1 Do you have any new technology or material improvements for slipliners coming up in the near future?

Table B.28: New Technology Recommended by Conduit Manufacturers

	Haviland Drainage	D A Van Dam & Associates LLC	ISCO Industries Inc.
Response	No	UVCIPP should really be considered. It is 4 times as strong as CIPP can do bends and has no styrenes or changing of the PH of streams or aquic life and has a much small footprint and much lower mobilization cost than CIPP. I have been told the State of New York will not allow the use of CIPP for culvert lining due to stream contamination. I do have an HDPE pipe company who is making HDPE pipe with corrugations on the inside (not a smooth pipe inside) to slow the flow for culvert lining. Would you like a sample? It was produced because the culverts in Maine have a need due to the marine life along their coastline. They have even been asked to put lights in culverts for marine life to spawn and add gravel for fish to lay eggs in. Hence the need for a ribbed culvert on the inside.	Not currently

B.2.6 Conclusions based on responses from conduit manufacturers

This section provides a summary of the responses provided by the nine conduit manufacturers who responded to the survey. The subsections below summarize the responses to questions about the types of conduit pipes that manufacturers/suppliers recommend using for the sliplining of culverts, how often different types of grouts (confined low-strength material (CLSM), low-strength material (LSM), and cellular grout) are used for conduits of various lengths, the recommended grout thickness used when sliplining with different conduits, and the recommended approach for installation.

B.2.6.1 *Types of Conduit Pipes Used for Sliplining*

Figure B.1 presents the responses to questions about the types of conduit pipes used for sliplining. From this table, it can be noticed that most conduits that can be used for the sliplining of culverts are corrugated polyethylene smooth lined pipes (ODOT CMS Item 707.33). The high demand for this conduit is based on specific characteristics of the pipe: it is lightweight and has a high strength-to-weight ratio. This pipe is also easy to handle and is available in long lengths, which allows rapid installation. Moreover, polyethylene smooth liner pipe is considered as one of the most economical pipes on the market. The second most frequently used conduit is corrugated steel spiral rib pipe (Item 707.12). Other conduits, such as reinforced concrete circular pipe (Item 706.02), glass-fiber-reinforced polymer mortar pipe (Item 707.75), and steel casing pipe (Item 748.06), were reported to be used less often for the sliplining of culverts. The lower demand for other conduit materials is believed to be related to their high cost as well as the difficulty in installation of the conduits, especially when the available space in a trench is too narrow to insert a liner pipe.

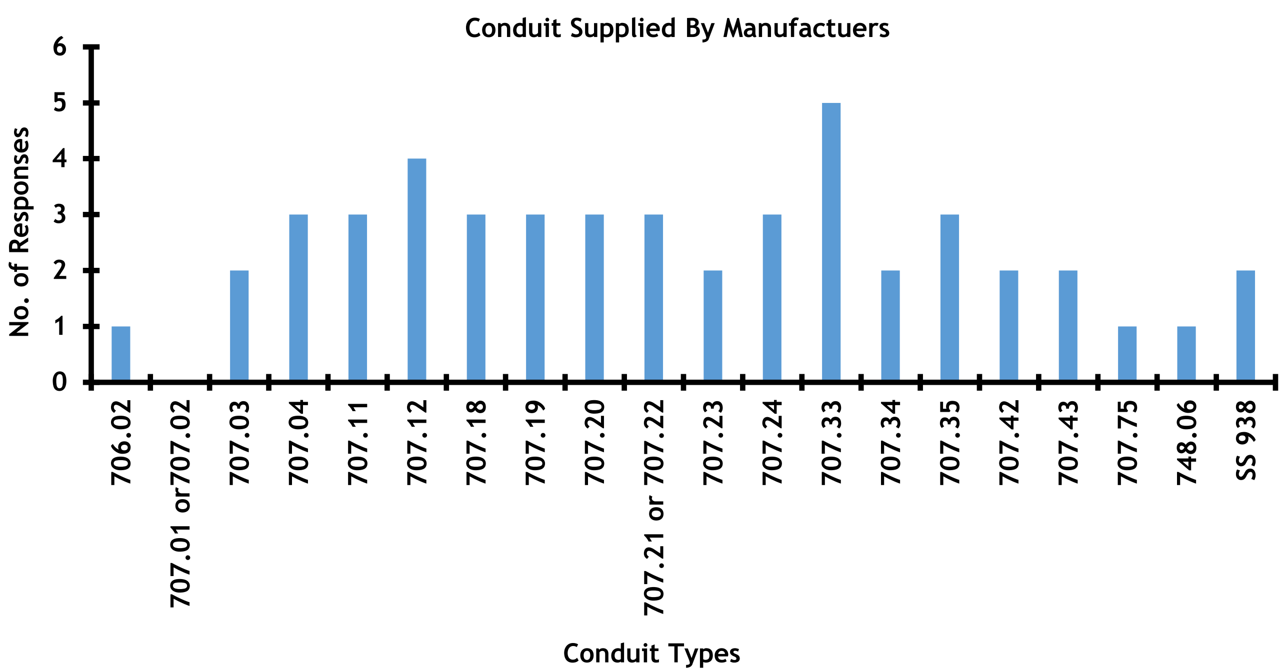

Figure B.1: Manufacturer Responses on the Use of Different Conduits for Sliplined Culverts.

B.2.6.2 *Importance of Grouting for Different Types of Conduits*

The responses on the importance of filling a culvert annulus with grout (where the response categories were "Unknown," "Not critical," "Somewhat critical," or "Very critical") was found to vary by conduit type, as shown in Figure B.2. A polyethylene smooth lined pipe (ODOT Item 707.33) was considered to be the liner pipe that is most critical to grout. About 56% of the respondents revealed that it is still critical to grout most liner pipes, whereas only 24% replied that it is "Somewhat critical" and only 20% responded with "Unknown." None of the responses indicated that the grouting is "Not critical" to any of the conduits considered in this study. It is also possible that the conduit manufacturers are not fully in line with owners on the importance of grouting.

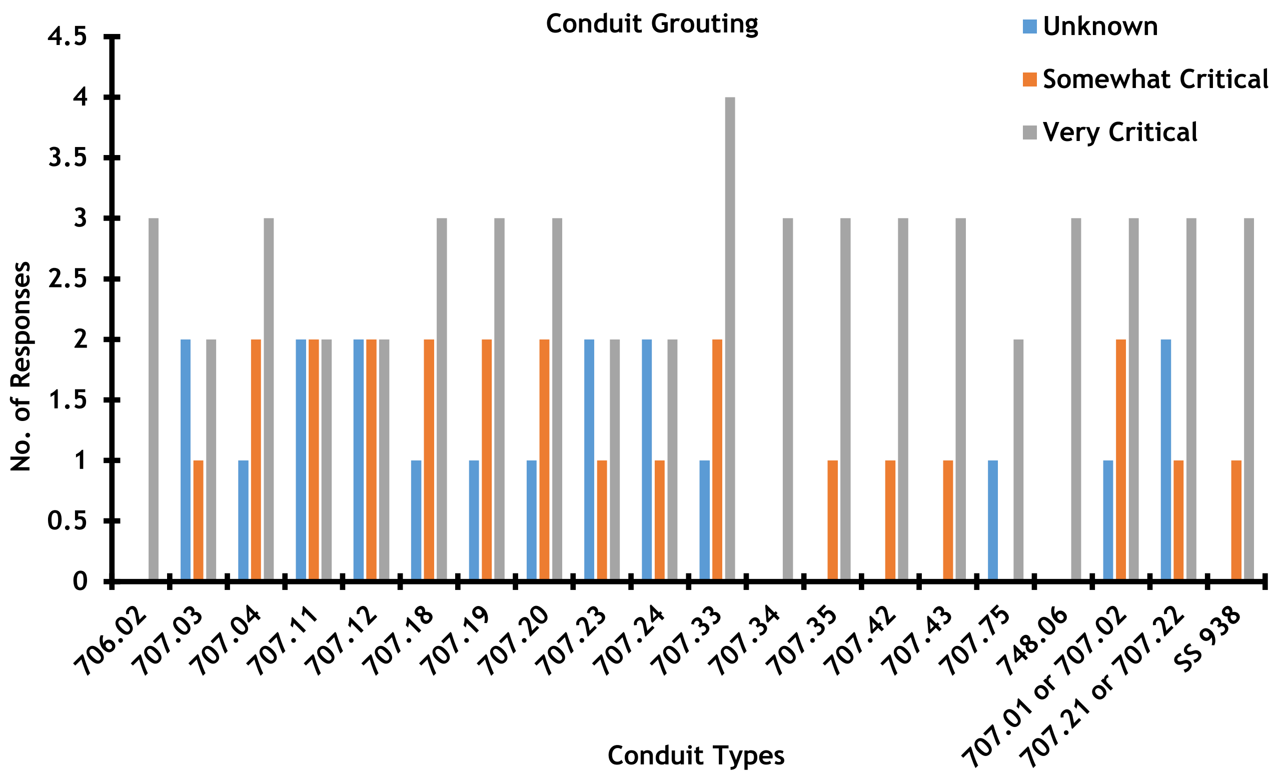

Figure B.2: Manufacturer Responses Regarding the Importance of Grouting for Conduits of Different Types.

B.2.6.3 Grout *Use for Conduits of Different Lengths*

Conduit manufacturers and suppliers were asked which of three different grouts (CLSM, LSM, and cellular grout) are used with various conduits as well as the recommended grout thickness for conduits of different types and the installation approach used for the grouting of sliplined culverts.

B.2.6.3.1 *Use of CLSM grout for different conduits*

Figure B.3 presents the responses on the use of CLSM grout (Item 613) for conduits of various lengths, where the responses for each grout type and conduit length are plotted individually. From this figure, it can be seen that approximately 3%, 47%, and 45% of the survey respondents replied “Sometimes” when asked if they grout the annulus with CLSM for conduits of up to 100 ft in length, from 100 to 200 ft in length, and from 200 to 300 ft in length, respectively. Almost no survey respondents replied “Always.” Thus, 95% of the survey respondents mentioned that they sometimes use CLSM for grouting sliplined culverts up to 300 ft in length.

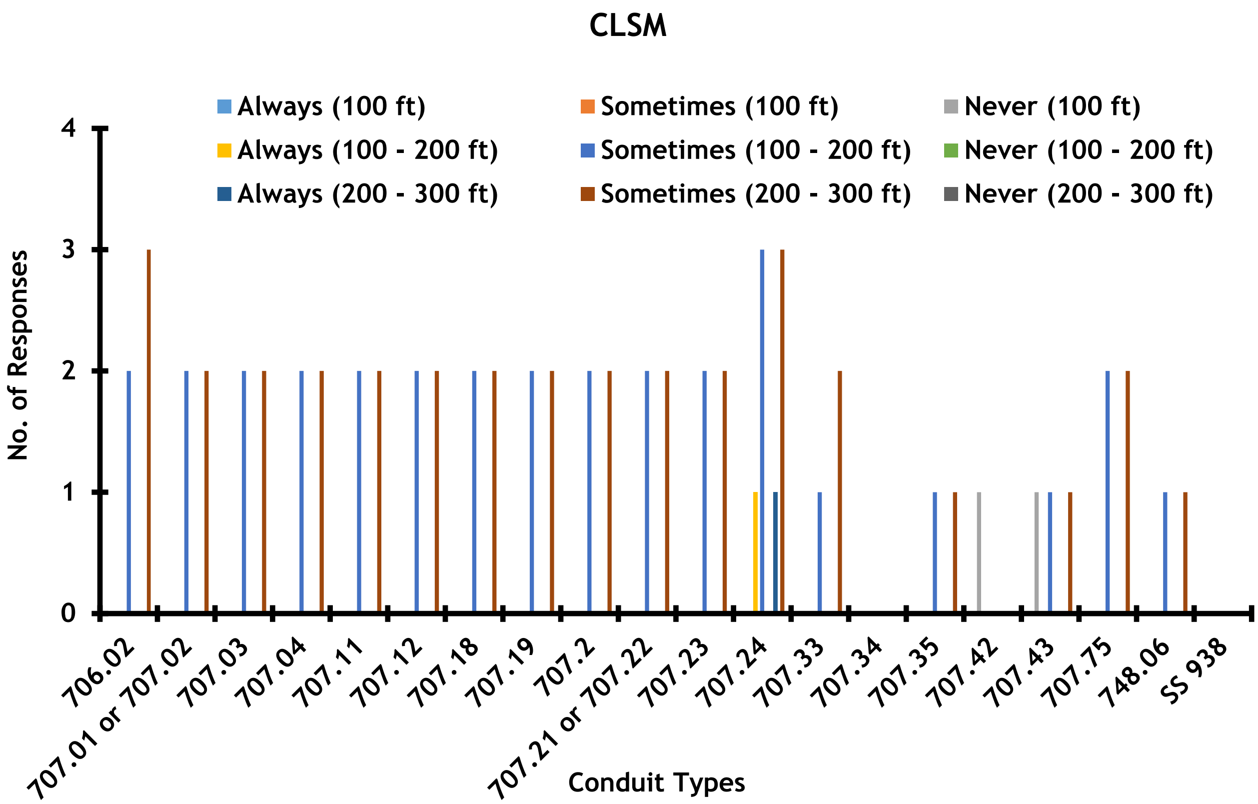

Figure B.3: Manufacturer Responses Regarding the Frequency of Use of CLSM Grout for Conduits of Different Lengths.

B.2.6.3.2 Use *of LSM grout for different conduits*

Figure B.4 shows that approximately 50% of conduit manufacturers “Never” use LSM grout (ASTM C869) for conduits with lengths of up to 300 ft. However, 18% of respondents replied “Sometimes” for conduits from 100 ft to 200 ft in length, and about 20% replied “Sometimes” for conduits from 200 to 300 ft in length. Only 2% of the respondents replied “Always” for conduits from 200 to 300 ft in length. Overall, 60% of respondents indicated that they “Never” use LSM grout for sliplining culverts of any length. In this figure, the responses for each grout type and conduit length are plotted individually. There is also some likelihood that the respondents did not differentiate between CLSM and LSM.

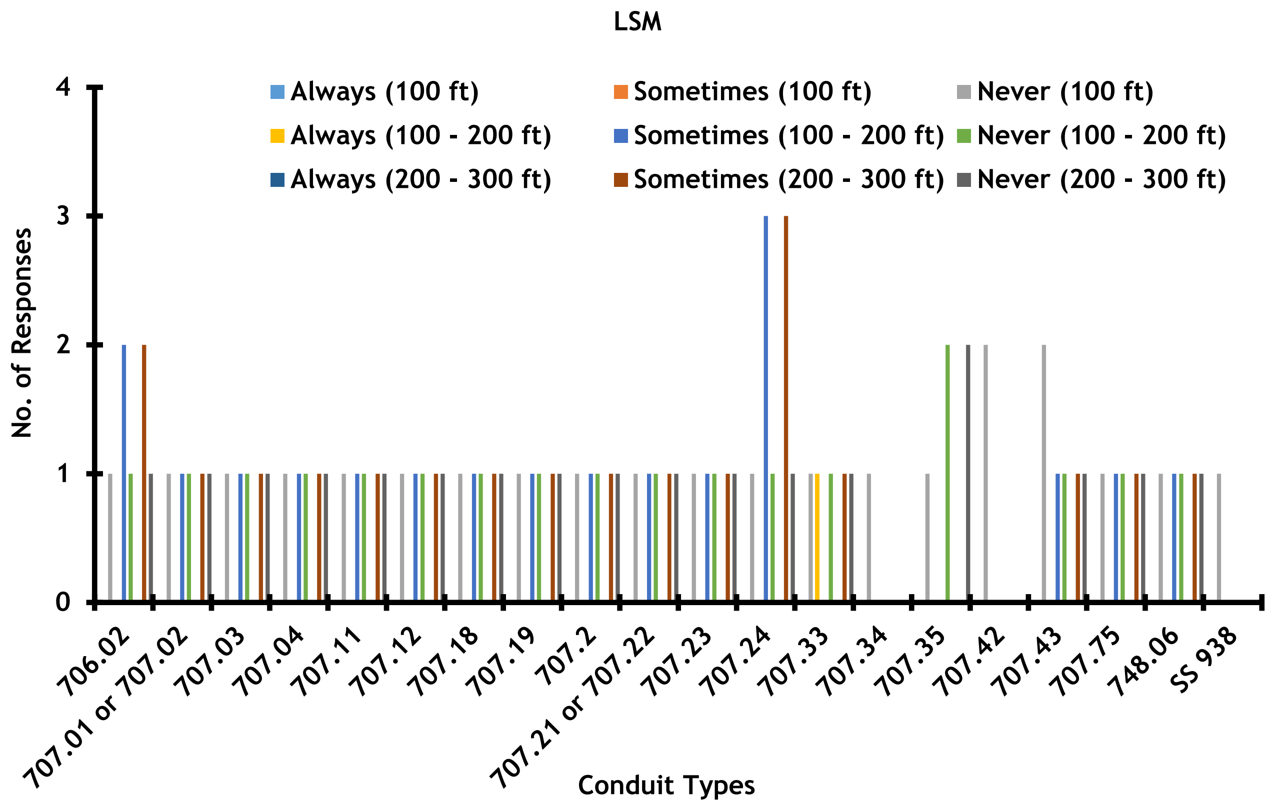

Figure B.4: Manufacturer Responses Regarding Frequency of Use of LSM Grout by Conduit Length.

B.2.6.3.3 *Use of cellular grout for different conduits*

Figure B.5 shows that most respondents “Always” use cellular grout (ODOT CMS Item 602). Approximately 13% of respondents indicated that they use cellular grout for conduits up to 100 ft in length. The percentage was even higher for longer lengths: 37% of respondents reported using this grout for conduits with a length from 100 to 200 ft, and 35% of respondents reported using this grout for conduit lengths from 200 to 300 ft. ISCO Industries recommends the use of cellular grout because of its light density, as this will reduce the risk for not flowing well as the length of the conduit increases. Only about 4% of respondents replied that they “Sometimes” use cellular grout for conduits from 100 to 200 ft in length or from 200 to 300 ft in length. About 2% replied that they “Never” use cellular grout for conduits of any length. For grouting sliplined culverts that are 200 to 300 ft in length, 94% of the survey respondents replied they “Always” use cellular grout, and just a few indicated they “Sometimes” use cellular grout. In this figure, the responses for each grout type and conduit length are plotted individually.

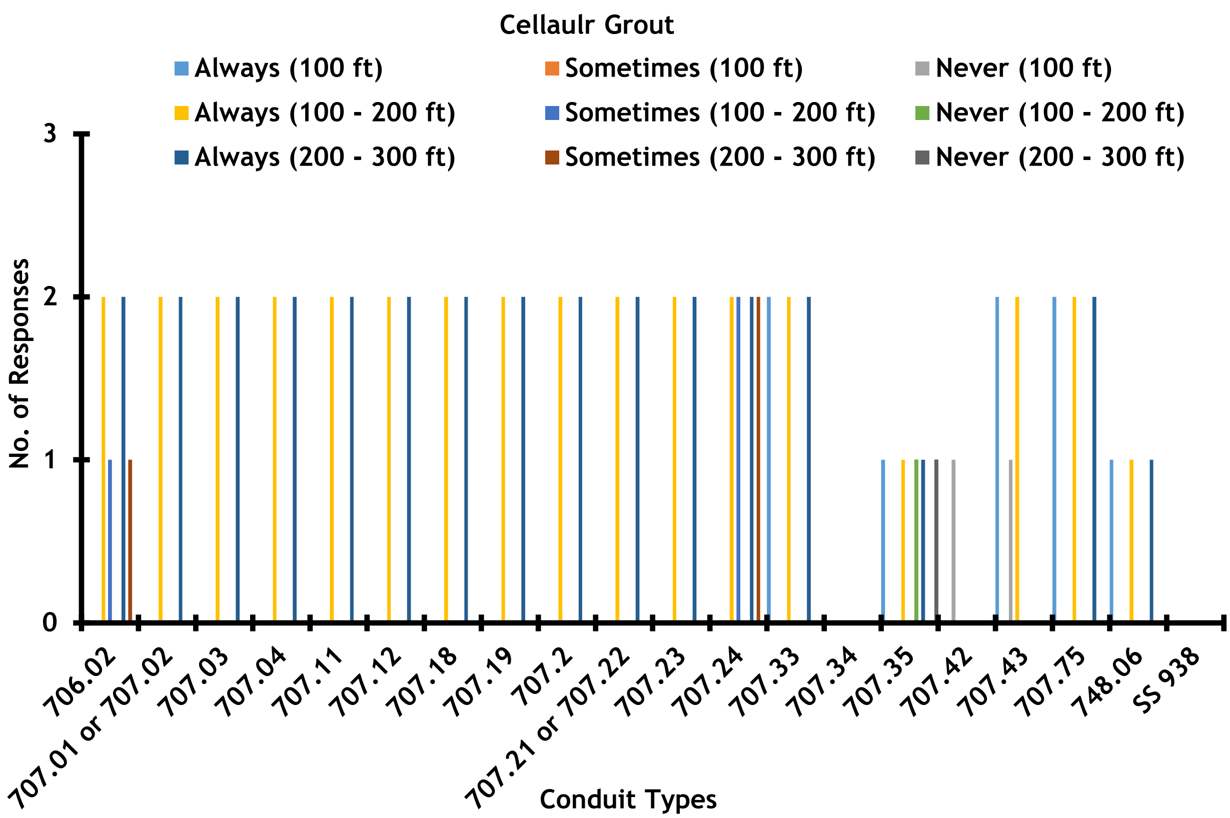

Figure B.5: Manufacturer Responses Regarding the Frequency of Use of Cellular Grout by Conduit Length.

B.2.6.4 *Grout Thickness Recommendations for Conduits of Different Types*

Grout thickness is the thickness of the grout in the annular space between the host pipe and the liner pipe. The annular space can vary in thickness at different clock positions along the diameter of the liner pipe, and the annular space can either be filled with grout, partially filled with grout, or empty. The survey questionnaire asked conduit manufacturers and suppliers about the recommended grout thickness to use for sliplining different types of conduits, and the responses are shown in Figure B.6. The manufacturers were asked to indicate minimum ("Min") and maximum ("Max") spaces in inches that can be grouted. As only three suppliers responded, the subscripts "1", "2" and, "3" for the "Min" or "Max" values indicates the response from a specific supplier. Supplier 3 recommended a minimum of 1 inch of space between the host pipe and liner pipe. However, for corrugated polyethylene smooth lined conduit pipe (Item 707.33), Supplier 2 suggested using a grout thickness as small as 0.25 inches. Other conduits, such as corrugated steel pipe (Item 707.01 or Item 707.02), corrugated polyethylene smooth lined pipe (Item 707.33), and polyethylene profile wall pipe (Item 707.35) were reported to accommodate a minimum grout thickness of 6 inches and a maximum of 8 inches. However, according to the survey results and the comments of the respondents, the grout thickness can be influenced by the host pipe size and the existing condition of the host pipe (e.g., if the host pipe has deflections at certain locations), and the size of the feed tube should also be considered.

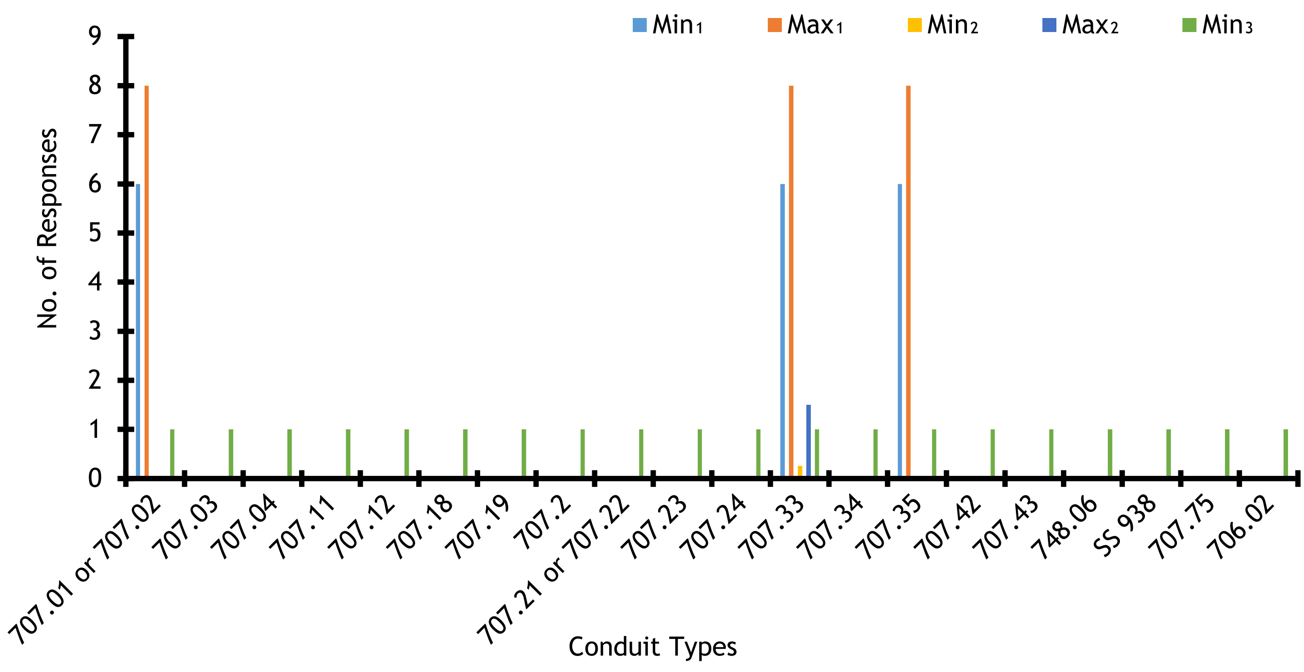

Figure B.6: Manufacturer Recommendations on Grout Thickness.

B.2.6.5 *Installation Approach Recommended by Conduit Manufacturers*

The installation of grout in a sliplined culvert can be approached in one of two ways: the first is to insert PVC feed tubes to pump grout into the annulus, and the second is to drill a hole in the liner pipe (known as a *port*) and install grout into the hollow spaces of the annulus. According to the survey, the main drawback of grouting the annulus through ports is that this method does not provide even filling at all locations in the annulus. For this reason, it is recommended to follow the feed tube method rather than grouting the annulus through ports. It is also recommended to use sounding with a hammer during grouting to confirm the level to which the grout has filled the annulus.

B.3 ODOT DISTRICTS

The survey distributed to Ohio District Offices consisted of nine questions, and most of these questions concerned the components and specifications used for sliplined culverts. When sliplining a culvert, ODOT District Offices often employ a variety of conduits, and the issues that follow concentrate on those conduit types. In addition, one consideration when grouting the annulus of a sliplined culvert is the use of the current ODOT grout specification (SS 837). This section also includes information on validating the culvert inspection results with either destructive or non-destructive methods. A total of 29 responses from 11 ODOT District Offices were obtained (from all districts except for District 4). The respondents included area engineers, transportation engineers, project engineers, transportation managers, district construction engineers, a construction manager, and a hydraulic engineer. The subsections that follow present the questions sent to ODOT District Offices; the responses are summarized in Tables B.29 to B.35.

B.3.1 Conduit types used

Q.3.1.1 Identify the conduit types you use for sliplining in your District.

Table B.29: Conduit Types Used for Sliplining in Different ODOT Districts

ODOT District	Conduit Types Used
1	Corrugated steel pipe (707.01 or 707.02) Precoated, galvanized steel culvert (707.04) Corrugated steel spiral rib pipe (707.12) Galvanized coated steel conduits (707.20) Precoated, galvanized steel culvert (707.04) Corrugated steel spiral rib pipe (707.12) Reinforced concrete circular pipe (706.02)
2	Corrugated steel pipe (707.01 or 707.02) Precoated, galvanized steel culvert (707.04) Galvanized coated steel conduits (707.20) Polyethylene plastic pipe based on outside diameter (707.34) Polyvinyl chloride corrugated smooth interior pipe (707.42) Steel casing pipe (748.06) Reinforced concrete circular pipe (706.02)
3	Steel casing pipe (748.06)
5	Corrugated steel pipe (707.01 or 707.02) Precoated, galvanized steel culvert (707.04) Corrugated steel spiral rib pipe (707.12) Aluminum coated steel conduit (707.19) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Steel casing pipe (748.06) Reinforced concrete circular pipe (706.02) Steel casing pipe (748.06) Corrugated steel pipe (707.01 or 707.02) Reinforced concrete circular pipe (706.02)
6	Polymer-precoated corrugated steel spiral rib pipe (707.11) Polyethylene plastic pipe based on outside diameter (707.34) Corrugated steel spiral rib pipe (707.12) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938) Other (please list and describe): Clay pipe

Table B.29: Conduit Types Used for Sliplining in Different ODOT Districts (Continued)

ODOT District	Conduit Types Used
9	Polyethylene plastic pipe based on outside diameter (707.34) Steel casing pipe (748.06) Structural plate corrugated steel structure (707.03) Corrugated polyethylene smooth lined pipe (707.33) Steel casing pipe (748.06) Corrugated steel spiral rib pipe (707.12) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Steel casing pipe (748.06)
10	Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34)
11	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated polyethylene smooth lined pipe (707.33) Steel casing pipe (748.06)
12	Structural plate corrugated steel structure (707.03) Polyethylene profile wall pipe (707.35) Polyvinyl chloride corrugated smooth interior pipe (707.42)
*N/A	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Corrugated steel spiral rib pipe (707.12) Steel casing pipe (748.06)

**N/A: not applicable*

B.3.2 Grouts other than those from SS 837

Q.3.2.1: Indicate if you use/used grouts other than those specified in SS 837 for filling annular space in sliplining applications. Please describe any deviation(s) from SS 837 you may have specified for sliplining projects in your District.

Table B.30: Use of Grouts Other Than Those Specified in SS 837

ODOT District	Grouts Other than SS 837 Grouts
1	Don't have experience with sliplining culverts.
2	N/A
3	None
5	I have not used grouts specified in SS 837 in any project yet, and I currently have no construction projects that plan to use SS 837
5	We used the Cellular Grout that conforms to SS 837 and ASTM C 869
5	N/A
6	No deviations from spec
7	No
9	None
9	None
11	No

B.3.3 Verification of complete grout filling

Q.3.3.1: How do your inspectors determine if annulus voids are fully filled with grout during grouting? How do they detect grout defects/voids after grout has hardened?

Table B.31: Verification of Grout Filling Recommended by Different ODOT Districts

ODOT District	Verification of Grout Filling - Before and After Hardening
1	Typically, we have holes at low spots to indicate the grout had filled the void when it runs out. I don't recall checking on gout hardens after it is done.
2	N/A
3	Sound with a hammer if large enough to enter
5	Sounding with hammer volume calcs before
5	Specification 611 reports display this during and after final inspection.
5	Voids were checked with small "breather" pipes installed at the outlet end of the liner pipe at various heights to ensure proper gravity flow. After it has hardened, the liner pipe is sounded to ensure there are no voids.
6	typically inspectors will stay out of the pipe during the actual grouting operations and they would sound the liner pipe the next day for any voids
9	Used grout ports, closed off from lowest elevation to highest elevation. Steel casing pipe can be sounded from the inside in an attempt to find voids.
9	Ensure that the grouting procedure is followed and inspect vent pipes. Can only check the ends after the bulkheads are removed. Voids are difficult to identify.
9	Grout return ports indicate fullness as well as checking grout quantities vs plan calculation. A hammer can indicate any "hollow" areas in the annulus.

B.3.4 Changes to Specifications

Q.3.4.1 Do you recommend any changes to ODOT material specification related to annulus void grouts?
Q.3.4.2 Do you recommend any changes to ODOT installation specification related to annulus void grouting?
Q.3.4.3 Do you recommend any changes to ODOT inspection protocols related to annulus void grouting, detection of voids, post-grouting performance verification and/or performance of hardened grout?

Table B.32: Specification/Insulation Recommended by ODOT Districts

ODOT District	Changes to Material Specification	Changes to Installation Specification	Changes to Inspection Methods
1			I have one recommendation for all the above questions. We should not allow the use of metal pipes. they seem to rust out especially the bottom in few years after installation.
2	I don't have enough experience with this to recommend changes.	I don't have enough experience with this to recommend changes.	I don't have enough experience with this to recommend changes.
3	No	No	No
5	Better pay items for cellular grout options		
5	I have not had lots of experience with annulus void grouts, so I have no recommendations.	I have not had lots of experience with annulus void grouts, so I have no recommendations.	I have not had lots of experience with annulus void grouts, so I have no recommendations. A possible solution is to include more inspection staff to ODOT to inspect these specifics in addition to 611 requirements.

Table B.32: Specification/ Insulation Recommended by ODOT Districts (Continued)

ODOT District	Changes to Material Specification	Changes to Installation Specification	Changes to Inspection Methods
5	I've only had experience with the cellular grout, but further clarification on the testing and basis of acceptance for cellular grout specifically would be helpful.	I would recommend clarification on the maximum allowable pressure because I'm assuming it refers to the preliminary pressure calculations and not physically testing the pressure in the field, but a physical test could be helpful	It would be helpful to have a testing protocol for detecting post-grouting voids because there is no visual way to be positive that grouting was completely successful without voids. Sounding can be helpful, but is not an exact method, so some kind of non-intrusive visual on The backfill would be helpful.
6	From field experience and discussions with liner contractors, the cellular grout material finds and fills the voids better than typical LSM material but the LSM is much cheaper and is allowed per the specifications, so the contractor provides it	the specification should not allow grout ports to be at the top of the pipe only. there should be witness holes near the 4 and 8 o'clock positions as well as the 2 and 10 o'clock positions. There should be more descriptive grouting procedures spelled out as the manufacture will not disagree with the contractor's methods as long as they are using their material.	I'm not too concerned with the hardened grout unless we feel shrinkage is a big problem con-tributing to the "voids" between the pipes down the road. Possibly require small diameter witness boreholes from the top surface drilled down and along the sides of the old pipe across the roadway portion and then refill with grout in hopes of finding any major voids that exist outside the limits of the old pipe that the liner grout did not address.
7	I have not witnessed this nor heard of issues with it.	No	No
9	No	Not at this time	Not at this time
9	Not at this time	Not at this time	not at this time
9	No	No	Ensure the actual quantity of grout used is very near plan quantity.

B.3.5 Potential projects for inspections

Q.3.5.1 Do you have any potential projects for the research team to review and inspect – projects that may have been poorly executed or projects with excellent annulus void fills? Please skip this question if a list from your District was already provided.

Please also share any lessons learned and improvements made related to sliplining projects in your District. What would you recommend to improve the effectiveness of sliplining culvert rehabilitation?

Table B.33: Potential Projects to Review and Inspect in Different ODOT Districts

ODOT District	Potential Projects for Inspections
2	No
5	I have not had lots of experience with sliplining at this current time.
5	Project 19-0264 (GUE 104755) is the slip lining project I have been a part of as a construction engineer and includes 3 different highway culverts being lined in Guernsey County. The annulus void fills were performed well with cellular grout mix, but there were a few issues we ran into that we're learning lessons. There was a miscommunication with the concrete supplier about the mix quantity before the foaming agent was added, so we weren't getting a full 10 cubic yard load out of each concrete truck. Also, the ultra-low density of the cellular grout led to more leaks through small gaps in welds that needed to be patched during grouting. We had one site with a significant void that was left at the outlet of the pipe due to a leak, but it was in an accessible section so it was easily corrected. Another unforeseen issue came from a lateral drainage pipe that fed into the existing pipe from the highway median that needed to be tied into the liner, but the grouting was able to successfully be performed and checked from the surface of the lateral pipe.
6	Depending on what the contractor selects to use for sleds and/or top runners to brace and hold the liner pipe on grade and where their grouting ports are located, could impact the ability to provide the grouting material in areas to fill all the voids present.
7	No
9	No

B.3.6 Destructive or non-destructive methods

Q.3.6.1 Are you aware of any in-situ destructive or non-destructive techniques used in your District for the evaluation of complete filling of annulus voids during grouting and after hardening of the grout? Include methods that can be used by inspectors to verify complete filling of annulus voids.

Table B.34: Destructive or Non-Destructive Evaluation Recommended by ODOT Districts

ODOT District	Any in-situ Destructive or Non-Destructive Techniques Used?
1	No
1	No
2	N/A
5	I have not had lots of experience with annulus void grouts, so I am not aware.
5	I am not aware of any techniques being used either destructive or non-destructive on a District level.
6	Sounding the liner pipe is the only method I know of that the ODOT inspector has to verify there are no voids present.
7	No
9	No
9	No

B.3.7 Other comments and information

Q.3.7.1 Please provide any other comments or information you would like to include regarding liner installation and annulus void grouting in order to improve the service life of sliplined culverts.

Table B.35: Other Information Provided by ODOT Districts

ODOT District	Any Other Information or Comments?
2	N/A
5	Some kind of infra-red or non-destructive test that could be performed from inside the pipe to determine annulus voids after grouting would be helpful to check the quality and method of the work performed.
6	Nothing else to add
9	N/A

B.3.8 Conclusions based on responses from ODOT District Offices

Based on the survey responses, the conduit types used by ODOT Districts and the grouts that they consider to be suitable for specific conduit types appear to vary depending on the project application. A total of 29 responses from different ODOT District Offices were received, and the results are plotted in Figure B.7. It can be noticed from this figure that the most common conduit type used for the sliplining of culverts is steel casing pipe (Item 748.06), followed by corrugated steel spiral rib pipe (Item 707.12), polyethylene plastic pipe based on outside diameter (Item 707.34), corrugated steel pipe (Item 707.01 or Item 707.02), precoated galvanized steel culvert (Item 707.04), and corrugated polyethylene smooth lined pipe (Item 707.33). The remaining conduit types were not as frequently used.

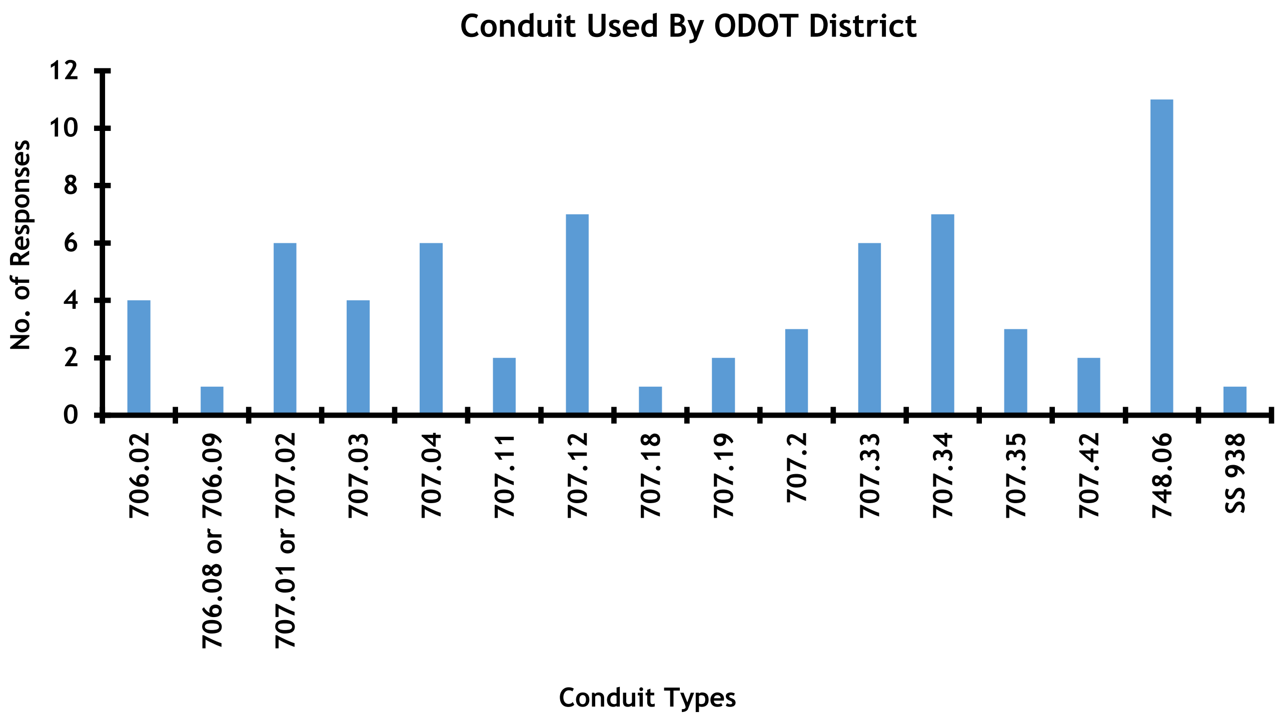

Figure B.7: Different Conduits Used for Sliplining by ODOT District Offices

Ensuring that the annulus of the sliplined culvert is completely full is the primary concern during the grouting process. Therefore, most ODOT District Offices recommend conducting sounding tests of the liner pipe to determine whether the annulus of the culvert is entirely filled with grout. The sounding can be performed during the grouting process due to its simplicity, as the inspector only needs to tap the liner pipe with a hammer and evaluate the resulting sound. District personnel also noted that when grout begins to flow out of the return ports, it can be considered as verification that the annulus is completely full. However, it is important to compare the actual amount of grout pumped into the annulus with the theoretical calculation of the amount of grout required based on the dimensions of the host pipe and liner pipe. After hardening, both bulkheads can be removed, and the grout can be visually inspected to verify that the annulus is completely full. As for the grout type, most respondents recommended using cellular grout for the grouting of sliplined culverts.

B.4 OHIO COUNTIES AND LOCALS

The survey sent to Ohio's county and local public agencies consisted of nine questions, most of which were concerned with the materials, installation specifications, and verification methods used for the sliplining of culverts. The questions center on the selection of conduit pipes and grout materials (grout meeting the current specification, SS 837, or other grouts), the specifications used for installing the grout, and the method(s) used by the agencies to verify the filling of the annulus (either destructive or non-destructive techniques).

The research team received a total of 26 responses to the survey. The respondents included county engineers, city engineers, an assistant city engineer, bridge engineers, a bridge specialist, a structural planning engineer, a construction area engineer, a staff engineer, a transportation engineer, hydraulic engineers, project engineers, a district bridge engineer, road superintendents, an operations deputy, a public works manager, a foreman, and a township trustee. The following subsections include the specific questions included in this survey. The responses received from county and local personnel are presented in Tables B.36 to B.42.

B.4.1 Conduit Types Used

Q.4.1 Identify the conduit types you use for sliplining in your District.

Table B.36: Conduit Types used by Ohio Counties and Locals

Agency	Conduit Types Used (ODOT Item/Spec. no.)	Other Conduit Types
Butler	Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34)	
Butler County/ Middletown	Glass-fiber-reinforced polymer mortar pipe (707.75)	
Butler County /Okeana	Polyethylene plastic pipe based on outside diameter (707.34) Polyvinyl chloride corrugated smooth interior pipe (707.42)	
Chardon Twp/ Geauga County	Other (please list and describe):	
City of Wooster	Corrugated steel pipe (707.01 or 707.02)	
Cuyahoga Co.		
Cuyahoga Co./ Garfield Heights	Corrugated steel pipe (707.01 or 707.02) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Corrugated aluminum alloy pipe (707.21 or 707.22)	
Cuyahoga Co./ Garfield Heights	Polyethylene plastic pipe based on outside diameter (707.34) Polyvinyl chloride corrugated smooth interior pipe (707.42)	
D4	Galvanized coated steel conduits (707.20) Polyvinyl chloride corrugated smooth interior pipe (707.42)	
Delaware	Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938)	
District 5	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Corrugated steel spiral rib pipe (707.12) Galvanized coated steel conduits (707.20) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Steel casing pipe (748.06) Glass-fiber-reinforced polymer mortar pipe (707.75)	
District 8 (Greater Cincinnati Area)	Corrugated aluminum spiral rib pipe (707.24)	

Table B.36: Conduit Types used by Ohio Counties and Locals (Continued)

Agency	Conduit Types Used (ODOT Item/Spec. no.)	Other Conduit Types
Erie County, Perkins Township	Precoated, galvanized steel culvert (707.04)	
Fulton County	Other (please list and describe):	N/A
Greene County /Beavercreek	Polyethylene plastic pipe based on outside diameter (707.34)	
Knox County /Mount Vernon	Corrugated polyethylene smooth lined pipe (707.33)	
Licking County	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03)	
Montgomery County	Polyvinyl chloride corrugated smooth interior pipe (707.42)	
Moraine, Ohio	Corrugated steel pipe (707.01 or 707.02) Corrugated aluminum alloy pipe (707.21 or 707.22) Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Polyvinyl chloride corrugated smooth interior pipe (707.42) Polyvinyl chloride profile wall pipe (707.43) Reinforced concrete circular pipe (706.02)	
Newark, Ohio	Other (please list and describe):	Have not performed any sliplining projects
Shelby County	Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Polyvinyl chloride corrugated smooth interior pipe (707.42) Polyvinyl chloride profile wall pipe (707.43)	
State of Ohio DOT	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated aluminum alloy pipe (707.21 or 707.22) Aluminum alloy structural plate conduit (707.23) Polyethylene plastic pipe based on outside diameter (707.34) Steel casing pipe (748.06)	
Summit County	Structural plate corrugated steel structure (707.03) Corrugated steel spiral rib pipe (707.12)	

Table B.36: Conduit Types used by Ohio Counties and Locals (continued)

Agency	Conduit Types Used (ODOT Item/Spec. no.)	Other Conduit Types
ODOT D09	Corrugated steel spiral rib pipe (707.12) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Polyvinyl chloride corrugated smooth interior pipe (707.42) Polyvinyl chloride profile wall pipe (707.43) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938)	CIPP
Cincinnati, Ohio	Polyethylene profile wall pipe (707.35)	
UA		½" thick Structural plate

B.4.2 Grouts Other than from SS 837

Q4.2.1 Indicate if you use/used grouts other than those specified in SS 837 for filling annular space in sliplining applications.
Please describe any deviation(s) from SS 837 you may have specified for sliplining projects in your District.

Table B.37: Grouts Other Than Those Specified in SS 837 By Ohio Counties and Locals

Agency	Grouts Other than SS 837 Grouts
Butler County/Okeana	none
Chardon Twp/ Geauga County	Have looked into this, but have not completed a project with it.
Cuyahoga County/ Garfield Heights	none that I am aware
District 5	None
District 8 (Greater Cincinnati Area)	Not sure. One value engineered and the other was a Type A Emergency. I don't have final plans for either.
Fulton County	Have not sliplined a culvert.
Greene County/ Beavercreek	None
Knox County/ Mount Vernon	grout with flow fill
Shelby County	Elastizell
ODOT D09	None

B.4.3 Verification of Complete Grout Filling

Q.4.3.1 How do your inspectors determine if annulus voids are fully filled with grout during grouting? How do they detect grout defects/voids after grout has hardened?

Table B.38: Verification of Grout Filling Recommendation by Ohio Counties and Locals

Agency	Verification of Grout Filling - Before and After Hardening
Butler County	The only way we know is once grout comes out of the vent tubes.
Butler County/City of Middletown	Inspection pipes installed behind the bulkhead so that once the annulus is filled, grout comes out of these pipes. Pipes are placed at various elevations. Also, grout quantity is monitored to compare to a calculated amount.
Butler County/ Okeana	after completion we saw cut a small patch and dig down to top. so give visual
Chardon Twp/ Geauga County	N/A
Cuyahoga County/ Garfield Heights	construction engineers deal with inspection
Delaware	sounding circumference with hammer if large enough culvert. Otherwise just the yield
District 5	Sounding
District 8 (Greater Cincinnati Area)	Sound if they can, but sounding a metal pipe is difficult. Not sure that either have been sounded in detail. The one did have ports at periodic locations.
Fulton County	N/A
Greene County/ Beavercreek	Visual and sound inspections
Knox County/ Mount Vernon	Add material through 2 or 3 holes cut in top of existing pipe until it does not take any more material.
Shelby County	quantified, smaller pipes used to fill voids
State of Ohio DOT	During filling, small inspection holes along the barrel and bulkheads at varying elevations are used to monitor the fill level until it pressures out the highest port hole. Estimated volumes are calculated to predict the volume of grout that should be required. If necessary, hammer sounding may be utilized to isolate any hollow areas that are unexpected.
Summit County	They use grout holes in the upside of the carrier pipe and run injection till its full.
ODOT D09	Visual Inspection. Inspection holes added at the top of the culvert.
UA	grout coming from upper grout holes

B.4.4 Changes to Specifications

Q.4.4.1 Do you recommend any changes to ODOT material specification related to annulus void grouts?

Q.4.4.2 Do you recommend any changes to ODOT installation specification related to annulus void grouting?

Q.4.4.3 Do you recommend any changes to ODOT inspection protocols related to annulus void grouting, detection of voids, post-grouting performance verification and/or performance of hardened grout?

Table B.39**:** Specification/Installation Recommended by Ohio Counties and Locals

Agency	Changes to Material Specification	Changes to Installation Specification	Changes to Inspection Methods
Butler County	No	no	no, not sure I see this a problem unless you are concerned about deflection.
Butler County/ City of Middletown	No.	No	No
Butler County/ Okeana	no	no	no
Geauga County/ Chardon Twp	Unknown	Unknown	Unknown
Delaware	no	Maybe just a better way to calculate it. The liner pipes I have been involved with have taken a lot more grout than expected.	I think the sounding method should be done relatively quickly after grout has had time to set up 1-2 days. As the grout cures it seems to shrink and you get a hollow sounding hammer impact. Other than random holes drilled in pipe it is difficult to determine the true grouting success.
District 5	no	no	no
District 8 (Greater Cincinnati Area)	Not familiar enough with the process to comment, but periodic ports seem reasonable.	Not familiar enough with spec.	Not familiar enough with spec.
Greene/Beavercreek	No	No	No

Table B.39: Specification/Installation Recommended by Ohio Counties and Locals (Continued)

Agency	Changes to Material Specification	Changes to Installation Specification	Changes to Inspection Methods
Knox County/Mount Vernon	N/A	N/A	N/A
Moraine	No	No	No
Shelby County	grout won't work, so SS is not useful	no	yes, see elastizell
State of Ohio DOT	not at this time	not at this time	not at this time
Summit County	No	No	No
ODOT D09	No	No	We have seen a couple of issues in the past, but not sure that it's specifically related to inspection shortcomings.

B.4.5 Potential Projects for Inspections

Q.4.5.1 Do you have any potential projects for the research team to review and inspect – projects that may have been poorly executed or projects with excellent annulus void fills?
Please skip this question if a list from your District was already provided.
Please also share any lessons learned and improvements made related to sliplining projects in your District. What would you recommend to improve the effectiveness of sliplining culvert rehabilitation?

Table B.40: Potential Projects by Ohio Counties and Locals

Agency	Potential Projects for Inspections
Butler County/ City of Middletown	We lined an 84" culvert in 2019 that could be inspected, but we have no reason to believe it was poorly executed (though it sounds like it would be possible there are voids based on the information in this survey).
Butler County/ Okeana	have one that we did over 10 years ago that has held up very well.
Chardon Twp/ Geauga County	Nothing at this time, although we have looked into it and opted to just change the pipe.
Delaware	I'm curious about a UNI-36 slip liner project. It took a lot more grout than expected.
District 5	
District 8 (Greater Cincinnati Area)	You can check our HAM-22-1741 pipe, (US 22, 1.25 miles north of I-275)
Moraine	N/A
State of Ohio DOT	We don't have a readily available example on either extreme (good or bad) of the process. This process can eliminate much work and traffic delay. Be sure to double check/survey that the proposed liner can fit through the existing for proper installation.
Summit County	One of the first slip lining District used back 20 yrs ago was o 10' CMP just south of I76 on SR 44.
ODOT D09	We have 1 culvert that was lined approximately 10 years ago that has lost much of it's annular grout filling. It is located at LAW-52-4.2.

B.4.6 Destructive or Non-Destructive Methods

Q.4.6.1 Are you aware of any in-situ destructive or non-destructive techniques used in your District for the evaluation of complete filling of annulus voids during grouting and after hardening of the grout? Include methods that can be used by inspectors to verify complete filling of annulus voids.

Table B.41: Destructive or Non-Destructive Evaluation by Ohio Counties and Locals

District	Any in-situ Destructive or Non-Destructive Techniques Used?
Butler County/ Okeana	no
Chardon Twp/ Geauga County	No
Delaware	no
District 5	no
District 8 (Greater Cincinnati Area)	no
Moraine	N/A
State of Ohio DOT	During filling, small inspection holes along the barrel and bulkheads at varying elevations are used to monitor the fill level until it pressures out the highest port hole. Estimated volumes are calculated to predict the volume of grout that should be required. If necessary, hammer sounding may be utilized to isolate any hollow areas that are unexpected. Non-destructive ultrasound equipment may exist also, but I have nothing to reference at this time.
Summit County	No
ODOT D09	Sounding of the sidewalls. Adding holes to top of liner pipe for visual inspection.

B.4.7 Other Comments and Information

Q.4.7.1 Please provide any other comments or information you would like to include regarding liner installation and annulus void grouting in order to improve the service life of sliplined culverts.

Table B.42: Information Provided by Ohio Counties and Locals

Agency	Any Other Information or Comments?
Chardon Twp/ Geauga County	Nothing at this time
District 5	no comment
District 8 (Greater Cincinnati Area)	I haven't had any issues with a slip lined pipe that I recall.
Knox County/ Mount Vernon	We don't slipline a lot of pipe. Maybe one every three years or more.
Licking County	Have not done a complete slip line but have done paved invert.
State of Ohio DOT	Second to perfecting the grout filling process, focusing on the bulkhead's ability to seal off the ends is also important to prevent any possible water piping in and around any pre-existing holes in the original culvert barrel walls.
ODOT D09	N/A

B.4.8 Conclusions based on Responses from ODOT Counties and Locals

The responses from ODOT Counties and Locals about the conduit types that they have used in their sliplining projects vary depending on the kind of conduit being used. In addition, Counties and Locals were asked to offer their recommendations about the type of grout that would be most appropriate for grouting various types of conduits. A total of 26 replies were received from the Ohio Counties and Locals. According to Figure B.8, the conduit type that is most commonly used for sliplining culverts is polyethylene plastic pipe with an outside diameter (OD) (707.34). This is followed by polyvinyl chloride corrugated smooth interior pipe (OD) (707.42), corrugated steel pipe (OD) (707.01 or 707.02), corrugated polyethylene smooth lined pipe (OD) (707.34), and corrugated polyethylene smooth lined pipe (OD) (707.33). Other conduits were recommended less frequently by ODOT Counties and Locals.

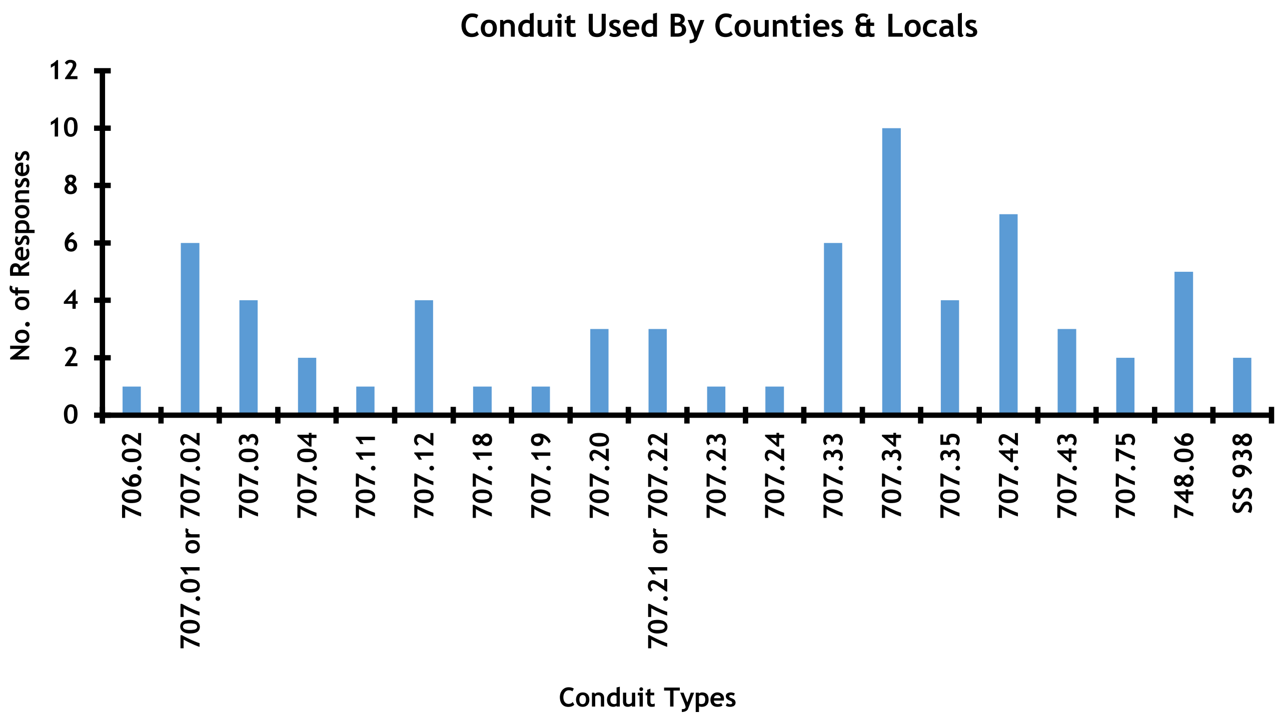

Figure B.8: ODOT County and Local Responses on the Use of Different Conduits for Sliplined Culverts.

For inspections of the culverts sliplined in their jurisdictions, tapping the liner pipe of a splined culvert in order to conduct a sounding test is a technique that ODOT Counties and Locals commonly use to check whether or not the annular spaces of sliplined culverts are entirely filled with grout. Another method is to verify the grout filling by watching for grout to emerge through the vent tubes installed in the bulkheads at both ends of the culvert. It was also recommended that a hole (or port) could be drilled at the crown of the liner pipe (i.e., at the 12 o'clock position) and a visual check performed to determine whether or not grout is present at that location. In addition, it is recommended that the actual volume of grout pumped into the annular space be compared to the theoretical volume of grout that was predicted based on the pipe dimensions.

B.5 ODOT Designers

The ODOT Design engineer survey comprised nine questions that mainly concerned the materials and specifications used for the sliplining of culverts. The questions focused on the many conduits selected by ODOT Design Engineers when designing sliplined culverts and if the grouting materials are selected based on the current grout specification (SS 837) or other grouts. Responses were received from a hydraulic engineer in District 8, a drainage engineer in District 12, and a design engineer in District 10. The questions are presented in the subsections below, and the responses are summarized in Tables B.43 to B.49.

B.5.1 Conduit Types Used

Q.5.1 Identify the conduit types you use for sliplining in your District.

Table B.43: Conduit Types Used by ODOT Designers

District	Conduit Types Used	Other Conduit Types
8	Corrugated steel pipe (707.01 or 707.02) Corrugated steel spiral rib pipe (707.12) Corrugated aluminum spiral rib pipe (707.24) Corrugated polyethylene smooth lined pipe (707.33) Steel casing pipe (748.06)	
12	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Polyethylene profile wall pipe (707.35) Other (please list and describe)	Structural spray lining

B.5.2 Grouts Other than from SS 837

Q.5.2.1 Indicate if you use/used grouts other than those specified in SS 837 for filling annular space in sliplining applications.
Please describe any deviation(s) from SS 837 you may have specified for sliplining projects in your District.

Table B.44: Grouts Other Than Those Specified in SS 837 by ODOT Designers

ODOT District	Grouts Other than SS 837 Grouts
8	We have never specified options for filling the voids, other than requiring that the contractor follow SS837 We were notified of issues with filling the voids in early 2017. We had one project that upcoming construction season that had already sold so we couldn't add special notes to the plans. We required the contractor to submit their procedure for filling the voids well in advance so we had time to review. There were multiple reiterations to their procedure, but in the end the contractor used air release ports/pipes to show that the voids were filled.
12	N/A

B.5.3 Verification of Complete Grout Filling

Q.5.3.1 How do your inspectors determine if annulus voids are fully filled with grout during grouting? How do they detect grout defects/voids after grout has hardened?

Table B.45: Verification of Grout Filling Recommendation by ODOT Designers

ODOT District	Verification of Grout Filling - Before and After Hardening
8	The construction inspectors use air release ports/pipes. Once the pipes leak the grout, then the void is assumed full. Once the grout has hardened, you can sound with a hammer to see if voids are filled. I do not know if construction uses this method, but the culvert inspector will during the project finalization.
12	Material exiting the port pipes

B.5.4 Changes to Specifications

Q.5.4.1 Do you recommend any changes to ODOT material specification related to annulus void grouts?
Q.5.4.2 Do you recommend any changes to ODOT installation specification related to annulus void grouting?
Q.5.4.3 Do you recommend any changes to ODOT inspection protocols related to annulus void grouting, detection of voids, post-grouting performance verification and/or performance of hardened grout?

Table B.46: Specification Changes Recommended by ODOT Designers

ODOT District	Changes to Material Specification	Changes to Installation Specification	Changes to Inspection Methods
8	No	These are not necessarily recommendations, but maybe out of the box ideas to consider: Maybe an option of using varying lengths of PVC pipe would really help guarantee the void is filled. Multiple lengths of PVC tubing can be placed along the top to get an idea of the grout being filled along the length of the culvert. For example, for a 50' long culvert, three pipes can be placed at the top: One pipe that is 48' long, one pipe that is 30' long, and one pipe that is 5' long. Each PVC pipe would leak grout at different times. The leaking pipe would be plugged. This gives an idea along the entire length of the culvert. I do not know the constructability issues this may cause. If long pipes are used, there just needs to be a way to confirm the PVC pipes are held in place, especially along the top of the pipe.	These are not necessarily recommendations, but maybe out of the box ideas to consider: Maybe after a few days, sounding is required as part of the spec. If the sound is hollow, the contractor could make "coupon cut" and inject additional grout. This may not be too desirable since we dont want a brand new pipe to be damaged, so I guess it depends on how critical the filling of the voids is.
12	No	No	No

B.5.5 Potential Projects for Inspections

Q5.5.1 Do you have any potential projects for the research team to review and inspect – projects that may have been poorly executed or projects with excellent annulus void fills?
Please skip this question if a list from your District was already provided.
Please also share any lessons learned and improvements made related to sliplining projects in your District. What would you recommend to improve the effectiveness of sliplining culvert rehabilitation?

Table B.47: Potential Projects Suggested by ODOT Designers

ODOT District	Potential Projects for Inspections
8	The following projects had slip lining completed in District 8. I do not know if there were issues: 98584, 87090, 105835, 82957, 86136, 91129, 108175. PID 98584 is the project in 2017 that seems to have done a great job, based on the procedure developed during construction. The following project is currently in design: 105967.
12	ODOT PID 92069; CUY IR 090 18.22/VAR. Sale in Fall, 2021.

B.5.6 Destructive or Non-Destructive Methods

Q.5.6.1 Are you aware of any in-situ destructive or non-destructive techniques used in your District for the evaluation of complete filling of annulus voids during grouting and after hardening of the grout?
Include methods that can be used by inspectors to verify complete filling of annulus voids.

Table B.48: Destructive or Non-Destructive Inspection Methods Recommended by ODOT Designers

ODOT District	Any in-situ Destructive or Non-Destructive Techniques Used?
8	See previous responses.
12	No

B.5.7 Other Comments and Information

Q.5.7.1 Please provide any other comments or information you would like to include regarding liner installation and annulus void grouting in order to improve the service life of sliplined culverts.

Table B.49: Information Provided by ODOT Designers

ODOT District	Any Other Information or Comments?
12	N/A

B.5.8 Conclusions based on Responses from ODOT Designers

As can be seen from Table B.43, ODOT design engineers suggest using just eight conduit types. In addition, they suggest that conducting hammer sounding tests during and after the grouting process might be of use in determining whether or not the annulus has been entirely filled. Moreover, the designers suggest positioning one grout feed tube pipe at the top of the annulus and others at different locations, both of which have the potential to facilitate the grouting process and ensure that the annulus is entirely filled.

B.6 ODOT CONTRACTORS

The ODOT contractor survey included 13 questions, the majority of which are concerned with details about sliplining projects. The questionnaire included four different categories of questions. To begin, there are many kinds of conduits that ODOT contractors have employed in their culvert sliplining projects, and dealing with grout pumping and ensuring that the annulus is full are typical challenges that contractors face during construction. Additionally, filling the annulus void that is located between the host pipe and the liner pipe is a crucial component. As a result, it is crucial to gain an understanding of the difficulties that the contractor faces throughout the sliplining process. In response to the survey questionnaire, replies were received from 15 ODOT contractors. The respondents included company presidents, company vice presidents, project managers, a project manager/estimator, a project engineer, a chief estimator, and a technical sales representative. The following subsections include the questions included in the survey. The responses provided by the ODOT contractors are summarized in Tables B.50 to B.68.

B.6.1 Conduit Types Used

Q.6.1.1 Identify the conduit type(s) you have installed for sliplining.

Table B.50: Conduit Types Used by ODOT Contractors

Company Name	Conduit Types Installed	Other Conduit Types
Axis Civil Construction LLC	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Corrugated steel spiral rib pipe (707.12) Corrugated polyethylene smooth lined pipe (707.33) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938)	
TURN – KEY TUNNELING	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Polymer precoated, galvanized steel conduit (707.18) Aluminum coated steel conduit (707.19) Galvanized coated steel conduits (707.20) Corrugated aluminum spiral rib pipe (707.24) Corrugated polyethylene smooth lined pipe (707.33) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938) Glass-fiber-reinforced polymer mortar pipe (707.75) Reinforced concrete circular pipe (706.02)	HDPE
Belgray, Inc	Corrugated polyethylene smooth lined pipe (707.33)	
R. C. Construction Co.	Corrugated steel pipe (707.01 or 707.02) Corrugated steel spiral rib pipe (707.12)	
Capitol Tunneling Inc.	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Corrugated steel spiral rib pipe (707.12) Aluminum coated steel conduit (707.19) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Polyvinyl chloride corrugated smooth interior pipe (707.42) Steel casing pipe (748.06) Steel reinforced thermoplastic ribbed pipe (SS 938) Reinforced concrete circular pipe (706.02)	
Union Industrial Contractors	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04)	

Table B.50: Conduit Types Used by ODOT Contractors (Continued)

Company Name	Conduit Types Installed	Other Conduit Types
The Righter Company Inc.	Corrugated steel pipe (707.01 or 707.02)	
State-Wide Concrete Pumping, Inc	Corrugated steel pipe (707.01 or 707.02) Structural plate corrugated steel structure (707.03) Precoated, galvanized steel culvert (707.04) Polymer-precoated corrugated steel spiral rib pipe (707.11) Corrugated steel spiral rib pipe (707.12) Polymer precoated, galvanized steel conduit (707.18) Galvanized coated steel conduits (707.20) Reinforced concrete circular pipe (706.02)	
Riley Contracting Inc.	Steel casing pipe (748.06)	
Geotech Services Inc.	Corrugated steel pipe (707.01 or 707.02) Corrugated steel spiral rib pipe (707.12) Aluminum coated steel conduit (707.19) Corrugated aluminum alloy pipe (707.21 or 707.22) Corrugated polyethylene smooth lined pipe (707.33) Polyethylene plastic pipe based on outside diameter (707.34) Steel reinforced thermoplastic ribbed pipe (SS 938)	
ISCO Industries Inc.	Polyethylene plastic pipe based on outside diameter (707.34) Polyethylene profile wall pipe (707.35) Steel reinforced thermoplastic ribbed pipe (SS 938) Glass-fiber-reinforced polymer mortar pipe (707.75)	

B.6.2 Annulus Filling

Q.6.2.1 How easy or hard is it to achieve complete filling of grout in the annulus void for the conduit type(s) you have installed?

Table B.51: Achieved Complete Filling of The Grout by ODOT Contractors

	Geotech Services Inc.	ISCO Industries Inc.	State-Wide Concrete Pumping, Inc	D A Van Dam & Associates LLC	TURN - KEY TUNNELING	Axis Civil Construction LLC	R. C. Construction Co.	Capitol Tunneling Inc.	Union Industrial Contractors	The Righter Company Inc	Belgray, Inc	Riley Contracting Inc.
Corrugated steel pipe	SWE	NE or H	SWE		VE	NE or H	SWE	SWH	SWE	NE or H		
Structural plate corrugated steel structure	SWE	NE or H	SWE		VE	NE or H		VE	SWE			
Precoated galvanized steel culvert	SWE	NE or H	SWE		VE				SWE			
Polymer-precoated corrugated steel spiral rib pipe	SWE	NE or H	SWE		VE							
Corrugated steel spiral rib pipe	SWE	NE or H	SWE	SWE	VE	VH	SWE	SWH				
Polymer precoated, galvanized steel conduit	SWE	NE or H			VE							
Aluminum coated steel conduit	SWE	NE or H			VE			SWH				
Galvanized coated steel conduits	SWE	NE or H			VE							
Corrugated aluminum alloy pipe	SWE	NE or H			VE							
Aluminum alloy structural plate conduit	SWE	NE or H			VE							
Corrugated aluminum spiral rib pipe	SWE	NE or H			VE							
Corrugated polyethylene smooth lined pipe	SWE	NE or H		VE	VE	SWH		NE or H			SWH	
Polyethylene plastic pipe based on outside diameter	SWE	NE or H		VE	VE			VE				

VE: Very Easy, VH: Very Hard, SWE: SomeWhat Easy, SWH: SomeWhat Hard, NE or H: Not Easy or Hard.

Table B.51: Achieved Complete Filling of The Grout by ODOT Contractors (Continued)

	Geotech Services Inc.	ISCO Industries Inc.	State-Wide Concrete Pumping, Inc	D A Van Dam & Associates LLC	TURN - KEY TUNNELING	Axis Civil Construction LLC	R. C. Construction Co.	Capitol Tunneling Inc.	Union Industrial Contractors	The Righter Company Inc	Belgray, Inc	Riley Contracting Inc.
Polyethylene profile wall pipe	SWE	NE or H		VE	VE							
Polyvinyl chloride corrugated smooth interior pipe	SWE	NE or H		VE	VE							
Polyvinyl chloride profile wall pipe	SWE	NE or H		VE	VE							
Steel casing pipe	SWE	NE or H		VE	VE	SWE		VE				VE
Steel reinforced thermoplastic ribbed pipe	SWE	NE or H		VE	VE	NE or H		VH				
Glass-fiber-reinforced polymer mortar pipe	SWE	NE or H			VE							
Reinforced concrete circular pipe	SWE	NE or H	SWE		VE			VE				

VE: Very Easy, VH: Very Hard, SWE: SomeWhat Easy, SWH: SomeWhat Hard, NE or H: Not Easy or Hard.

Table B.52: Achieved Complete Filling of The Grout by ODOT Contractors – Other

	TURN - KEY TUNNELING	ISCO Industries Inc.	Comment
Other	VE	NE or H	The host pipe material type plays no significant role in grouting considerations using the SnapTite rehabilitation approach

Q.6.2.2 Indicate which grout is most suitable for annulus voids with each type of conduit you have installed:

Table B.53: Controlled Low-Strength Mortar Grout Considered Most Suitable by ODOT Contractors

Controlled Low-Strength Mortar (ODOT Item 613)	**Geotech Services Inc.**	**ISCO Industries Inc.**	**State-Wide Concrete Pumping, Inc**	**D A Van Dam & Associates LLC**	**TURN - KEY TUNNELING**	**Axis Civil Construction LLC**	**R. C. Construction Co.**	**Capitol Tunneling Inc.**	**Union Industrial Contractors**	**The Righter Company Inc**	**Belgray, Inc**	**Riley Contracting Inc.**
Corrugated steel pipe		S	S			S	S	S				
Structural plate corrugated steel structure		S	S					S	S			
Precoated galvanized steel culvert		S	S						S			
Polymer-precoated corrugated steel spiral rib pipe		S	S									
Corrugated steel spiral rib pipe		S	S	S		S	S					
Polymer precoated, galvanized steel conduit		S	S									
Aluminum coated steel conduit		S										
Galvanized coated steel conduits			S		S							
Corrugated aluminum alloy pipe		S										
Aluminum alloy structural plateconduit		S										
Corrugated aluminum spiral rib pipe		S										
Corrugated polyethylene smooth lined pipe		S		S							S	

A: Always, S; Sometimes, N: Never.

Table B.53: Controlled Low-Strength Mortar Grout Considered Most Suitable by ODOT Contractors (Continued)

Controlled Low-Strength Mortar - (ODOT Item 613)	**Geotech Services Inc.**	**ISCO Industries Inc.**	**State-Wide Concrete Pumping, Inc**	**D A Van Dam & Associates LLC**	**TURN - KEY TUNNELING**	**Axis Civil Construction LLC**	**R. C. Construction Co.**	**Capitol Tunneling Inc.**	**Union Industrial Contractors**	**The Righter Company Inc**	**Belgray, Inc**	**Riley Contracting Inc.**
Polyethylene plastic pipe based on outside diameter		S		S								
Polyethylene profile wall pipe		S		S								
Polyvinyl chloride corrugated smooth interior pipe		S		S								
Polyvinyl chloride profile wall pipe		S										
Steel casing pipe		S		S		S						
Steel reinforced thermoplastic ribbed pipe		S										
Glass-fiber-reinforced polymer mortar pipe		S										
Reinforced concrete circular pipe		S	S									

A: Always, S; Sometimes, N: Never.

Table B.54: Grout Considered Most Suitable by ODOT Contractors (Other Grouts)

	ISCO Industries Inc.	**Comment**
Other	S	We always promote the use of cellular concrete grout for the rehabilitated pipe system. But will use CLSM when required by owner or deemed necessary to meet loading demands.

A: Always, S; Sometimes, N: Never.

Table B.55: Low-Shrinkage Mortar Considered Suitable by ODOT Contractors

Low-Shrinkage Mortar (ODOT Item 602)	**Geotech Services Inc.**	**ISCO Industries Inc.**	**State-Wide Concrete Pumping, Inc**	**D A Van Dam & Associates LLC**	**TURN - KEY TUNNELING**	**Axis Civil Construction LLC**	**R. C. Construction Co.**	**Capitol Tunneling Inc.**	**Union Industrial Contractors**	**The Righter Company Inc**	**Belgray, Inc**	**Riley Contracting Inc.**
Corrugated steel pipe		N	S			S			S			
Structural plate corrugated steel structure		N	S									
Precoated galvanized steel culvert		N	S									
Polymer-precoated corrugated steel spiral rib pipe		N	S									
Corrugated steel spiral rib pipe		N	S	N		S						
Polymer precoated, galvanized steel conduit		N	S									
Aluminum coated steel conduit		N										
Galvanized coated steel conduits		N	S									
Corrugated aluminum alloy pipe		N										
Aluminum alloy structural plate conduit		N										
Corrugated aluminum spiral rib pipe		N										
Corrugated polyethylene smooth lined pipe		N		N								
Polyethylene plastic pipe based on outside diameter		N		N								
Polyethylene profile wall pipe		N		N								
Polyvinyl chloride corrugated smooth interior pipe		N		N								

A: Always, S; Sometimes, N: Never.

Table B.55: Low-Shrinkage Mortar Considered Suitable by ODOT Contractors (Continued)

Low-Shrinkage Mortar (ODOT Item 602)	**Geotech Services Inc.**	**ISCO Industries Inc.**	**State-Wide Concrete Pumping,**	**D A Van Dam & Associates LLC**	**TURN - KEY TUNNELING**	**Axis Civil Construction LLC**	**R. C. Construction Co.**	**Capitol Tunneling Inc.**	**Union Industrial Contractors**	**The Righter Company Inc**	**Belgray, Inc**	**Riley Contracting Inc.**
Polyvinyl chloride profile wall pipe		N										
Steel casing pipe		N		N		S						N
Steel reinforced thermoplastic ribbed pipe		N										
Glass-fiber-reinforced polymer mortar pipe		N										
Reinforced concrete circular pipe		N	S									

A: Always, S; Sometimes, N: Never.

Table B.56: Low-Shrinkage Mortar Considered Suitable By ODOT Contractors (Other)

	ISCO Industries Inc.	**Comment**
Other	N	We always promote the use of cellular concrete grout for the rehabilitated pipe system. But will use CLSM when required by owner or deemed necessary to meet loading demands.

A: Always, S; Sometimes, N: Never.

Table B.57: Cellular Concrete Grout Considered Suitable by ODOT Contractors

Cellular Concrete Grout (ASTM C869)	**Geotech Services Inc.**	**ISCO Industries Inc.**	**State-Wide Concrete Pumping, Inc**	**D A Van Dam & Associates LLC**	**TURN - KEY TUNNELING**	**Axis Civil Construction LLC**	**R. C. Construction Co.**	**Capitol Tunneling Inc.**	**Union Industrial Contractors**	**The Righter Company Inc**	**Belgray, Inc**	**Riley Contracting Inc.**
Corrugated steel pipe	A		N					A	S			
Structural plate corrugated steel structure		A	N		A			A	S			
Precoated galvanized steel culvert	A	A	N		A				S			
Polymer-precoated corrugated steel spiral rib pipe	A	A	N		A							
Corrugated steel spiral rib pipe	A	A	N	A	A	S		A				
Polymer precoated, galvanized steel conduit		A	N		A							
Aluminum coated steel conduit	A	A			A			A				
Galvanized coated steel conduits		A	N		A							
Corrugated aluminum alloy pipe	A	A			A							
Aluminum alloy structural plate conduit		A			A							
Corrugated aluminum spiral rib pipe	A	A			A							
Corrugated polyethylene smooth lined pipe	A	A		A	A	S		A			S	
Polyethylene plastic pipe based on outside diameter	A	A		A	A			A				
Polyethylene profile wall pipe		A		A	A							

A: Always, S; Sometimes, N: Never.

Table B.57: Cellular Concrete Grout Considered Suitable by ODOT Contractors (Continued)

Cellular Concrete Grout (ASTM C869)	Geotech Services Inc.	ISCO Industries Inc.	State-Wide Concrete Pumping, Inc	D A Van Dam & Associates LLC	TURN - KEY TUNNELING	Axis Civil Construction LLC	R. C. Construction Co.	Capitol Tunneling Inc.	Union Industrial Contractors	The Righter Company Inc	Belgray, Inc	Riley Contracting Inc.
Polyvinyl chloride corrugated smooth interior pipe	A	A		A	A							
Polyvinyl chloride profile wall pipe	A	A			A							
Steel casing pipe		A		A	A			A				N
Steel reinforced thermoplastic ribbed pipe		A			A							
Glass-fiber-reinforced polymer mortar pipe		A			A							
Reinforced concrete circular pipe		A	N		A			A				

A: Always, S; Sometimes, N: Never.

Table B.58: Cellular Concrete Grout Considered Suitable by ODOT Contractors – Other

	ISCO Industries Inc.	Comment
Other	A	We always promote the use of cellular concrete grout for the rehabilitated pipe system. But will use CLSM when required by owner or deemed necessary to meet loading demands.

A: Always, S; Sometimes, N: Never

Q.6.2.3 How does the length of the conduit impact the selection of grout?

Table B.59: Length Impact on Grout Selection by ODOT Contractors

Company Name	The Length of The Conduit
Axis Civil Construction LLC	Somewhat- Slope of conduit larger factor.
TURN – KEY TUNNELING	Does not
Belgray, Inc	Used what was recommended by the manufacturer
R. C. Construction Co.	The longer pipes need more concrete in the mix for better flow
D A Van Dam & Associates LLC	Determines whether you use grout tubes or grout ports, we prefer grout tubs have more control over the placement of the grout
Capitol Tunneling Inc.	It is dictated by buoyancy, not the length.
Union Industrial Contractors	The longer the length, the more grout ports we install.
The Righter Company Inc	In our case, the selection of grout was more based on what suppliers quoted and material price. When you are trying to be the low bidder you typically go with the lowest priced material that meets the specifications.
State-Wide Concrete Pumping, Inc	Difficulty increases with distance
Riley Contracting Inc.	Determines if the grout needs to be installed under pressure or not.
Geotech Services Inc.	In my opinion, the only grout suitable for grouting the annular space is Cellular. The length of the pipe is irrelevant if you have grout ports spaced at a uniform distance through the entire length of the pipe. ODOT 613 is not a suitable mix for grouting the annular space. There is not enough cement content to keep the sand lubricated or in suspension while pumping. Ready-mix suppliers have varying experiences with airing it up. We have never had a good experience pumping ODOT 613.
ISCO Industries Inc.	The length of the culvert is generally not the primary consideration in grout mix formulations, but it often may influence the approach used during grouting injection. From experience, lighter density grouts pose less risk during the placement as length increases.

Q.6.2.4 What grouting procedures do you recommend for complete filling of annulus voids? What measures do you take to ensure complete filling of annulus voids? Please respond only for conduit type(s) that you have installed.

Table B.60: Grouting Procedures Recommended by ODOT Contractors

Company Name	Grouting Procedure
Axis Civil Construction LLC	Grouting points at a max spacing of 25', less for cdf unless large fly ash component- Q2 Inspection ports, sounding, keep bulkheads down from the top for visual until the final stage.
TURN – KEY TUNNELING	Don't stop pouring until you have grout coming out the other end
Belgray, Inc	Monitor the interior of the pipe for deflection. Used ports at the ends to make sure the grout reached over the pipes.
R. C. Construction Co.	Pumps a plug holes
D A Van Dam & Associates LLC	we run the calculations and make sure we are very close to this amount usually we are greater than this due to the voids under and around the pipe. We have a person inside the pipe taking hammer tests as we are filling each tub and making sure he is hearing the changing sounds as it fills. Grouting is a slow process and should not be rushed, this allows the voids to be filled.
Capitol Tunneling Inc.	We feel that Cellular Grout is the absolute best solution. Quality control and understanding the material volume and specifications are the key items to make sure that the annular space is full.
Union Industrial Contractors	We used grout tubes on ours. We would run a grout tube from the high point to 3/4 of the length, then another to 1/2 the length and another to 1/4 the length. We used one last one to finish it off. Sometimes we used more tubes if the length made it necessary. We used a sub that installed ports to grout from the inside instead of the end.
The Righter Company Inc	If lumber (or other material) rails are used to slide the liner pipe in, make sure the rails have frequent staggered gaps to allow grout to flow through and between them. Order grout with a proper slump. It should be decently flow- able to make it more self-filling, but not too flow-able as that increases the risk of causing the pipe to float. Numerous ports should be fabricated into the liner pipe for grout pumping. We had a 90" diameter liner pipe that came in 20' long sections. And ordered each section with 6 ports... 2 along the top centerline of the pipe, and 4 in the middle of each pipe section at roughly the 1, 4:30, 7:30, and 11 O'clock Positions. Start filling the annulus from the low/outlet end of the pipe and work up. Utilize the low ports to introduce the grout first until the grout level reaches the port then move to the next port / further up pipe port. Ports should be used for both grout pumping and as a means to visually verify that the grout is filling as intended.

Table B.60: Grouting Procedures Recommended by ODOT Contractors (Continued)

Company Name	Grouting Procedure
State-Wide Concrete Pumping, Inc	Use the proper flowable material
Riley Contracting Inc.	Using a concrete pump to install grout helps to ensure it is full. When the grout is pumped or gravity filled we find when the grout comes up the vent pipe the void is full.
Geotech Services Inc.	Cribbing the top of the pipe to resist lift and vent/grout ports located at the crown of the pipe and bulkheads. For larger diameter culverts it is necessary to grout in 2 - 3 lifts. Once the lower lifts are in place and set, you should be able to start pumping at one end of the culvert at the crown and continue port to port in the crown until grout flows from the top port at the other end of pipe.
ISCO Industries Inc.	Use of a cellular grout that has low viscosity with fluidatic properties rather than a high viscosity grout that is stiff and hard to flow. Use of vent ports to monitor grout fill levels. Guide and support rails that allow for free flow of grout in the annulus. Monitor the total volume placed (generally actual placement volumes will be 30% more or greater than annulus volume.

Q.6.2.5 How do you determine if the annulus void is fully filled with grout during grouting for conduit type(s) you have installed? How do you detect grout voids after grout has set?

Table B.61: Verification of Grout Filling Recommendation by ODOT Contractors

Company Name	Verification of Grouting
Axis Civil Construction LLC	See above
TURN – KEY TUNNELING	Grout coming out another side - cellular grout is extremely flowable
Belgray, Inc	We had the Manufacturer's Rep inspect and be onsite to confirm.
R. C. Construction Co.	we only check when filling
D A Van Dam & Associates LLC	Hammer testing, you will always have some settling at the top of the pipe due to grout settling. This is not a problem as long as it is not more than a few inches if it is several feet you have a problem and need to refill with ports from the inside. Rare if you have grout tubs.
Capitol Tunneling Inc.	1.) to calculate the annular space, check product weights (QC), and getting consistent material in the vent pipe opposite of the fill location. if in structural liner or steel casing you can inspect with grout ports at the surface of the pipe. other than that there is no way to inspect after the face that we have found.
Union Industrial Contractors	Sounding
The Righter Company Inc	I think it's impossible to completely determine if the annulus is fully filled since you can't see through the walls of the liner pipe. We utilized numerous ports in a linear sequence as mentioned in the previous answer to help ensure and visually verify (as much as possible) that the annulus is filling.
State-Wide Concrete Pumping, Inc	Vent pipes
Riley Contracting Inc.	We use calculations to determine how much grout should be needed versus how much grout was used. N/A
Geotech Services Inc.	We pump port to port at the crown of the pipe. Starting one end and ports located approximately 12' apart. Pump port to port until grout comes out of the top port at the other end.
ISCO Industries Inc.	See 4.4 above. Also, studies have been conducted on past installations using pipeline assessment tools including soundings, ground-penetrating radar, and backscatter chromatography using radioactive isotopes, along with physical dig-ups. All show not only is the annulus between the host pipe and the liner completely filled but that the grout also efficiently fills voids in the surrounding embedment materials.

Q.6.2.6 Do you see any limitations of different coupling and/or jointing methods for the conduit type(s) you install?

Table B.62: Coupling or Jointing Limitation by ODOT Contractors

Company Name	Limitations of Coupling/Jointing
Axis Civil Construction LLC	Sealed joints are vital- spiral pipe joint bands with gasket material are unacceptable- the joint needs to be essentially watertight, cmp bands are better but not best, welded steel best or gasketed male/female polyethylene. Although the lightweight of the plastic gives a high likelihood of floating and thereby losing initial seal then your beginning step one of the groutings again.
TURN – KEY TUNNELING	Yes.
Belgray, Inc	Size is the biggest issue - the pipes are sized as big as possible, so some couplings will not work.
R. C. Construction Co.	Yes.
D A Van Dam & Associates LLC	We use a threaded pipe or fusion-welded pipe. Will be determined by the diameter of the host pipe and the outside diameter of the lining pipe and if there are any deflections in host pipe, the length of the push, bends, grout tub or grout ports, staging area we will have, will we be allowed to be in the creek bed or need to install from above, how deep is the cover. We will also use threaded and as a safety factor on long pushes and fusion weld from inside and outside. Each job is different and is evaluated at the time of the quote and then before we order pipe.
Capitol Tunneling Inc.	Yes! all of the lightweight pipes, CMP, HDPE Profile, and PVC profiles are absolutely the most miserable to backfill. they are so flimsy and it takes almost no load to get some sort of deformation of the pipe causing the joints to leak - crap pipe = Crap liner...
Union Industrial Contractors	Not unless the pipe is really tight going through that does not allow for tubes.
The Righter Company Inc	I would not recommend field welded joints, as the liner pipe installation is difficult enough without having the time-consuming task of welding joints and having to repair coatings with a significant risk of breaking those welds shortly thereafter. Mechanical external band couplings seem to make the most sense from an install standpoint. That said, I doubt the coupling method has much affect on the filling of the annulus.
State-Wide Concrete Pumping, Inc	National pipe thread is the normal
Riley Contracting Inc.	No.
Geotech Services Inc.	Metal liners with internal bands need to be screwed to the liner pipe and sealed with spray foam.

Table B.62: Coupling or Jointing Limitation by ODOT Contractors (Continued)

Company Name	Limitations of Coupling/Jointing
ISCO Industries Inc.	For solid wall pipe installations, we use a mechanical SnapTite joining system. For profile wall products a threaded connection or a bell and spigot connection is necessary. The allowable tensile load and compression load for the joining system is usually assumed to be 1/3 of the strength of the parent pipe material (actual ratings change with diameters). The joining methods meet the sealing requirements of AASHTO M326. Thermal extrusion welding has been utilized for additional mechanical reinforcement in limited cases.

Q.6.2.7 What equipment do you use for grouting? Is it specialized and/or proprietary?

Table B.63: Equipment used for Grouting by ODOT Contractors

Company Name	Grouting Equipment
Axis Civil Construction LLC	Pump trailer- No, specialized cellular is not cost-effective, difficult to schedule the subs, few locally available and this work is so dependent on rain events. The contractor must be able to react in hours not weeks based on the forecast. Working with good ready mix suppliers with high fly ash content much better.
TURN – KEY TUNNELING	Specialized.
Belgray, Inc	Concrete Pump.
R. C. Construction Co.	Proprietary.
D A Van Dam & Associates LLC	We have our own grout machine but we use local gout suppliers. We are at the mercery of the supplier and give them our formula and once we turn back a truck for not following the formula they get the message. It must be very flowable.
Capitol Tunneling Inc.	Pumps-foamers-scales - all specialized.
Union Industrial Contractors	Grout pumps.
The Righter Company Inc	We used a truck-mounted trailer pump. I would say it is specialized. We don't own it, it is from the subcontractor that their entire business is concrete pumping.
State-Wide Concrete Pumping, Inc	Small line concrete pump with rock valve.
Riley Contracting Inc.	Grout pump if necessary. No, standard.
Geotech Services Inc.	We have a foam generator that we have onsite. Ready-mix truck delivers slurry and we add preformed foam onsite. We also have a peristaltic pump for pumping cellular grout without breaking down the bubble structure.
ISCO Industries Inc.	The cellular grout formulations promoted and installed by ISCO/SnapTite require the use of a concentrated wetting agent along with a foam generator to enable the production of the low-density products designed for the Rehabilitated Pipe System. While there is an initial equipment investment required to use this approach that equipment is neither highly specialized nor proprietary and available from a number of commercial manufacturers.

Q.6.2.8 Do you do grouting in lifts or in a single operation?

Table B.64: Grouting Methods by ODOT Contractors

Company Name	Grout Lift or Single Operation
Axis Civil Construction LLC	Both- Depends on numerous factors, conduit type, yardage, slope, diameter
TURN – KEY TUNNELING	Only when we can't get enough material the same day
Belgray, Inc	Both - Depends on the manufacturer representative
R. C. Construction Co.	Single operation
D A Van Dam & Associates LLC	Always lifts and often over a few days depending on the size and length of the culvert. Each job is different
Capitol Tunneling Inc.	Depending on the liner material and grout material. - again calculated on buoyancy.
Union Industrial Contractors	Lifts
The Righter Company Inc	Lifts
State-Wide Concrete Pumping, Inc	Both
Riley Contracting Inc.	Both depend on the size, length, and grade of the project.
Geotech Services Inc.	We usually grout in 2 - 3 lifts. On smaller diameter pipes with less than 40 cubic yds to fill the entire annular space, we will pump all in the same day.
ISCO Industries Inc.	Grout placement and grout lift heights are a function of the loading conditions placed on the liner during injection and is based on the unconstrained buckle limits of the piping product used. For most SnapTite installations, the conservative allowable load is 2 psi. Grout density often has greater impact on the external loads placed on the pipe than differences in elevation. For some applications it is possible to grout the annular space in a single lift, in other instances multiple lifts may be necessary.

Q.6.2.9 What methods do you use for liner stabilization?

Table B.65: Liner Stabilization by ODOT Contractors

Company Name	Liner Stabilization
Axis Civil Construction LLC	Various based on above
TURN – KEY TUNNELING	Blocking / filling with ballast
Belgray, Inc	Blocking on top, bottom, and sides. Blocking inside liner also.
R. C. Construction Co.	Cribbing
D A Van Dam & Associates LLC	We try to use a pipe that is a close fit ...we have a 2-inch grout tub and a 2-inch running board..and like about a 2-inch wiggle room so we are usually very close. Should we have a greater void area we use bracing to hit grade and to stabilize. We have pipe manufactures who make pipe up to 17 feet in diameter so we can usually get very close to any size culvert needed. How can I get Krah pipe approved for use in Ohio? they make pipe in the USA now up to 17 feet in diameter and I sell it for them. I am a certified WBE / WOSB company and I applied for OHIO EDGE and then Covid 19 hit Krah pipe is custom made and not sold through distributors. This would be a great help to the bridge design people who have large culverts under their responsibility.
Capitol Tunneling Inc.	Spacers, wood blocking, welded steel structure, water, dead men - again depending on the liner type, host pipe type, and grout requirements.
Union Industrial Contractors	We have used spacers, spreaders, and runners to stabilize the pipe.
The Righter Company Inc	Lots of bracing through the various ports and however else you can. And we anchored into the existing culvert's concrete bottom.
State-Wide Concrete Pumping, Inc	We provide the pumping service ONLY
Riley Contracting Inc.	We may increase the wall thickness of the steel casing to sustain the weight of the grout. If a large diameter pipe is used we will leave cross member supports in place until the grouting is complete.
Geotech Services Inc.	We usually use 2 x 4 lumber. 2 rails on the bottom and 2 -3 rails on the crown of the host pipe. Making sure the liner will clear using a template to adjust the top cribbing.
ISCO Industries Inc.	We calculate the loads placed on the liner during grout placement and then create a grout injection plan that limits the loading created during grout placement to be significantly less than the allowable limits on the liner. Utilizing a safety factor of 2 to 1 or greater to ensure stabilization during the injection procedures.

B.6.3 Successful Projects

Q.6.3.1 Do you have details of any successful past projects that you can share? Please also share any lessons learned and improvements made from these projects. What would you do differently to improve the effectiveness of sliplining culvert rehabilitation?

Table B.66: Successful Past Projects Shared by ODOT Contractors

Company Name	Lessons Learned
Axis Civil Construction LLC	Many- structural sealed joints and stiff pipe greatly improve outcomes and constructability.
TURN – KEY TUNNELING	Each project has its own challenges - there are many ways to ensure the annulus is full
Belgray, Inc	Unknown
R. C. Construction Co.	Yes, you most go slow so that you don't put a lot of pressure on the pipe
D A Van Dam & Associates LLC	I have many and I can send them. Please give me an email address and I will forward them to you.
Capitol Tunneling Inc.	we perform carrier pipe installations on a continual basis so we have a lot of knowledge on what works and what is not so good!!. I.E. for storm pipes, we are not fans of the thin wall pipes! we have chosen not to install them unless we can control the grouting process and materials that we use - almost all cellular grouts. We have done lines as small as 6" to 13' from steel to plastic to plate structures all over the country. We try to help the client-inspector-owner where we can understand the means and methods but there are times that it is difficult.
Union Industrial Contractors	I think it would be wise to come up with a procedure for grouting from the end or internally. If the tubes and ports are not installed to the correct elevations and locations, there is no way that the culvert will get fully grouted. Some of it is common sense to have air reliefs to allow for the air to push out while the grout is filling the space.
The Righter Company Inc	I think I answered this in previous responses.
Riley Contracting Inc.	Pipe type is a big factor in a successful project. On our boring and jack operations, we install many types of pipe inside the steel casing and grout the annular space. We have learned that many types of pipes cannot support the heat and the weight of the grout causing the pipe to deform or collapse. When a steel casing pipe is used as the slip lining pipe you can use a pump to install the grout with no concerns of a void as long as the pipe is blocked in place to avoid becoming misaligned. Sizes of the host pipe and slip lined pipe is also critical as you need enough annular space to allow the grout to pass if there is too much annular space the volume of grout needed may deform, misalign or collapse the pipe.

Table B.66: Successful Past Projects Shared by ODOT Contractors (Continued)

Company Name	Lessons Learned
Geotech Services Inc.	Masonry bulkheads do not leak. Do not use plywood for bulkheads.
ISCO Industries Inc.	City of Huber Heights, OH Various locations and sizes throughout city limits. Used 40 lb wet cast density grout. No issues on grout installations. We learned that proper bulkhead building is key to successful grout projects. City of Oak Hill TN Various location and sizes throughout city limits. Used 40 lb wet cast density grout. 6 sites. KYTC Maintenance Grout Contract. 40 lb wet cast density grout. Multiple sites throughout the state.

B.6.4 Destructive or Non-Destructive Methods

Q6.4.1 Are you aware of any non-destructive evaluation techniques suitable for the evaluation of annulus void grout when liners are made from conduit type(s) you install?

Table B.67: Non-Destructive Evaluation Methods Recommended by ODOT Contractors

Company Name	Non-Destructive Evaluation Techniques
Axis Civil Construction LLC	Sounding, thermal imaging might be investigated?
TURN – KEY TUNNELING	Yes
Belgray, Inc	No
R. C. Construction Co.	No
D A Van Dam & Associates LLC	What about sonic sounding?
Capitol Tunneling Inc.	No
Union Industrial Contractors	Sounding
The Righter Company Inc	No
State-Wide Concrete Pumping, Inc	
Riley Contracting Inc.	No
Geotech Services Inc.	While you are grouting condensation forms on the inside of metal liners. This helps to determine the height of the grout while pumping in lifts. You can lightly tap on the liner after the grout has set. Similar to determining delaminated concrete on a concrete repair project. If you have full- encapsulation there should be a uniform sound all around the circumference of the pipe.
ISCO Industries Inc.	There are many pipeline assessment tools available on the market. Pipe soundings can be used to quickly gain knowledge of any significant voids between the host pipe and the liner. Ground Penetrating Radar can be used to investigate voids that may be present in the fill beyond the host pipe. But the presence of clays or salts (often used for snow and ice removal) can influence the electromagnetics used by the GPR systems. Backscatter Chromatography has also been utilized to evaluate how the low-density grouts can fill and mitigate voids beyond the host pipe, but the necessary radioactive isotopes used and obtained from the DOE make that evaluation very expensive to conduct.

B.6.5 Other Comments and Information

Q.6.5.1 Please include any other comments or information you would like to include regarding installation and grouting.

Table B.68: Information from ODOT Contractors Regarding Installation/Grouting

Company Name	Other Recommendation
Belgray, Inc	None
R. C. Construction Co.	It is a hard and difficult job to do this type of a work we just did one in district 10 that another company tried the state had to throw them off the job after 6 weeks of them trying to install we got the job and did the installation in 3 days.
D A Van Dam & Associates LLC	There is a new HDPE pipe on the market that is corrugated inside and outside the wall that will slow the velocity of the follow, important when lining culverts. I represent them also. How do I get this evaluated and approved for use? It is a High Strength Steel Reinforced HDPE pipe. We showed at last year's OTEC showing. I just signed with them last August.
Capitol Tunneling Inc.	If you would like to discuss more please feel free to contact me!
The Righter Company Inc	I think it is mainly about fabricating the pipe with as many ports as reasonably possible, and common sense techniques that will provide the best chance for a good outcome.
State-Wide Concrete Pumping, Inc	We are a concrete pumping company ONLY - not a supplier or installer.
Geotech Services Inc.	ODOT needs to stop specifying the use of ODOT 613 LSM for filling the annular space for all liner jobs.
ISCO Industries Inc.	The grout serves multiple roles in the Rehabilitated Pipe System. It stabilizes the liner and controls bottom invert elevation, it also becomes a structural member in the RPS approach, it can be used to displace groundwater when present, and it can be utilized to fill existing voids beyond the host. It is critical that the surrounding fill is stabilized during the grouting and rehabilitation process to ensure the long-term performance of the above roadway.

B.6.6 Conclusions based on Responses from ODOT Contractors

The survey to ODOT contractors requested information on the conduits employed for sliplining culverts. A total of 15 responses were received from ODOT contractors regarding the types of conduits they use, and a summary of the responses is presented in Figure B.9. From this figure, it can be noticed that the majority of sliplined culverts are constructed using corrugated steel pipes (707.01 or 707.02), followed by spiral rib pipe made of corrugated steel (707.12), corrugated polyethylene smooth lined pipe (707.33), steel reinforced thermoplastic ribbed pipe (SS 938), and structural plate corrugated steel structure (707.03). Fewer contractors mentioned using other types of conduits.

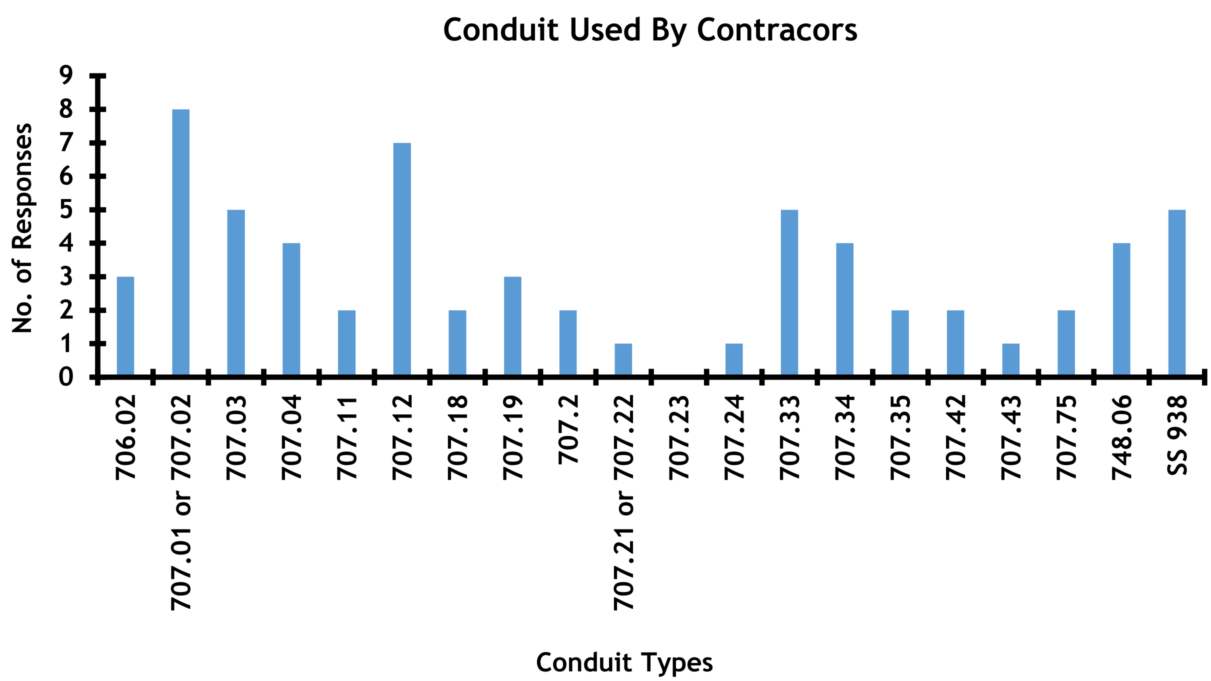

Figure B.9: Types of Conduits Used by ODOT Contractors.

One survey question focused on the ease of grouting when using different types of conduits, as the conduit type may have an effect on the filling of the annulus. Figure B.10 displays the responses to this question that were received from ODOT contractors. Contractors found steel casing pipe (Item 748.06) to be "Very Easy" for grouting, while corrugated steel pipe (Item 707.01 or 707.02) and corrugated steel spiral rib pipe (Item 707.12) were reported to be "Somewhat Easy" for installing grout. Other conduits such as corrugated steel spiral rib pipe (Item 707.12) and steel reinforced thermoplastic ribbed pipe (Item SS 938) were reported to be "Very Hard" to grout. Overall, 66% of the respondents reported finding it “Very Easy” or “Somewhat Easy” to install grout for the conduits typically used in the sliplining of culverts.

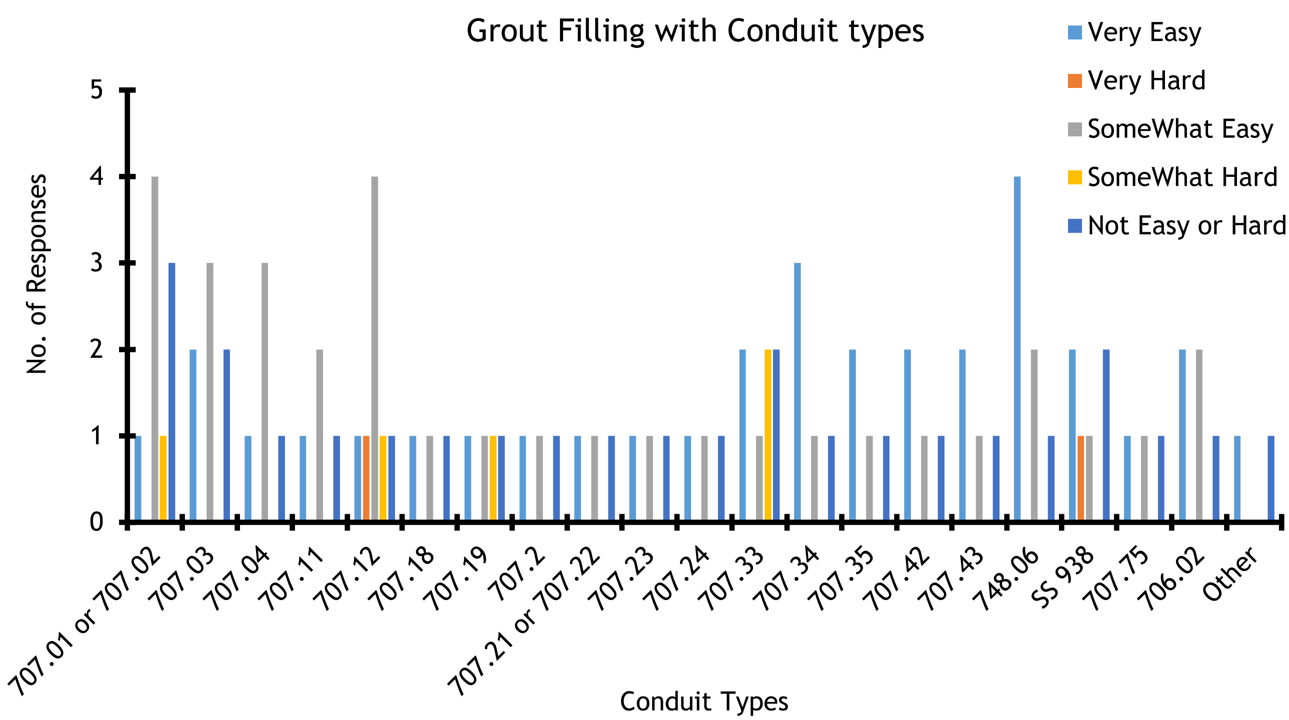

Figure B.10: ODOT Contractor Responses on Ease of Grout Filling for Various Conduits.

Other survey questions focused on how often different types of grouts were used for annulus filling of different types of conduits, as the type of conduit used for sliplining may influence the selection of the grout used to fill the annulus. The responses from ODOT contractors regarding the use of CLSM grout (Item 613) are shown in Figure B.11. As can be noticed from this figure, the contractors indicated that they "Sometimes" use CLSF for filling the vast majority of conduits used in the sliplining of culverts, with the most responses recorded for corrugated steel spiral rib pipes (Item 707.12), followed by corrugated steel pipe (Item 707.01 or Item 707.02). CLSM grout was not reported to be used by any contractors for aluminum coated steel conduits (Item 707.19) or corrugated aluminum alloy pipe conduits (Item 707.21 or Item 707.22).

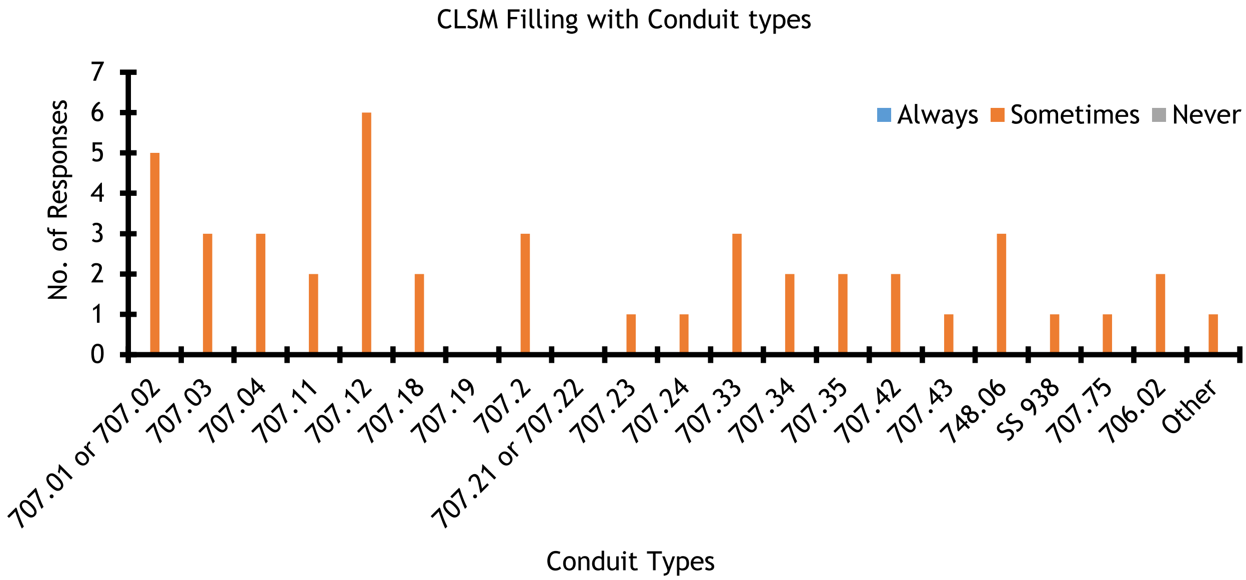

Figure B.11: ODOT Contractor Responses on Annulus Filling with CLSM.

The responses from ODOT contractors regarding the use of cellular grout are shown in Figure B.12. In general, a majority of respondents chose "Always" for each conduit type, with smaller numbers of respondents reporting that they “Sometimes” or “Never” use cellular concrete for filling conduits of the same type.

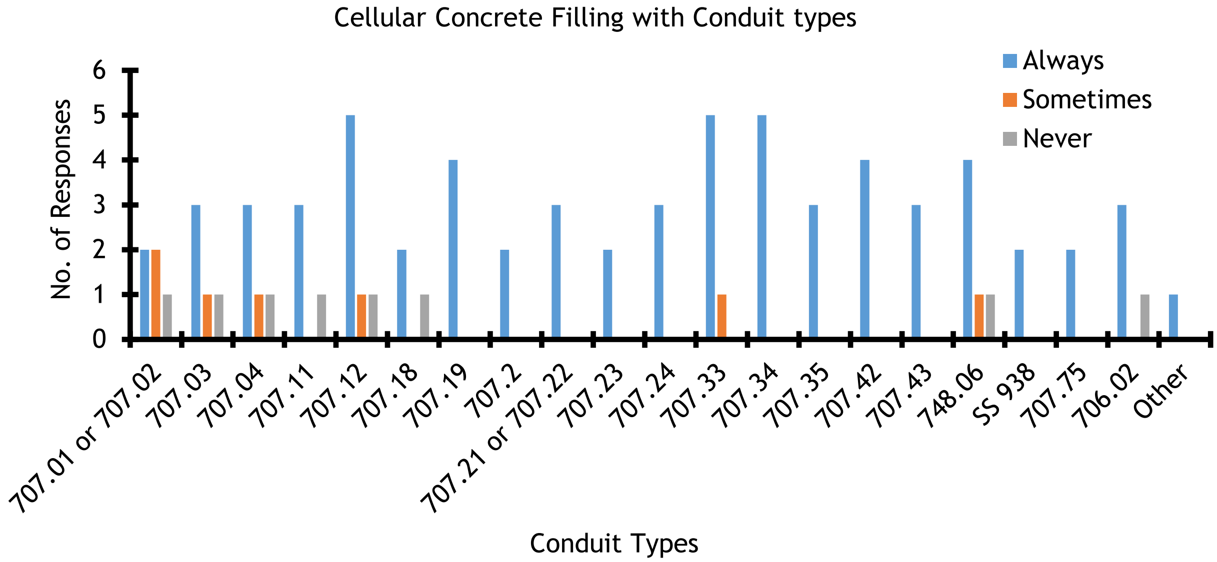

Figure B.12: ODOT Contractor Responses on Annulus Filling with Cellular Grout.

Because ODOT contractors work directly on site and observe the sliplining of culverts, the majority agree that using cellular grout (which in some projects is recommended at a density 40 lb/ft^3) to fill the annulus is a better option than using grouts such as LSM (ODOT 602) and CLSM (ODOT 613). In addition, many contractors have asserted that CLSM is not suitable for grouting the annular space, since it does not contain enough cement to keep the sand in the mix lubricated or suspended while the grout is being pumped.

The site and pipe conditions also impact the grout that should be used. The respondents indicate that they prefer to install grout in a single lift in certain circumstances, while they choose to install the grout in multiple lifts in others. However, most agree that grouting should be installed slowly so that any voids behind the host pipe, if any, can be closed. They also agree that it is vital to avoid applying high loads to the liner pipe by placing high density grout behind the pipe—especially when using flexible pipe (such as corrugated metal pipe, high density polyethylene pipe, and polyvinyl chloride pipe), where the walls of these pipes might be thin. For steel casing pipes, which have a thick wall, grouting in a single lift is no cause for concern. However, based on the site inspections conducted in this project, most steel casing pipes showed significant levels of corrosion, which will reduce their service life.

During grouting, it is important to verify if the annulus is full by performing a sounding test of the wall of the liner pipe, by checking to see if any grout comes out of inspection ports at various levels, or by watching for grout to come out of the vent pipes constructed at the bulkheads. At some locations, such as the crown of the culvert (at the 12 o'clock position), there is a high probability that the grout will not completely reach the host pipe wall, and the grout at those locations cannot be seen while grouting.

B.7 Conclusions

To obtain essential information about common processes of sliplining culverts, the following groups were surveyed in this research project: conduit manufacturers, ODOT Districts, Counties and Locals, ODOT designers, and ODOT contractors. This survey aimed to gather input on the present practice in applying sliplining to culverts as well as to better understand the standard components that make up these structures. The following conclusions can be made based on the survey results:

- Conduit manufacturers reported that corrugated polyethylene smooth lined pipe (Item 707.33) is the conduit they use most frequently for the sliplining of culverts, while ODOT Districts most often use steel casing pipe (Item 748.06) and counties and locals most often recommend polyethylene plastic pipe with an outer diameter (Item 707.34). ODOT contactors indicate that corrugated steel pipes (Item 707.01 or Item 707.02) are most often employed in the sliplining they conduct for ODOT.

The designers from ODOT provided alternative suggestions regarding the number of conduits. Their perspectives differ markedly from one another based on their experiences.

- The annulus space in sliplined culverts can be filled with various grouts including cellular grout (ASTM C869), low-shrinkage mortar (Item 602), and controlled low strength mortar (Item 613). Because of its low viscosity and its capacity to be pumped over long distances, most respondents prefer to grout sliplined culverts using cellular concrete grout.
- Two distinct installation strategies can be used for pumping grouts into the annulus of a sliplined culvert: pumping the grout through polyvinyl chloride pipes installed at the top of the culvert or drilling holes in the liner pipe conduit of the culvert and then injecting the grout into the annular space to fill any voids. When deciding which installation technique to use, the circumstances of the annulus should be given primary consideration; based on the grout quantity, a decision can be made about whether the grout is installed either in a single lift or in multiple lifts.
- It is important to conduct an inspection to determine if the annulus is completely filled with grout. This can be accomplished during the grouting process by sounding the wall of the liner pipe with a hammer and listening to the response. A second method is to drill an inspection port and perform a visual inspection. Another method of verifying if the annulus has been completely filled is to check to see if grout flows out from the vent tubes installed at the bulkheads.
- It is of the utmost importance to examine the difference between the theoretical volume that is anticipated to be pumped and the actual volume of grout that has been pumped to the annulus. If the amount pumped is lower than the theoretical volume, the annulus may not have been completely filled.

The survey in this project summarized the experiences of numerous professionals involved in the sliplining of culverts at various locations in the state. The results of this study can inform the materials and procedures selected for sliplining culverts in Ohio in the future.

Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX C

Sliplined Culverts Inspection By Sounding Tests

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The Ohio Department of Transportation,
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U.S. Department of Transportation
Federal Highway Administration

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APPENDIX C

INSPECTION OF SLIPLINED CULVERTS USING SOUNDING TESTS

C.1 Introduction

A wide variety of inspection technologies and methods exist to assist in the evaluation of culvert conditions. These inspection methods range from a simple visual inspection to inspections that use more advanced technology. However, most of the studies on culvert inspection methods that are included in the literature review (Appendix A) only emphasize the capabilities of methods used for evaluating the condition of the culvert wall or the condition of the soil behind the culvert wall, rather than those methods used to evaluate the condition of the grouted annulus in a sliplined culvert.

This appendix describes the methodology used in this project for inspecting sliplined culverts, the process for selecting and locating the culverts that were included in this project, the results obtained from the evaluation of the selected culverts, and some conclusions based on the inspection results.

C.2 Method for Inspecting Culverts

One of the simplest methods used for evaluating reinforced concrete culverts is a hammer sound test (or "sounding test"), in which the inspector taps the interior wall of the culvert with a hammer and listens to the sound that is produced when the wall responds. When a concrete culvert corrodes, voids can form inside the culvert wall. During a sounding test, the response of a culvert with voids behind the pipe wall will have a different sound than that for a culvert where the materials behind the pipe are solid (i.e., without voids). This concept is useful for evaluating the condition of the cementitious grout in the annular space behind the liner pipe wall of a sliplined culvert.

The tools and equipment required for a culvert inspection are shown in Figure C.1. The tools needed to conduct the evaluation include a hammer that weighs 8 oz, a 300-foot tape measure, a cordless hammer, drill bits (sizes from 1/16 inch to 1½ inches), plugs, a digital single-lens reflex (DSLR) camera, an endoscope camera, a can of compressed air, flashlights, and orange spray paint. Safety equipment and personal protective gear for the inspector include a helmet, a safety vest, eye protection, and waders (for culverts with standing/running water).

Figure C.1: Inspection Tools and Safety Gear for Conducting Sounding Tests.

At the start of the inspection, the total length of the culvert from the inlet to the outlet is measured using a tape measure. The total length of the culvert is then divided into equal segments to assist the inspector in mapping the culvert and evaluating each segment individually. Next, the inspector taps the inside of the liner pipe of the sliplined culvert at set distances along the length of the pipe, starting from the inlet side, and proceeds to tap around the circumference of the pipe at intervals of approximately 12 inches. The inspector listens and evaluates the sound created in response to the tapping, and the approximate locations of any voids are marked using orange spray paint. The locations of the voids are then recorded, with the inspector indicating the location on the circumference of the pipe by using clock positions: the invert is at 6 o'clock, the crown is at 12 o'clock, the left side of the springline (which is the horizontal mid-height line of a pipe having a circular cross section through the invert) is at 9 o'clock, and the right side of the springline is at 3 o'clock, with the field inspector oriented facing downstream from the inlet to the outlet (with the inlet at their back).

At the approximate locations of severe voids, the inspector will validate the sounding results by examining the annulus with an endoscope inspection camera. To accomplish this, the inspector drills a ½-inch hole in the liner pipe and inserts the endoscope into the hole to inspect the physical condition behind the liner pipe wall, viewing and recording the images using a camera attached to the probe (cable) of the endoscope. Figure C.2 illustrates the process of evaluating a culvert using the sounding method and an endoscope.

(a) Tapping the Liner Pipe with a Hammer

(b) Marking the Location of a Suspected Void with Orange Paint

(c) Drilling a Hole in the Liner Pipe.

(d) Inserting an Endoscope into the Hole to Inspect the Annulus

Figure C.2: Sounding Method for Culvert Inspection

C.3 Selection of Culverts to include in the Survey

The Ohio Department of Transportation (ODOT) provided the research team with an initial list of 68 culverts that were sliplined in recent years and were located in different ODOT districts (Table C.1). The culverts on the list were lined with pipes made from various materials. Examples of some materials that are used for liner pipes are illustrated in Figure C.3.

(a) Corrugated Steel Spiral Rib Pipe (b) Polyethylene Double-Layered Pipe

(c) Sectional Corrugated Metal Pipe (d) Steel Casing Pipe

Figure C.3: Various Materials used for Sliplining Culverts.

ODOT identifies culverts within the state according to the ODOT district where the culvert is located, the project identification number (PID), and a code that indicates the county, route, and section (CRS) where the culvert is located. As the list of culverts obtained from ODOT did not indicate the exact location of a culvert along the route or include complete details about the structure of the culvert and the materials used, it was necessary for the research team to find the precise location and other details for each of the 68 culverts on the initial list provided by ODOT.

To obtain the needed information, the research team accessed ODOT's Transportation Information Mapping System (TIMS) website to search for details on each culvert by inputting the PID number to obtain the location and the associated culvert plans and drawings. The culvert plan provided the following details for each culvert: geographic coordinates (longitude and latitude), culvert length, liner pipe diameter, host pipe diameter, and pipe materials. The research team then entered the longitude and latitude for each culvert into Google Earth or Google Maps to find their precise locations.

Table C.1: Initial List of Culverts provided by ODOT

ODOT DISTRICT	PID	CRS	Length (ft)	Host Pipe Diameter (in)	Host Pipe Shape	Liner Diameter (in)	Liner Shape
2	76032	LUC-75-6.70	90	33	Circular	27	Circular
2	77254	LUC-75-4.52	259	50	Circular	48	Circular
3	90362	HUR-61-15.93 Part 1	77	48	Circular	42	Circular
3	90362	HUR - 162 - 8.72 Part 2	86	72	Circular	72	Circular
3	14018	MED - 71 - 10.77	200.4	120	Circular	102	Circular
4	25869	ATB - 90 - 22.06	364	120	Circular	108	Circular
4	76721	SUM - 8 - 7.81	233	33	Circular	27	Circular
4	76721	SUM - 8 - 7.81	199	24	Circular	18	Circular
4	76721	SUM - 8 - 7.81	224	42	Circular	36	Circular
4	76721	SUM - 8 - 7.81	202	60	Circular	54	Circular
4	76721	SUM - 8 - 7.81	358	42	Circular	36	Circular
4	76721	SUM - 8 - 7.81	238	30	Circular	24	Circular
4	77260	MAH/TRU-80-4.50/0.00	390.4	54	Circular	48	Circular
4	82092	STA - 183 - 18.87	160	72	Circular	60	Circular
4	82919	POR - 224 -0.00	83	42	Circular	38 × 24	Rectangular
4	92932	SUM - 21 4.05	169	54	Circular	48	Circular
5	81254	GUE - 70 - 13.21/13.34L	186	96	Circular	84	Circular
5	54810	LIC - 70 -24.23	236	48	Circular	36	Circular
5	54810	LIC - 70 - 25.82	203	96	Circular	84	Circular
5	54810	LIC - 70 - 29.08	320	96	Circular	78	Circular
5	85540	LCT - 70 - 13.00	302	78	Circular	60	Circular
5	87535	FAI - 37 - 23.09	282	72	Circular	60	Circular
6	81747	FRA - 270 - 21.67 Part 1	126	84	Circular	84	Circular
7	94787	AUG - 33 - 20.87	240	60	Circular	54	Circular
8	82957	WAR - 22 - 1745	158	84, 84, 12 × 8	Two Circular, One Box	108	Circular
8	82957	WAR - 22 - 1753	111	90	Circular	84	Circular
8	82957	WAR - 22 - 1786	154	72	Circular	66	Circular
8	82957	WAR - 22 - 1828	111	42	Circular	42	Circular
8	82957	WAR - 123 - 0208	54	48	Circular	48	Circular

Table C.1: Initial List of Culverts provided by ODOT [Continued]

ODOT DISTRICT	PID	CRS	Length (ft)	Host Pipe Diameter (in)	Host Pipe Shape	Liner Diameter (in)	Liner Shape
8	86136	PER - 121 - 0567	50	102 × 53	Rectangular	96 × 60	Rectangular
8	86136	PER - 732 - 1142	60	96 × 54	Rectangular	72	Circular
8	86136	PER - 732 - 1276	195	102,108	Circular	96	Circular
8	87090	BUT-177-0411-STA 302 +26.27	80	72 × 48	Rectangular	42	Circular
8	91129	HAM - 52 - 37.88	436	84	Circular	66	Circular
8	98584	HAM - 71 - 1090	120	42 & 48	Circular	36, 42	Circular
9	180543	JAC-35-0.418	256	72	Circular	60	Circular
9	96957	PIK-772-7.89	120	108 × 52	Arch	90	Circular
9	97240	BRO - 62 - 11.41	452	114	Circular	102	Circular
9	97228	BRO - 68 - 40.91	184	96	Circular	84	Circular
9	86702	LAW - 7 - 0.27	312	168	Circular	150 TWIN	Circular
9	86586	BRO-40-0.89	180.5, 188.75	144 TWIN	Circular	108 TWIN	Circular
9	20429	LAW - 52 - 4.24	326	144	Circular	108	Circular
9	20429	JAC - 35 - 7.55	254	84	Circular	72	Circular
10	96629	WAS - 550 - 21.75	317	66	Circular	60	Circular
10	96596	NOB - 285 - 3.31	80	72	Circular	66	Circular
10	95138	MOE - 7 - 16.40	218	60	Circular	54	Circular
10	84147	MOE - 7 - 057	126	156	Circular	132	Circular
10	84147	WAS - 7 - 52.38	310	132	Circular	108	Circular
10	84147	WAS - 7 - 45.40	128	144	Circular	120	Circular
10	108830	MRG - 266 - 2.73	94	72	Circular	60	Circular
10	100205	NB - 77 -2.84	332	36	Circular	54	Circular
10	104895	GAL - 218 - 6.47	70	76 × 57	Arch	42 × 62	Arch
10	106051	GAL - 35 - 15.70	125	84	Arch	60	Arch
10	108758	ATH - 33 - 8.56	72	54	Circular	48	Circular
10	108830	MRG - 266 - 2.73	94	72	Circular	60	Circular
10	84147	MOE - 7 - 057	126	156	Circular	132	Circular

Table C.1: Initial List of Culverts provided by ODOT [Continued]

ODOT DISTRICT	PID	CRS	Length (ft)	Host Pipe Diameter (in)	Host Pipe Shape	Liner Diameter (in)	Liner Shape
10	84147	WAS - 7 - 45.40	128	144	Circular	120	Circular
10	84147	WAS - 7 - 52.38	310	132	Circular	108	Circular
10	94701	NB - 145 - 2.48	56	48	Circular	36	Circular
10	94701	NB - 340 - 6.70	214	36	Circular	30	Circular
10	94107	NOB - 14 -7.22	60	36	Circular	30	Circular
10	94701	NB - 340 - 6.74	214	48	Circular	42	Circular
11	97421	JEF-150-4.968	154	114 × 77	Arch	84	Circular
11	97421	JEF-151-1.530	138	96	Circular	78	Circular
12	75477	LAK-90-21.40/ATB-90-0.00	248	54	Circular	48	Circular
12	75477	LAK-90-21.40/ATB-90-0.00	274	42	Circular	36	Circular
12	98548	CUY - MIK BLVD - 5.029M	158	252 x 105	Arch	240 × 99	Arch
12	98550	CUY - MIK BLVD - 5.055M	28	408	Arch	323	Arch

More than half of the culverts on the initial list provided by ODOT had to be eliminated from the final inspection list. Some culverts were excluded because the research team was unable to find their precise locations, while other culverts were excluded because of the non-standard shape of the liner (e.g., rectangular liners). In addition, the diameters of liners in some of the culverts were less than 54 inches, which is the minimum diameter that was safe and suitable for our inspectors to perform an in-person entry. For this reason, the culverts having liner pipes that were below the minimum diameter were also excluded from the inspection list. This left a total of 30 culverts for the research team to inspect.

Table C.2 presents a list of the culverts on the final inspection list, along with their identifiers, geographic locations, and other details obtained from TIMS.

Table C.2: Summary of the Culverts Selected for Inspection

ODOT Dist.	PID	CRS	Location	Length (ft)	Host Size (in)	Host Shape	Host Pipe Material	Liner Size (in)	Liner Shape	Liner Pipe Material	Year Sliplined	Date Inspected
3	14018	MED - 71 - 10.77	39°33' 08.4" N 81°01' 41.9" W	200.40	120	Circular	Corrugated Metal Pipe	102	Circular	Corrugated Steel Spiral Rip Pipe	2005	12/3/2020
4	76721	SUM - 8 - 7.81	39°31' 40.1" N 81°03' 25.2" W	202	60	Circular	Corrugated Metal Pipe	54	Circular	Corrugated Steel Spiral Rib Pipe	2018	5/14/2021
4	25869	ATB-90-28.406	41°56' 04.8" N 80°31' 26.0" W	380	120	Circular	Corrugated Metal Pipe	108	Circular	Corrugated Steel Spiral Rib Pipe	2010	12/7/2020
5	81254	GUE-70-13.321	40°00' 19.4" N 81°29' 38.6" W	96	186	Circular	Corrugated Metal Pipe	84	Circular	Corrugated Steel Spiral Rib Pipe	2014	12/7/2020
5	84810	LIC-70-25.82	39°56' 20.4" N 82°17' 16.9" W	203	96	Circular	Corrugated Metal Pipe	84	Circular	Corrugated Steel Spiral Rib Pipe	2015	9/6/2021
5	84810	LIC-70-29.08	39°57' 05.4" N 82°12' 17.6" W	320	96	Circular	Corrugated Metal Pipe	78	Circular	Corrugated Steel Spiral Rib Pipe	2015	9/6/2021
5	87535	FAI-37-23.09	39°43' 07.5" N 82°27' 41.4" W	282	72	Circular	Corrugated Metal Pipe	60	Circular	Corrugated Steel Spiral Rib Pipe	2011	5/14/2021
5	85540	LCT-70-13.00	39°56' 32.8" N 82°31' 07.3" W	302	78	Circular	Reinforced Concrete Pipe	60	Circular	High density polyethylene (HDPE)	2012	6/11/2021
5	19628	GUE - 541 - 8.20	40°08' 50.0" N 81°33' 17.0" W	259	168	Circular	Sectional Plate Corrugated Metal Culvert	144	Circular	Structural Corrugated Steel	2006	7/9/2021

Table C.2: Summary of the Culverts Selected for Inspection [Continued]

ODOT Dist.	PID	CRS	Location	Length (ft)	Host Size (in)	Host Shape	Host Pipe Material	Liner Size (in)	Liner Shape	Liner Pipe Material	Year Sliplined	Date Inspected
8	91129	HAM - 52 - 37.88	39° 02' 27" N 84° 21'18" W	436	84	Circular	Corrugated Metal Pipe	66	Circular	Corrugated Steel Spiral Rib Pipe	2011	7/21/2021
8	82957	WAR - 22 - 1786	39°23' 52.1" N 84°01' 07.1" W	154	72	Circular	Reinforced Concrete Pipe	66	Circular	Steel Casing Liner Pipe	2011	7/21/2021
8	82957	WAR - 22 - 1753	39°18' 33" N 84°01' 38.3” W	111	90	Circular	Corrugated Metal Pipe	84	Circular	Steel Casing Liner Pipe	2011	7/21/2021
9	180543	JAC-35-0.418	39°11' 08.4" N 82°45' 29.8" W	256	72	Circular	Corrugated Metal Pipe	60	Circular	Corrugated Steel Sprial Rip Pipe	2018	6/11/2021
9	96957	PIK-772-7.89	39°01' 41.0" N 83°08' 28.0" W	120	108 × 52	Arch	Corrugated Metal Pipe	90	Circular	Corrugated Aluminum Alloy Pipe	2018	12/10/2020
9	97240	BRO - 62 - 11.41	38° 46' 18" N 83° 48' 48" W	452	114	Circular	Corrugated Metal Pipe	102	Circular	Corrugated Steel Spiral Rib Pipe	2017	7/19/2021
9	97228	BRO - 68 - 40.91	39° 11' 03" N 83° 55’ 56"W	184	96	Circular	Corrugated Metal Pipe	84	Circular	Corrugated Polyethylene Smooth Lined Pipe	2016	7/22/2021
9	86702	LAW - 7 - 0.27	38° 25’ 25" N 82° 29’ 17" W	312	168 TWIN	Circular	Corrugated Metal Pipe	150 TWIN	Circular	Steel Casing Pipe	2016	6/18/2021

Table C.2: Summary of the Culverts Selected for Inspection [Continued]

ODOT Dist.	PID	CRS	Location	Length (ft)	Host Size (in)	Host Shape	Host Pipe Material	Liner Size (in)	Liner Shape	Liner Pipe Material	Year Sliplined	Date Inspected
9	86586	BRO-40-0.89	38° 46’ 18" N 83° 48’ 48" W	180.5, 188.75	144 TWIN	Circular	Corrugated Metal Pipe	108 TWIN	Circular	Polyethylene profile wall pipe	2014	7/19/2021
9	20429	LAW - 52 - 4.24	38° 33’ 34" N 82° 43’ 08" W	326	144	Circular	Corrugated Metal Pipe	108	Circular	Polyethylene profile wall pipe	2009	7/18/2021
9	20429	JAC - 35 - 7.55	39° 06’ 38" N 82° 40’ 43" W	254	84	Circular	Corrugated Metal Pipe	72	Circular	Polyethylene profile wall pipe	2009	7/18/2021
10	96629	WAS - 550 - 21.75	39°24' 17.3" N 81°28' 19.5" W	317	66	Circular	Reinforced Concrete Pipe	60	Circular	Steel Casing Pipe	2018	7/14/2021
10	96596	NOB - 285 - 3.31	39°47' 23.1" N 81°29' 32.3" W	80	72	Circular	Corrugated Metal Pipe	66	Circular	Steel Casing Pipe	2015	7/14/2021
10	95138	MOE - 7 - 16.40	39°42' 24.7" N 80°51' 01.6" W	218	60	Circular	Corrugated Metal Pipe	54	Circular	Polyethylene Profile Wall Pipe	2014	7/16/2021
10	84147	MOE - 7 - 057	39°33' 08.4" N 81°01' 41.9" W	126	156	Circular	Corrugated Metal Pipe	132	Circular	Polyethylene Profile Wall Pipe	2011	7/16/2021
10	84147	WAS - 7 - 52.38	39°31' 40.1" N 81°03' 25.2" W	310	132	Circular	Corrugated Metal Pipe	108	Circular	Polyethylene Profile Wall Pipe	2011	7/16/2021
10	84147	WAS - 7 - 45.40	39°26' 55.4" N 81°08' 04.0" W	128	144	Circular	Corrugated Metal Pipe	120	Circular	Polyethylene Profile Wall Pipe	2011	7/16/2021

Table C.2: Summary of the Culverts Selected for Inspection [Continued]

ODOT Dist.	PID	CRS	Location	Length (ft)	Host Size (in)	Host Shape	Host Pipe Material	Liner Size (in)	Liner Shape	Liner Pipe Material	Year Sliplined	Date Inspected
10	108830	MRG - 266 - 2.73	39°33' 03.5" N 81°48' 54.5" W	94	72	Circular	Corrugated Metal Pipe	60	Circular	Steel Casing Pipe	2018	6/9/2021
11	97421	JEF-150-4.968	40°11' 14.4" N 80°47' 38.0" W	154	114 × 77	Arch	Corrugated Pipe Arch	84	Circular	Corrugated Metal Pipe	2015	12/7/2020
11	97421	JEF-151-1.530	40°18' 07.7" N 80°50' 55.3" W	138	96	Circular	Corrugated Metal Pipe	78	Circular	Corrugated Steel Spiral Rib Pipe	2015	12/7/2021
12	98548	CUY - MIK - 5.029 M	41°32' 04.1" N 81°37' 48.4" W	158	252 × 105	Arch	Corrugated Metal Pipe	240 × 99	Arch	Corrugated Metal, Sectional Plate	2017	12/4/2020

C.4 Surveying the Selected Culverts

The inspections of culverts on the final inspection list were conducted by the research team between December 4, 2020 and December 7, 2021. In the field inspection, the main challenge for the survey team was in finding the culverts, as the culverts are located below the level of the road and could not be easily seen when arriving at the specified locations.

While the research team was able to inspect the majority of culverts on the final list, some inspections could not be conducted due to prevailing unsafe conditions or difficult access. These conditions included high water levels (at LAW-7-0.27 in Lawrence County, MOE-7-057 in Monroe County, and WAS-7-52.38 and WAS-7-45.40 in Washington County), marshy conditions and snakes (at GUE-70-13.321 in Guernsey County), or too much vegetation in the culvert for the survey team to perform an entry inspection (MOE-7-16.40 in Monroe County). In addition, three of the culverts on the list (WAR-22-1753 in Warren County, JEF-150-4.968 in Jefferson County, and CUY-MK-5.029M in Cuyahoga County) turned out to be culverts that were not sliplined. Only a basic visual inspection was performed for the culverts where it was not feasible to conduct a detailed inspection, and photographs were taken to document the current condition of these culverts from the outside.

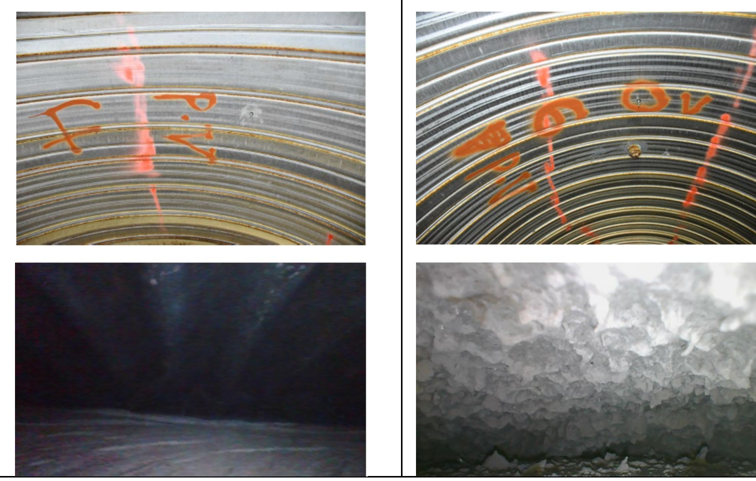
For each of the 21 sliplined culverts where a full inspection could be conducted, a sounding test was performed to evaluate the condition of the annulus behind the liner wall. Photographic images were obtained to document the void locations and the culvert conditions. These images were obtained using a DSLR camera and an endoscope camera.

Once the survey data was obtained from the field, the research team was able to evaluate the culvert conditions. For the 21 culverts that underwent full inspections, the research team evaluated each segment of the liner pipe individually. Maps were created for the 21 culverts using *AutoCAD* computer-aided design and drafting software (Autodesk, San Rafael, California). For each of these culverts, two maps were created for the liner pipe wall: one map represents the positions from 6 o'clock to 12 o'clock through 9 o’clock along the length of the culvert, and the second map represents the positions from 12 o'clock to 6 o'clock through 3 o’clock. The photographs of the culverts as well as the associated maps and annulus conditions are presented in Figures C.4 to C.33.

Culvert Access

Delamination at the Pipe Wall

Solid Annulus Grout



Partial -Voids

Figure C.4: Culvert Inspection and Map for MED - 71 – 10.77 (District 3, Medina County)

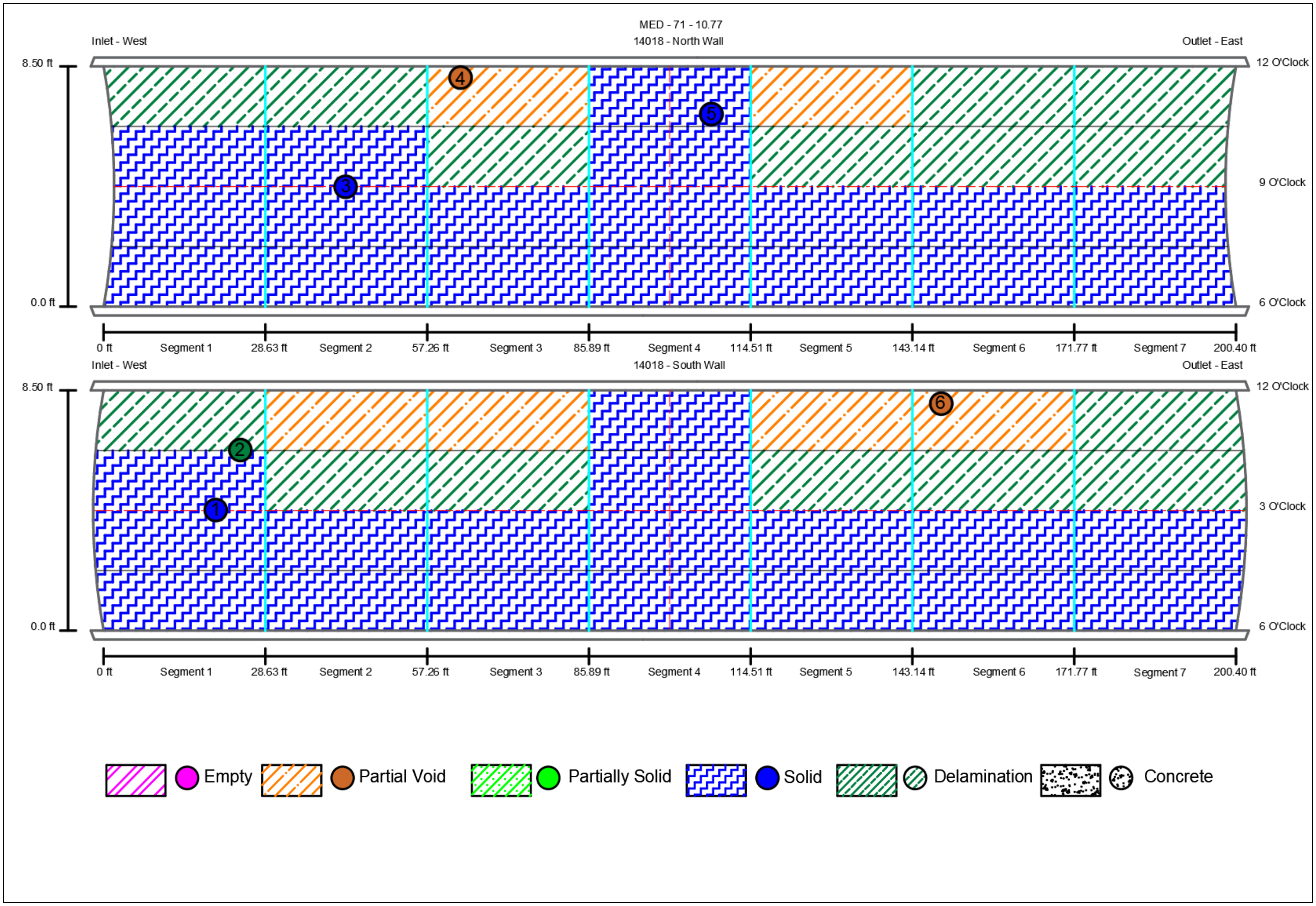


Figure C.4: Culvert Inspection and Map for MED - 71 – 10.77 (District 3, Medina County) [Continued]

Figure C.5: Culvert Inspection and Map for SUM - 8 – 7.81 (District 4, Summit County)

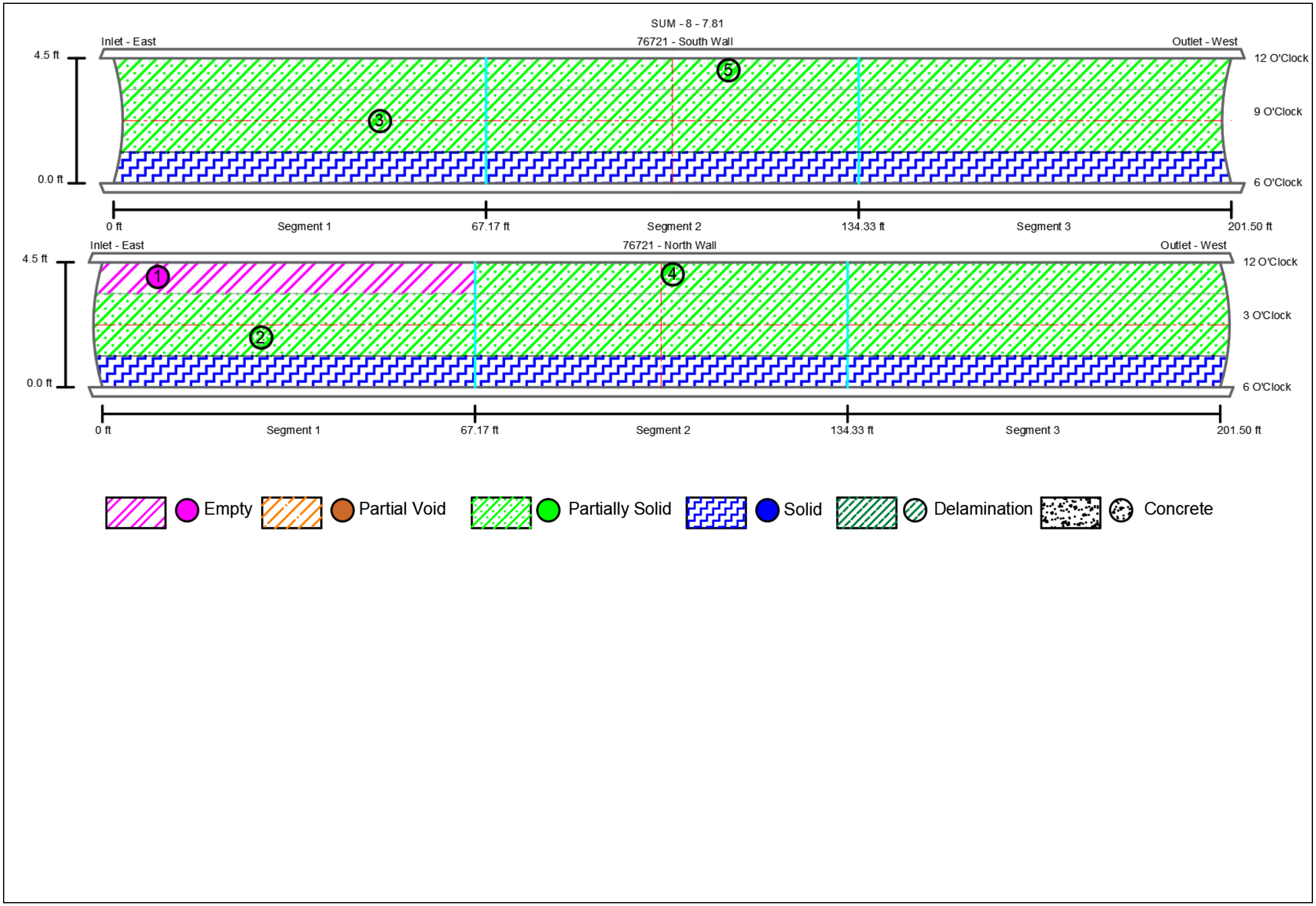


Figure C.5: Culvert Inspection and Map for SUM - 8 – 7.81 (District 4, Summit County) [Continued]

Culvert Access

Empty

Delamination

Figure C.6: Culvert Inspection and Map for ATB - 90 – 28.406 (District 4, Ashtabula County)

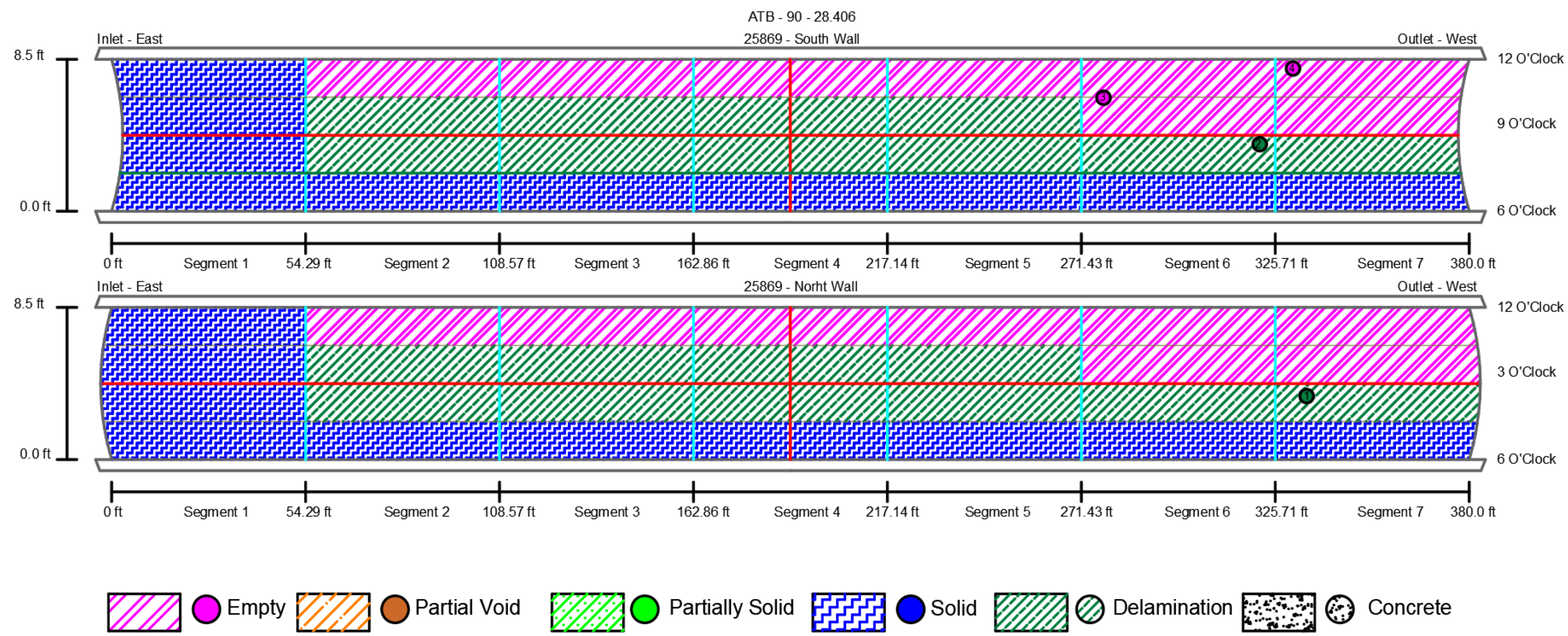
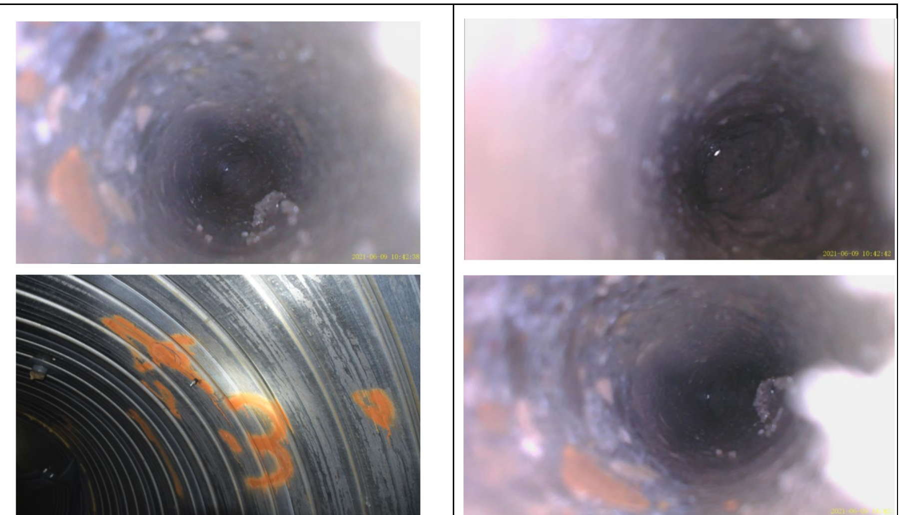
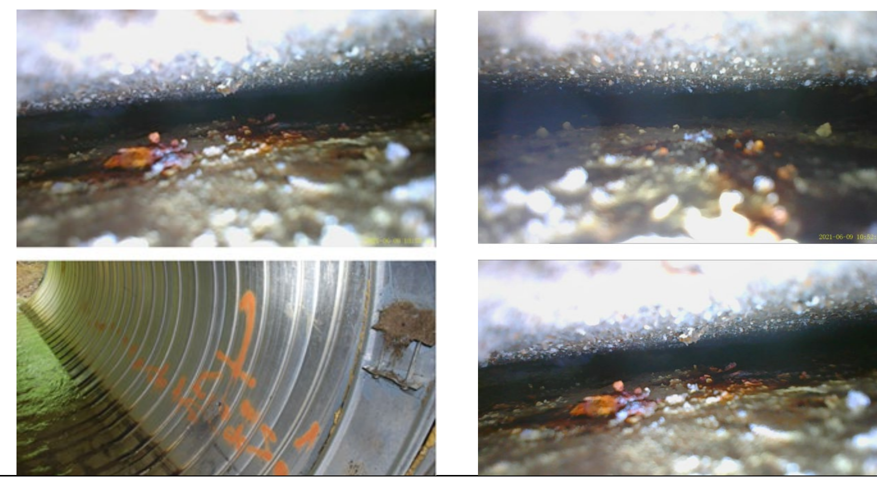


Figure C.6: Culvert Inspection and Map for ATB - 90 – 28.406 (District 4, Ashtabula County) [Continued]

Culvert Access



Solid



Delamination

Figure C.7: Culvert Inspection and Map for LIC - 70 – 25.82 (District 5, Licking County)

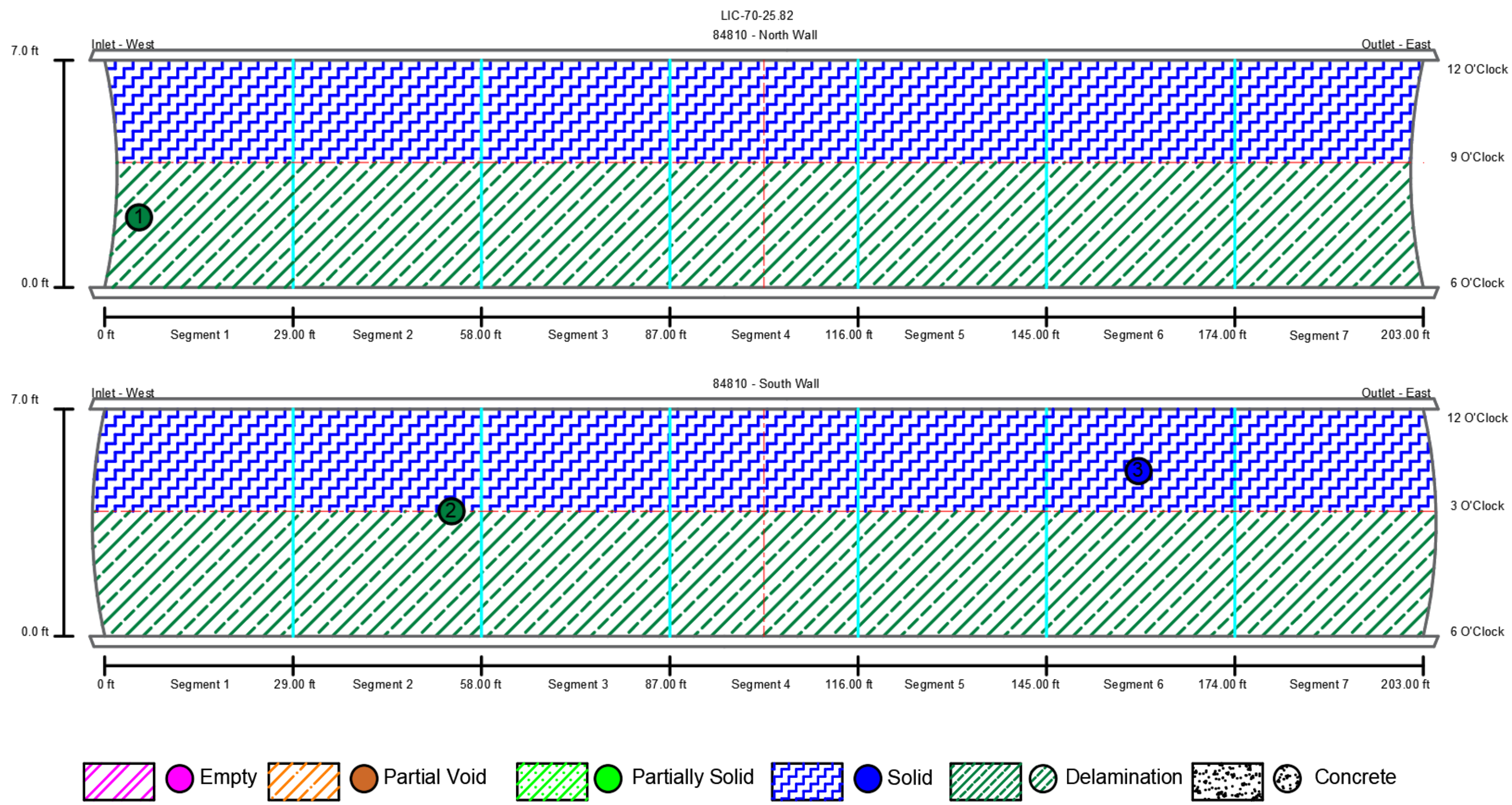
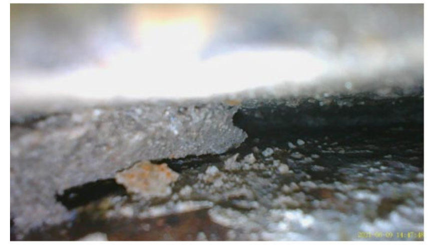
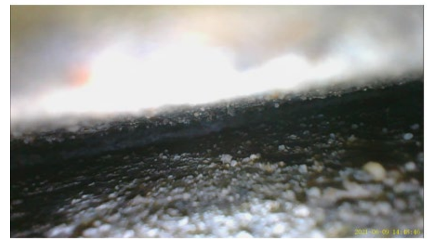
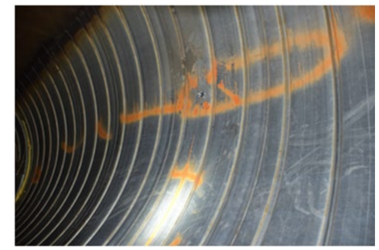


Figure C.7: Culvert Inspection and Map for LIC - 70 – 25.82 (District 5, Licking County) [Continued]







Culvert Access	Delamination

Figure C.8: Culvert Inspection and Map for LIC - 70 – 29.08 (District 5, Licking County)

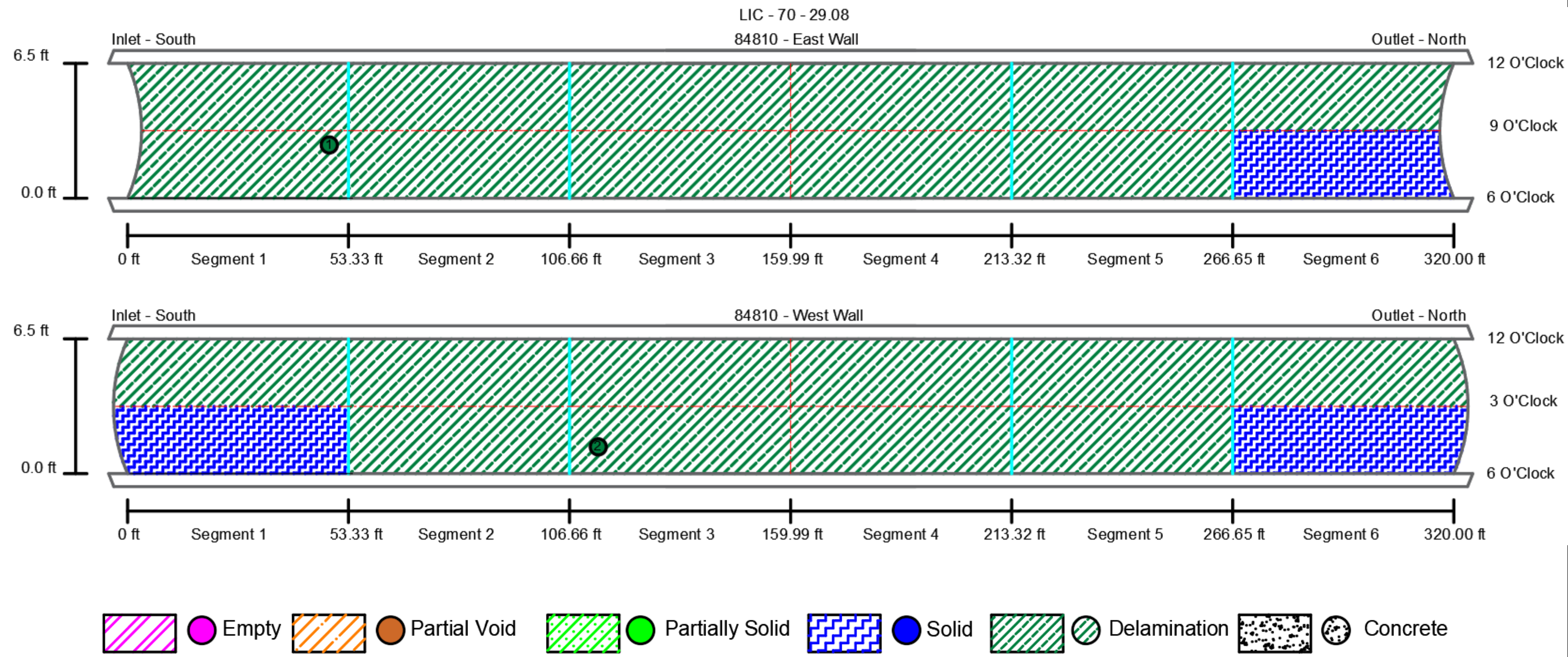
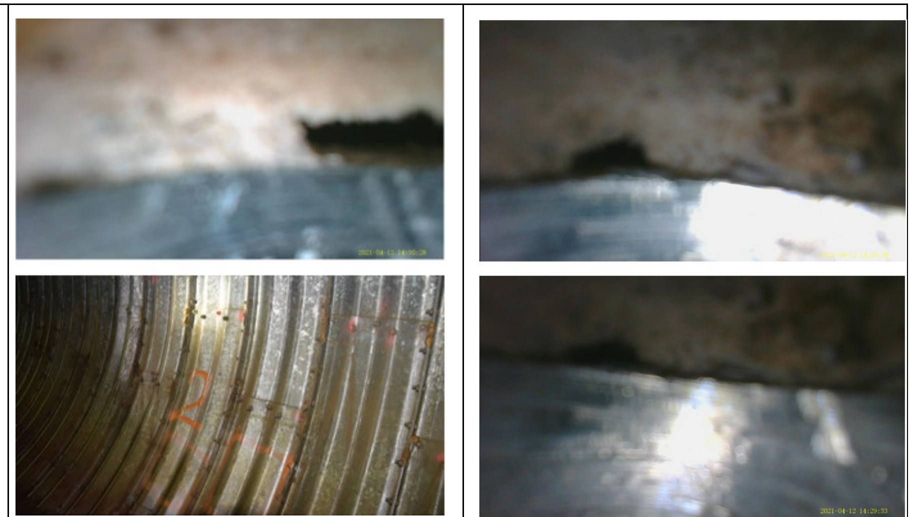


Figure C.8: Culvert Inspection and Map for LIC - 70 – 29.08 (District 5, Licking County) [Continued]

Culvert Access



Delamination

Solid

Figure C.9: Culvert Inspection and Map for GUE - 541 – 8.20 (District 5, Guernsey County)

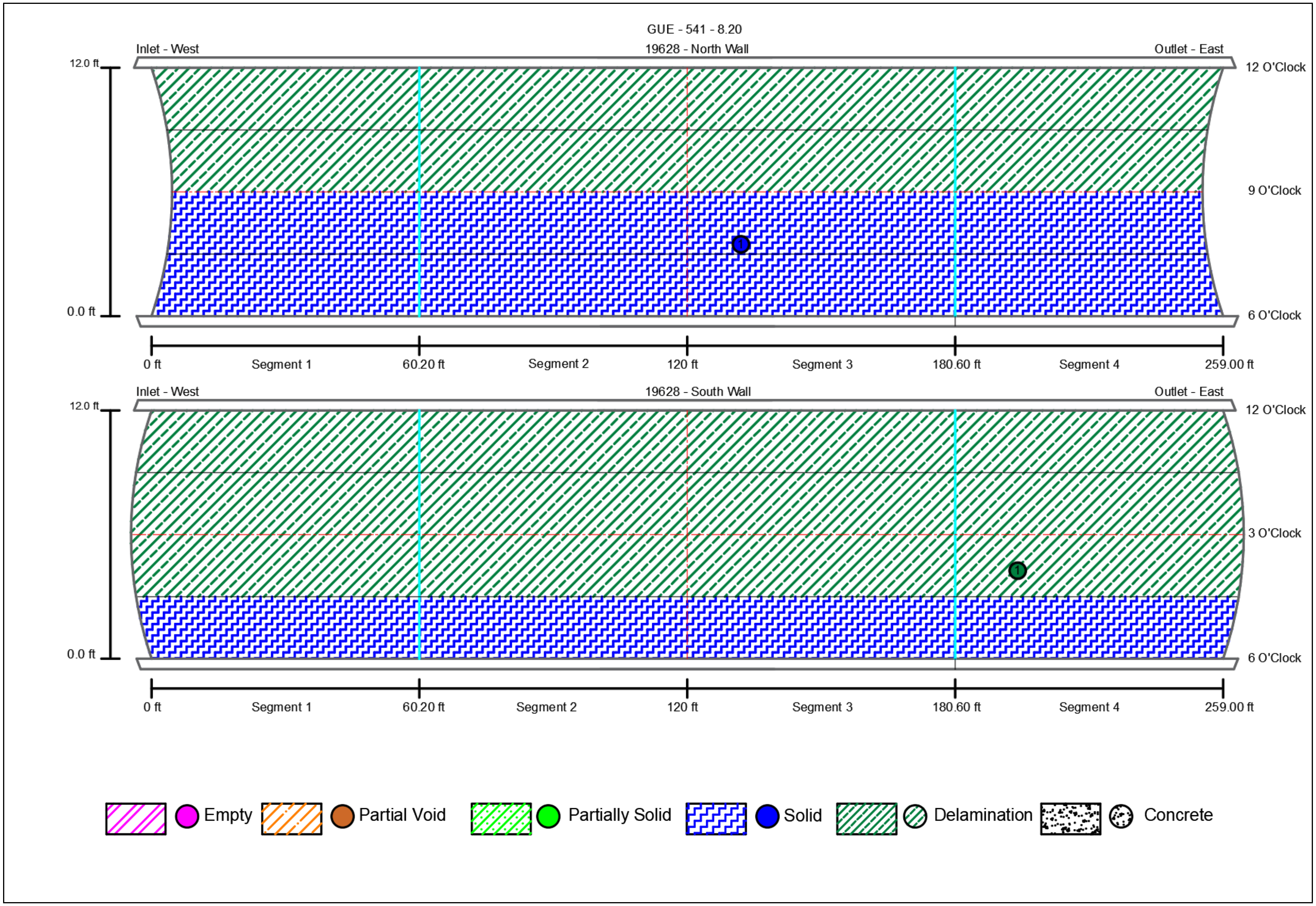
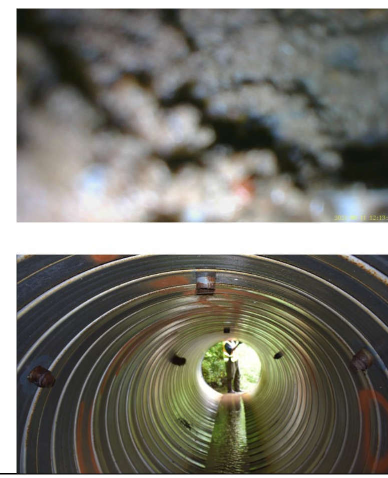


Figure C.9: Culvert Inspection and Map for GUE - 541 – 8.20 (District 5, Guernsey County) [Continued]

Culvert Access

Empty



Delamination

Figure C.10: Culvert Inspection and Map for FAI - 37 – 23.90 (District 5, Fairfield County)

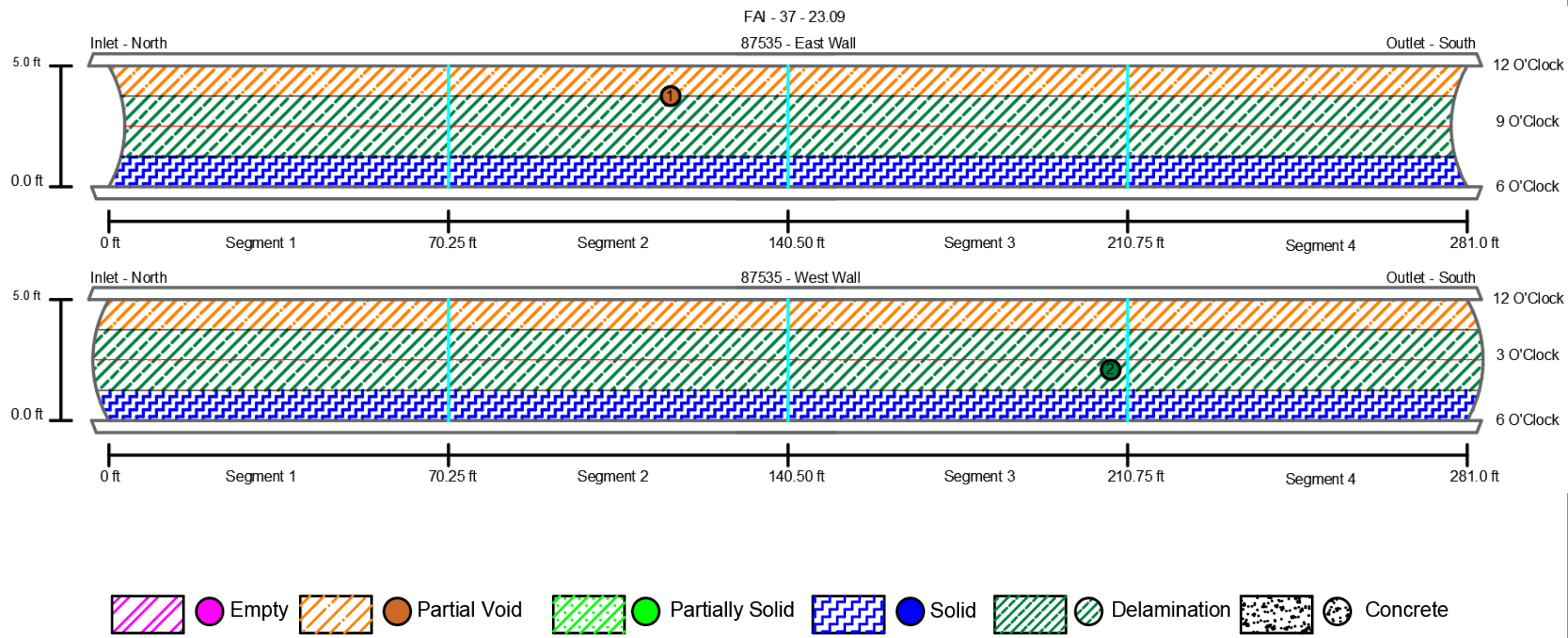


Figure C.10: Culvert Inspection and Map for FAI - 37 – 23.90 (District 5, Fairfield County) [Continued]

Culvert Access

Empty

Solid

Figure C.11: Culvert Inspection and Map for LIC - 70 – 13.00 (District 5, Licking County)

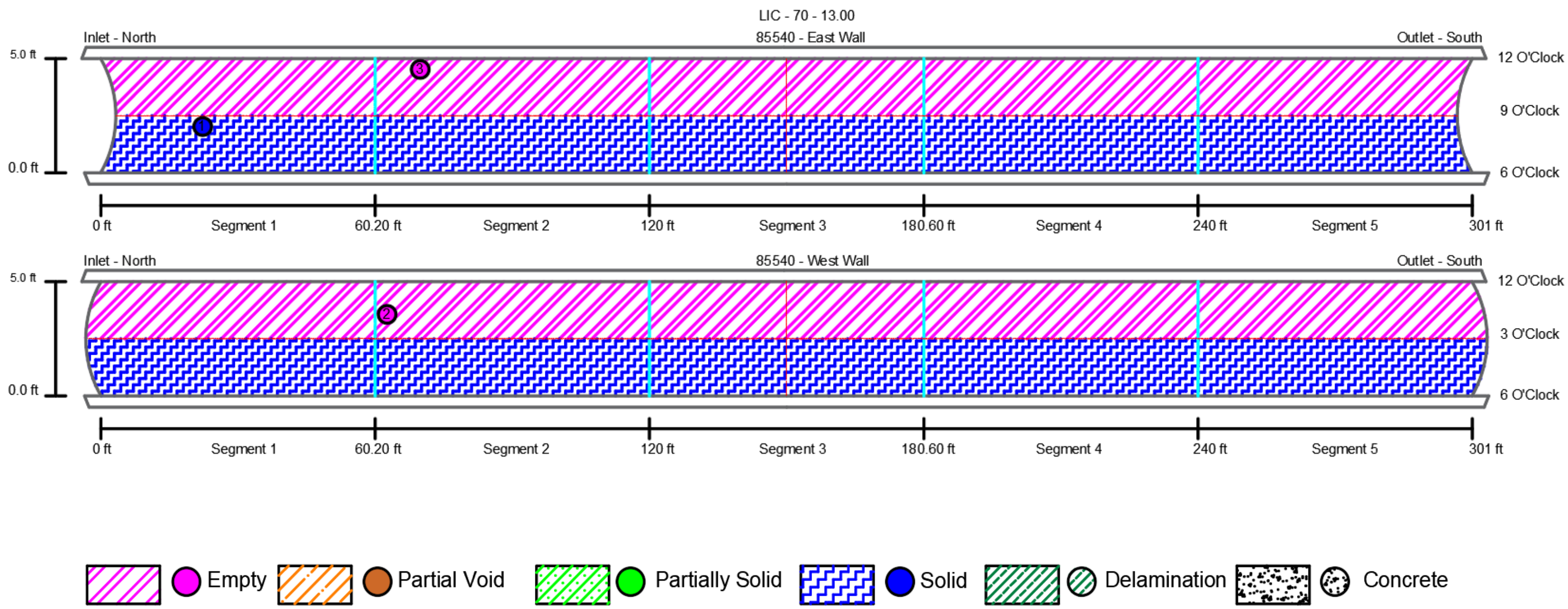
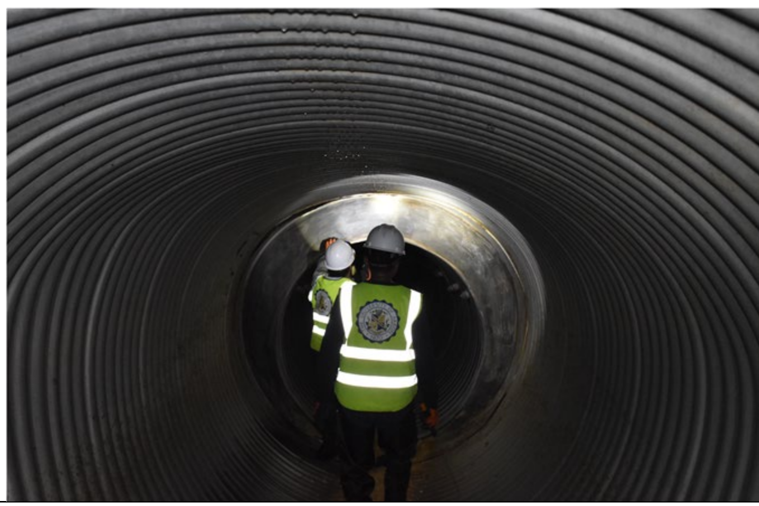
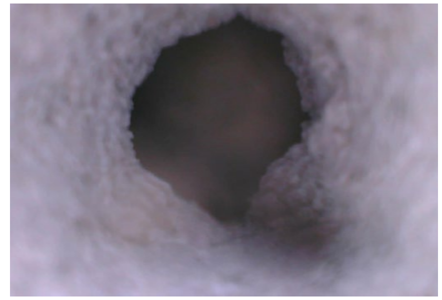
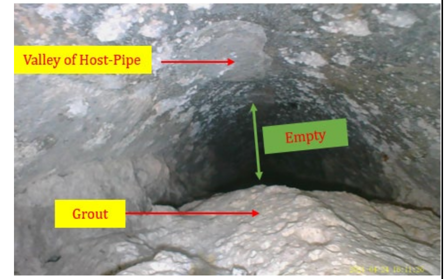


Figure C.11: Culvert Inspection and Map for LIC - 70 – 13.00 (District 5, Licking County) [Continued]



Culvert Access





Partial Void

Partial Void

Figure C.12: Culvert Inspection and Map for HAM - 52 – 37.88 (District 8, Hamilton County)

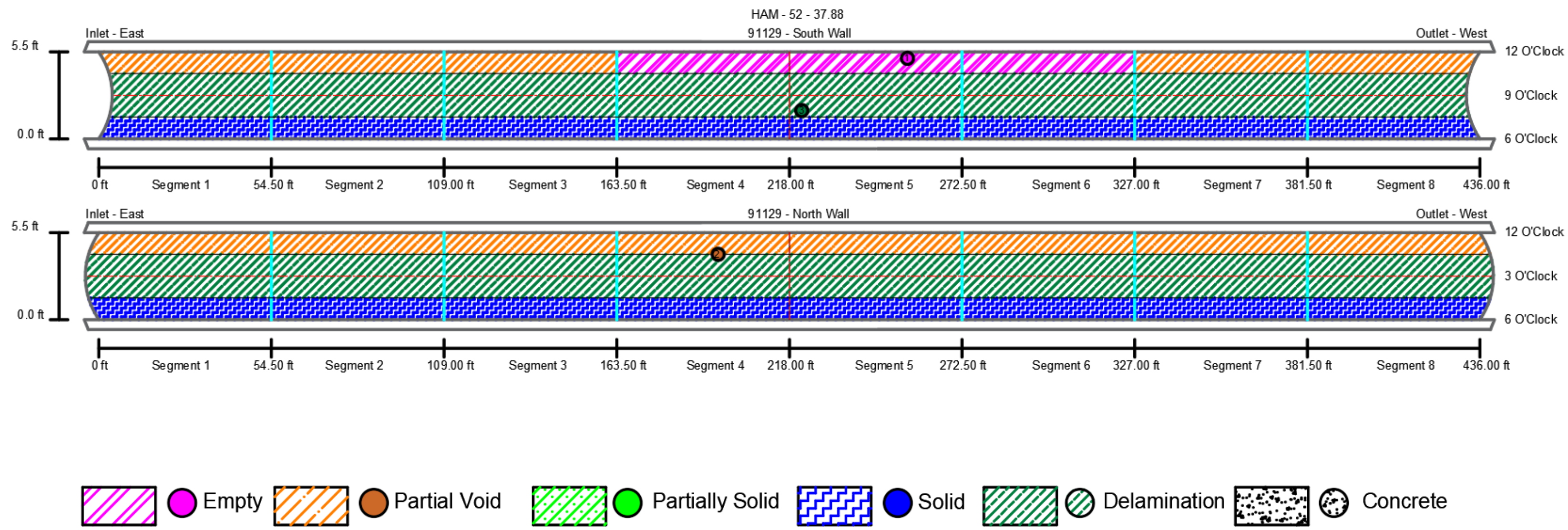
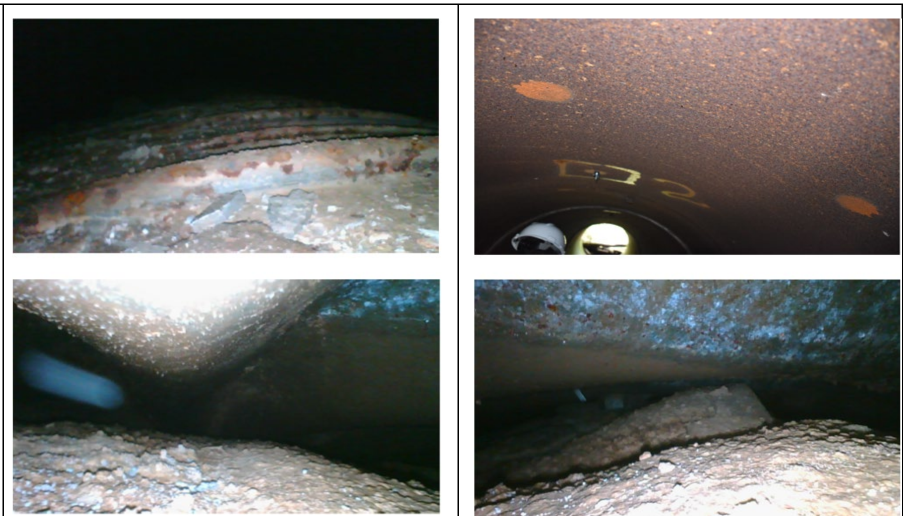


Figure C.12: Culvert Inspection and Map for HAM - 52 – 37.88 (District 8, Hamilton County) [Continued]

Culvert Access



Empty

Delamination

Figure C.13: Culvert Inspection and Map for WAR - 22 – 1786 (District 8, Warren County)

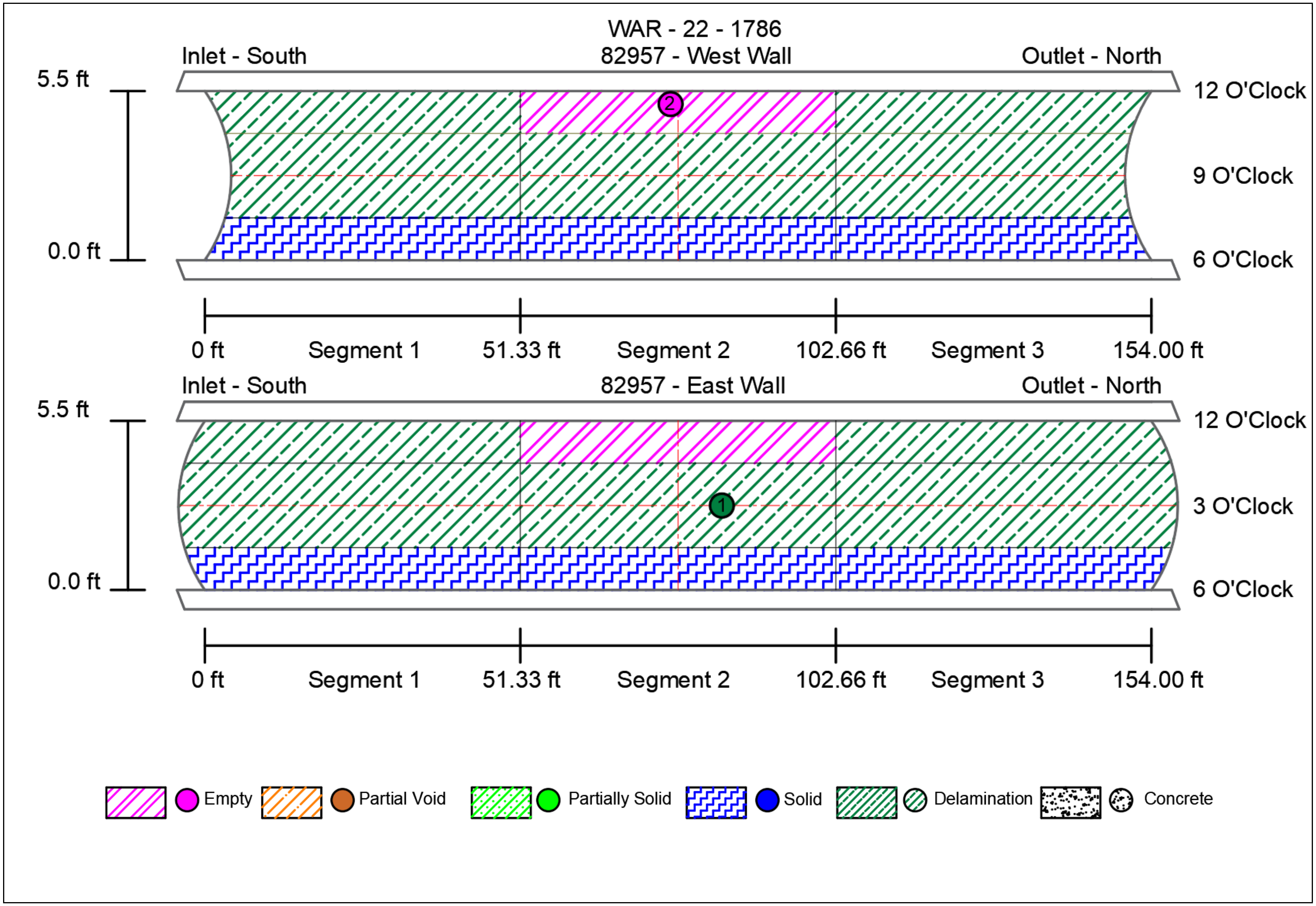


Figure C.13: Culvert Inspection and Map for Culvert WAR - 22 – 1786 (District 8, Warren County) [Continued]

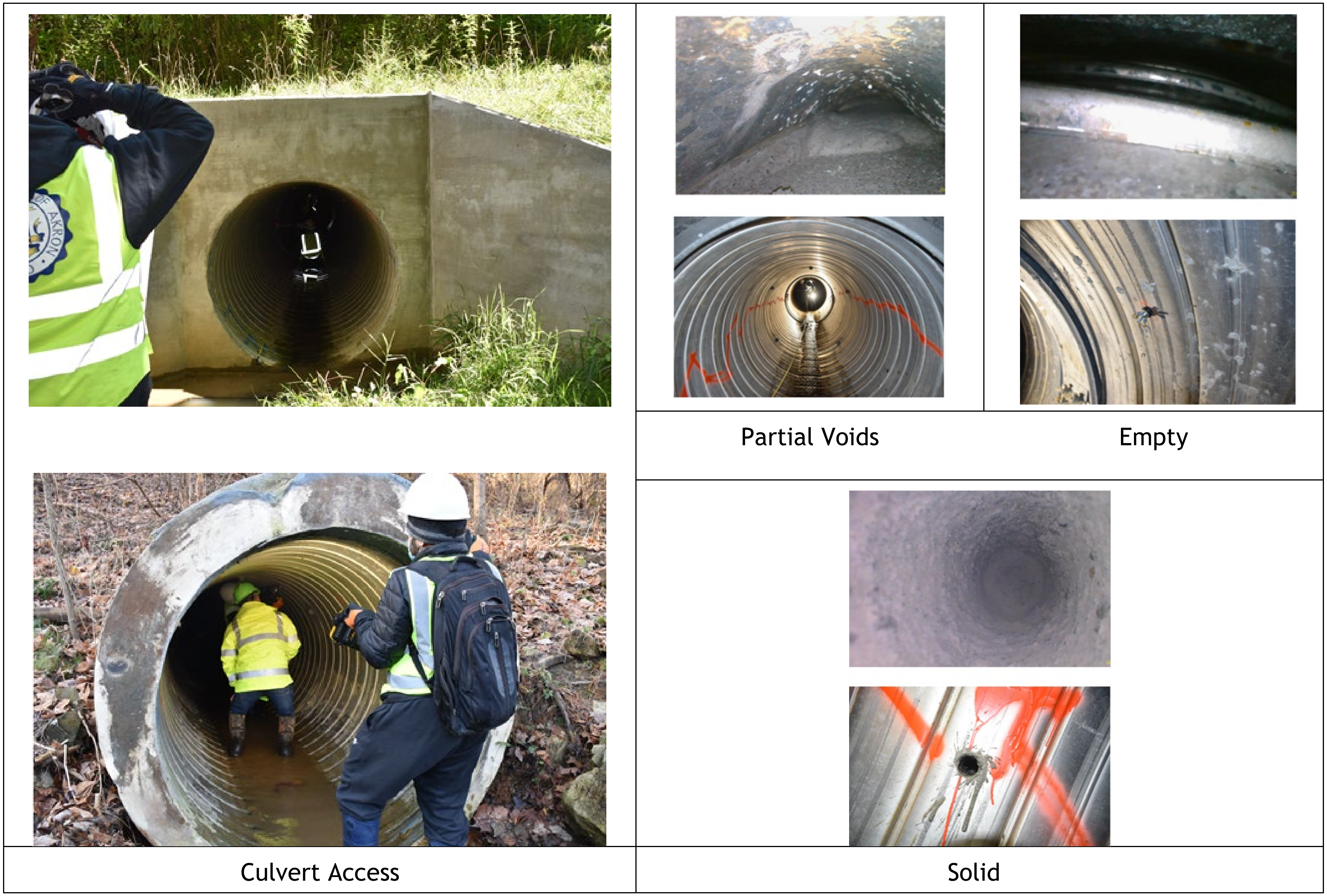


Figure C.14: Culvert Inspection and Map for WAR - 22 – 1786 (District 8, Warren County)

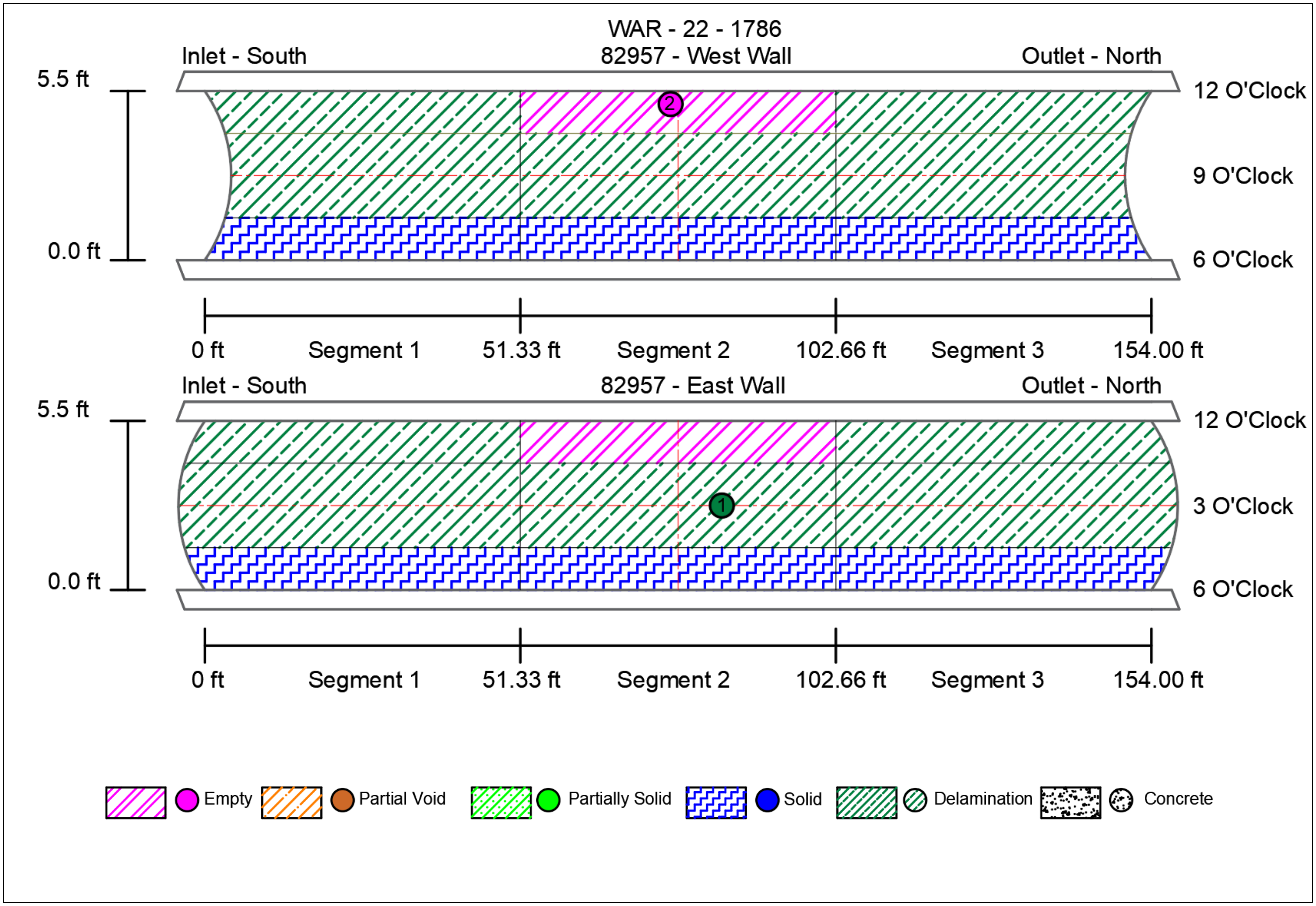
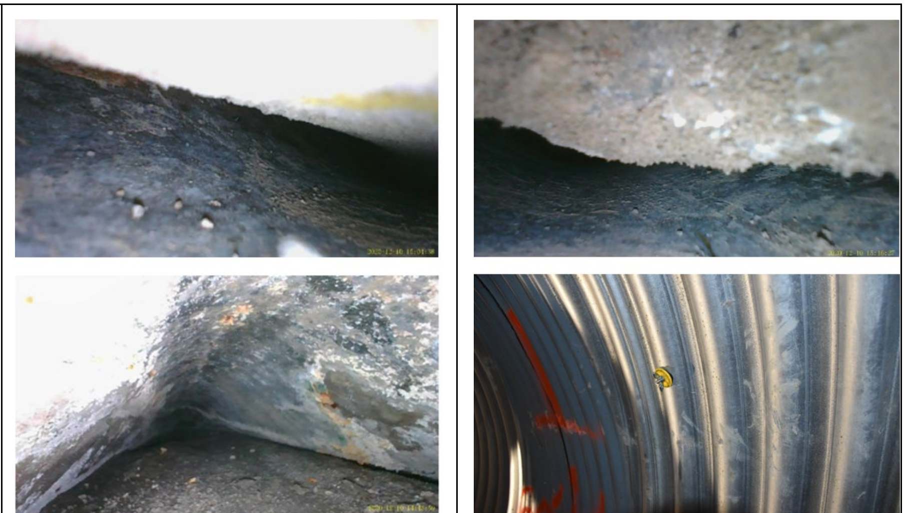


Figure C.14: Culvert Inspection and Map for WAR - 22 – 1786 (District 8, Warren County) [Continued]

Culvert Access



Partial Voids

Solid

Figure C.15: Culvert Inspection and Map for PIK - 772 – 7.89 (District 9, Pike County)

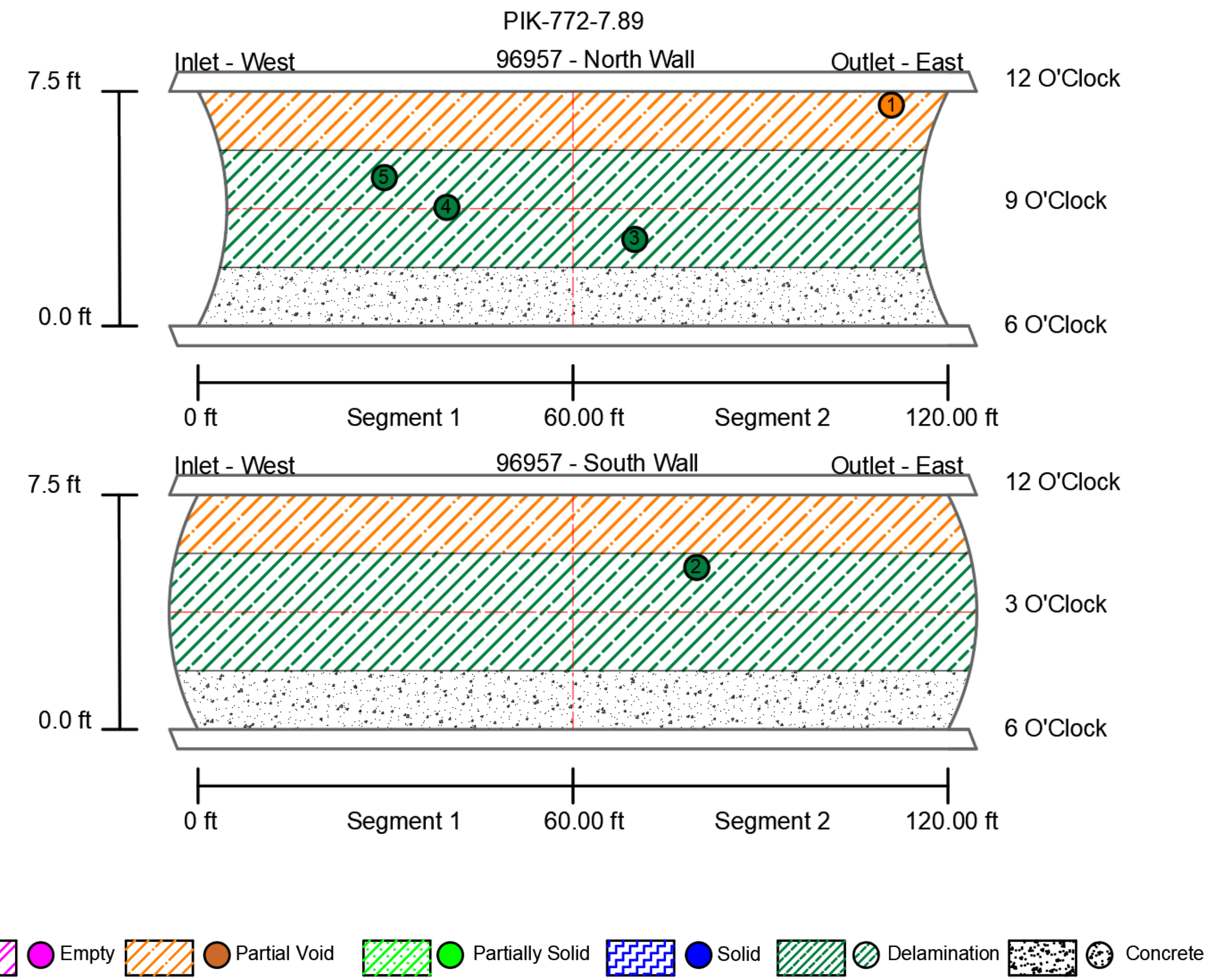


Figure C.15: Culvert Inspection and Map for PIK - 772 – 7.89 (District 9, Pike County) [Continued]

Culvert Access

Delamination

Solid

Figure C.16: Culvert Inspection and Map for BRO - 62 – 11.41 (District 9, Brown County)

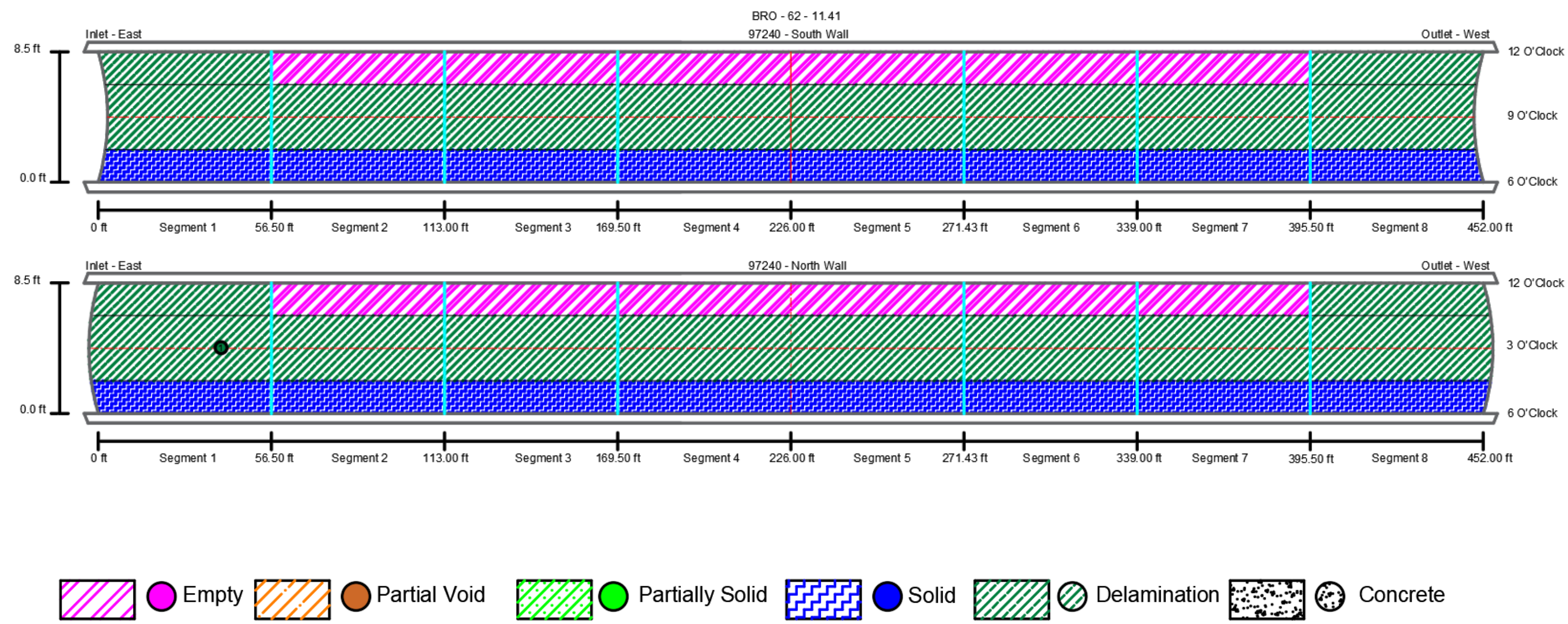
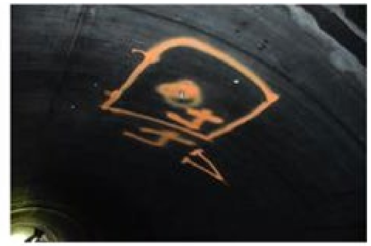
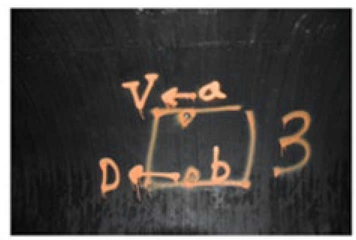


Figure C.16: Culvert Inspection and Map for BRO - 62 – 11.41 (District 9, Brown County) [Continued]

Culvert Access



Empty



Empty & Delamination

Solid

Figure C.17: Culvert Inspection and Map for BRO - 68– 40.91 (District 9, Brown County)

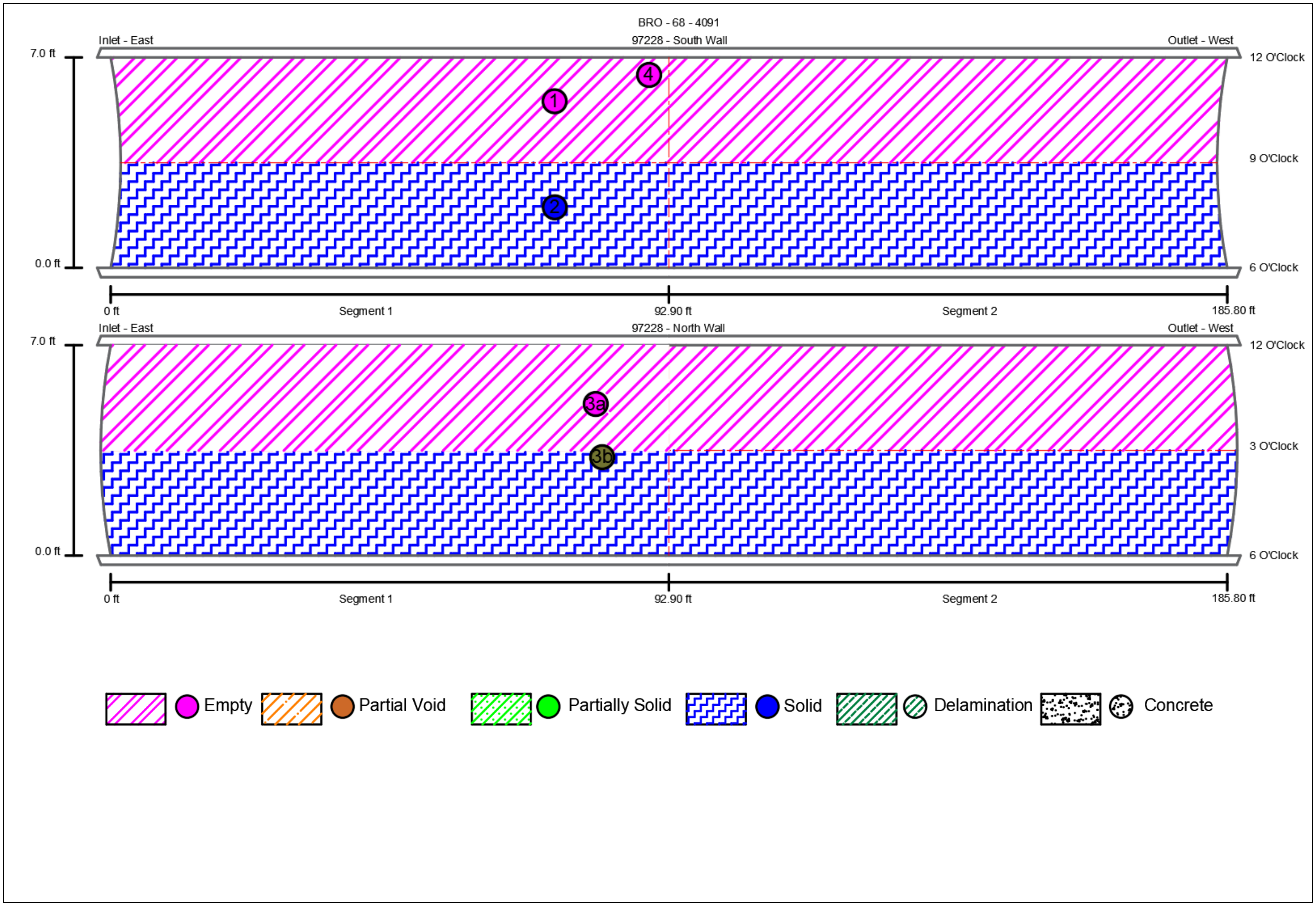
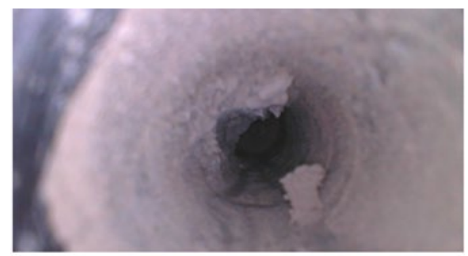
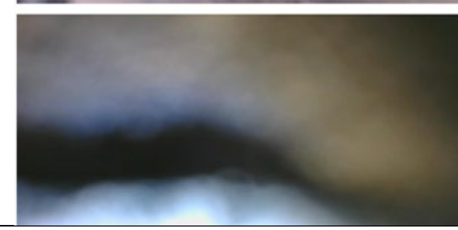


Figure C.17: Culvert Inspection and Map for BRO - 68– 40.91 (District 9, Brown County) [Continued]

Solid





Culvert Access

Delamination

Figure C.18: Culvert Inspection and Map for BRO - 40– 0.89 (District 9, Brown County)

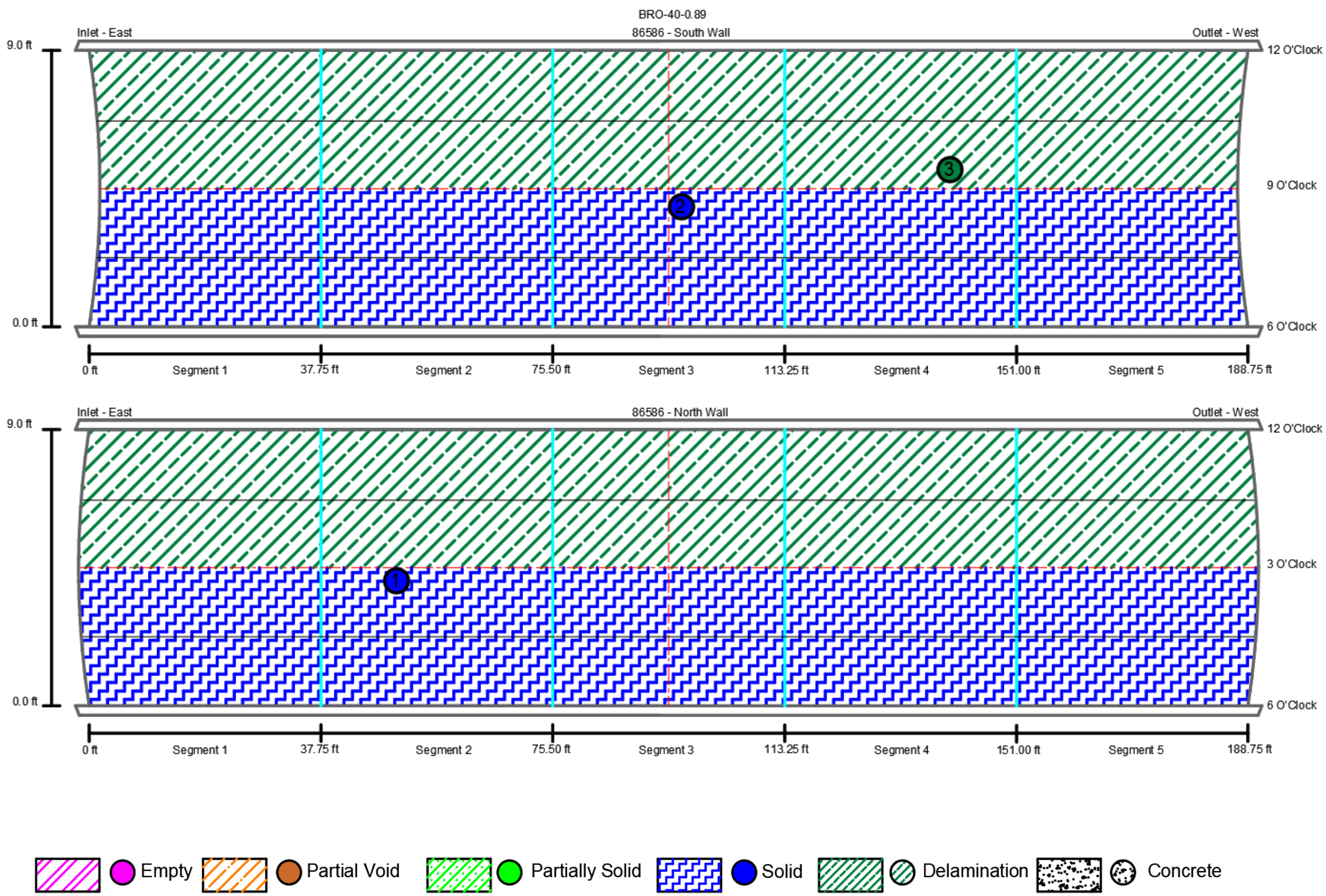


Figure C.18: Culvert Inspection and Map for BRO - 40– 0.89 (District 9, Brown County) [Continued]

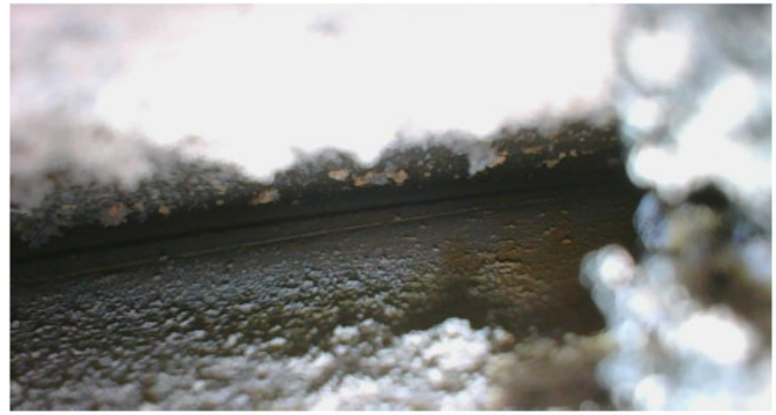
 	  
Culvert Access	Delamination

Figure C.19: Culvert Inspection and Map for LAW - 52– 4.24 (District 9, Lawrence County)

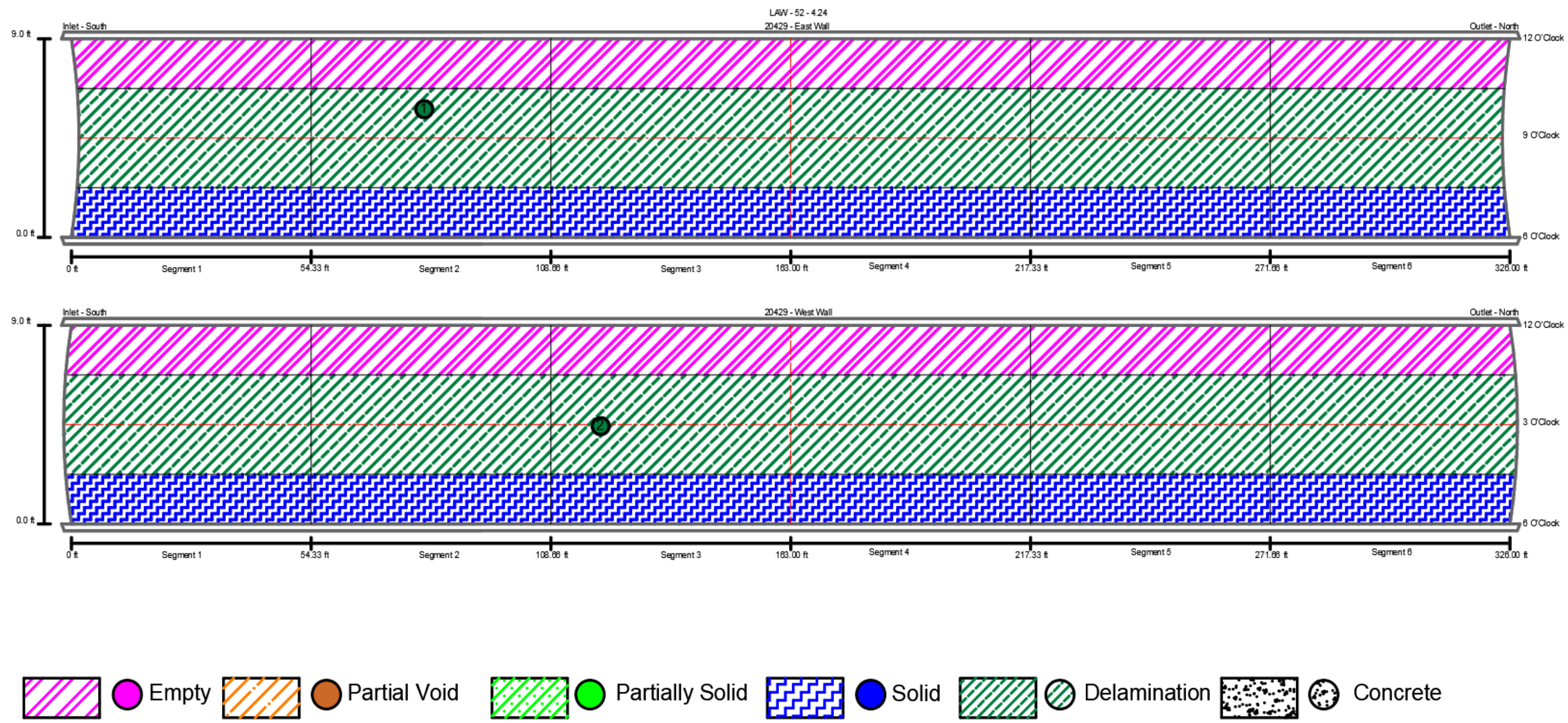
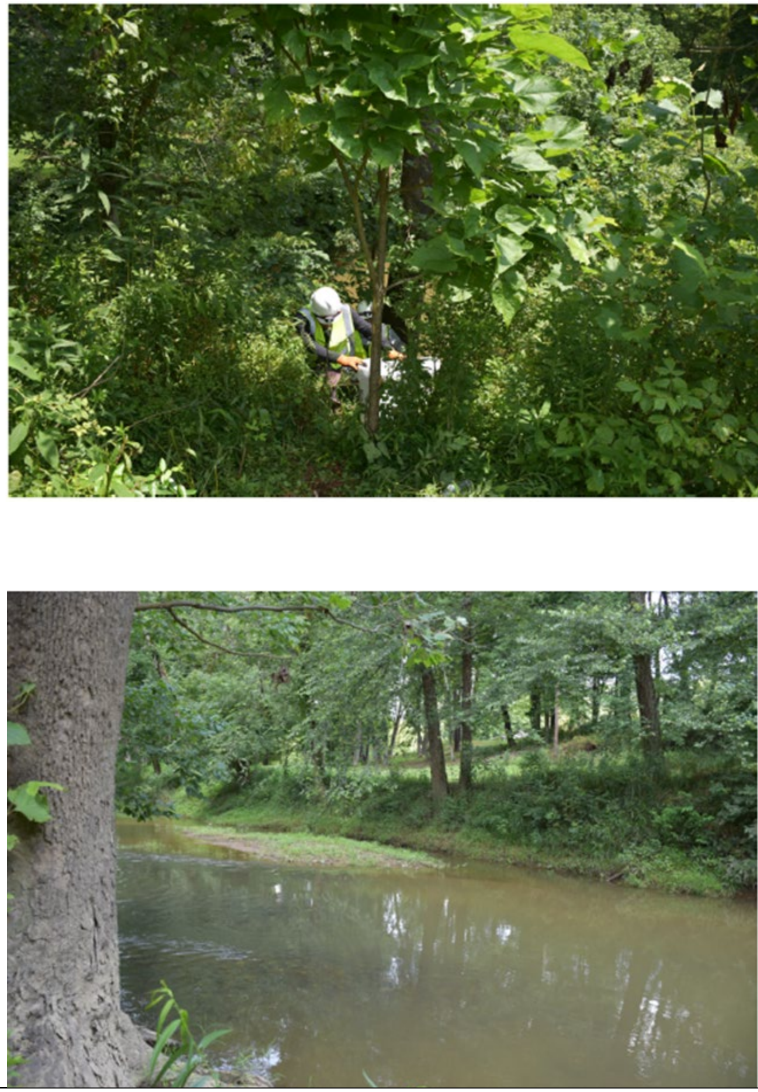


Figure C.19: Culvert Inspection and Map for LAW - 52– 4.24 (District 9, Lawrence County) [Continued]



Culvert Access

Empty

Figure C.20: Culvert Inspection and Map for JAC - 35– 7.55 (District 9, Jackson County)

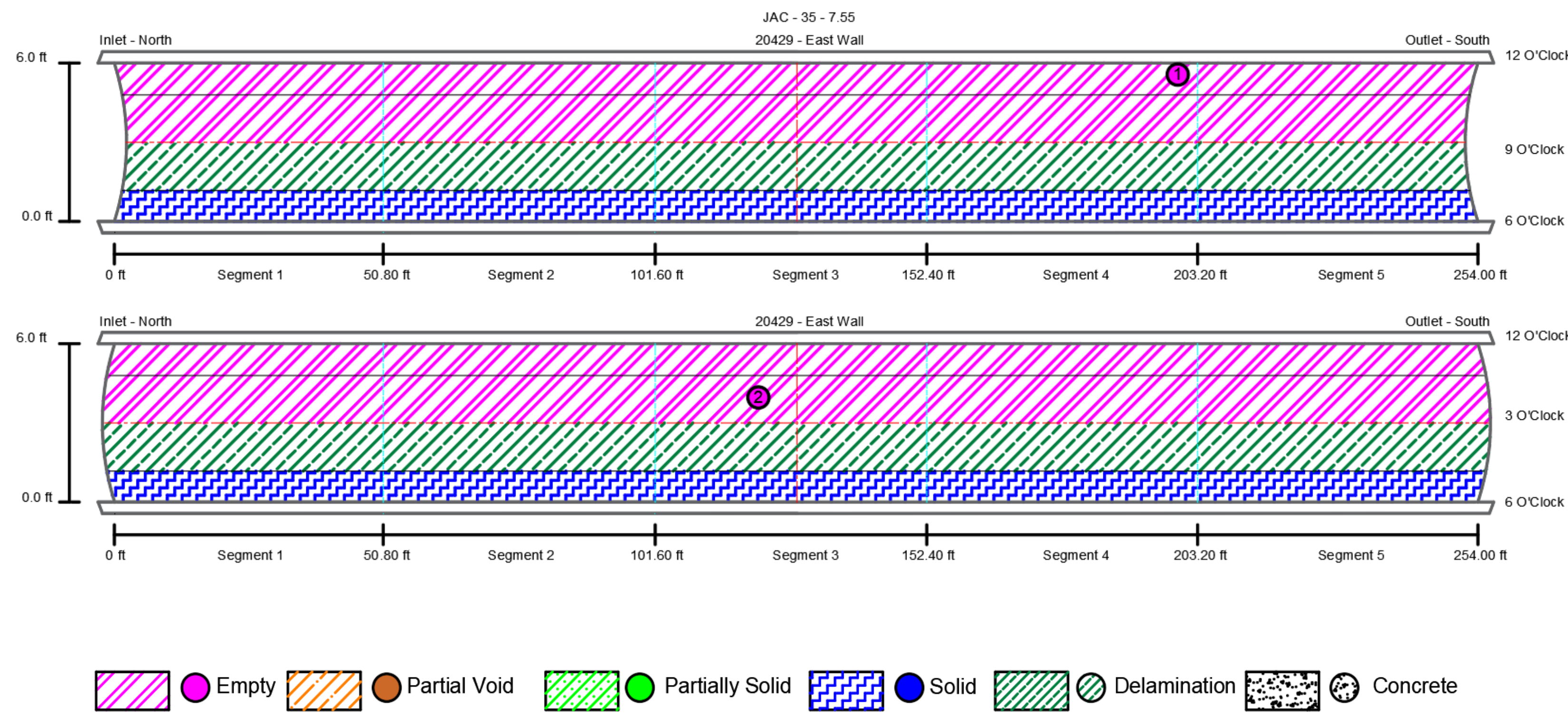


Figure C.20: Culvert Inspection and Map for JAC - 35– 7.55 (District 9, Jackson County) [Continued]





Culvert Access	Empty

Figure C.21: Culvert Inspection and Map for WAS - 550 - 21.75 (District 10, Washington County)

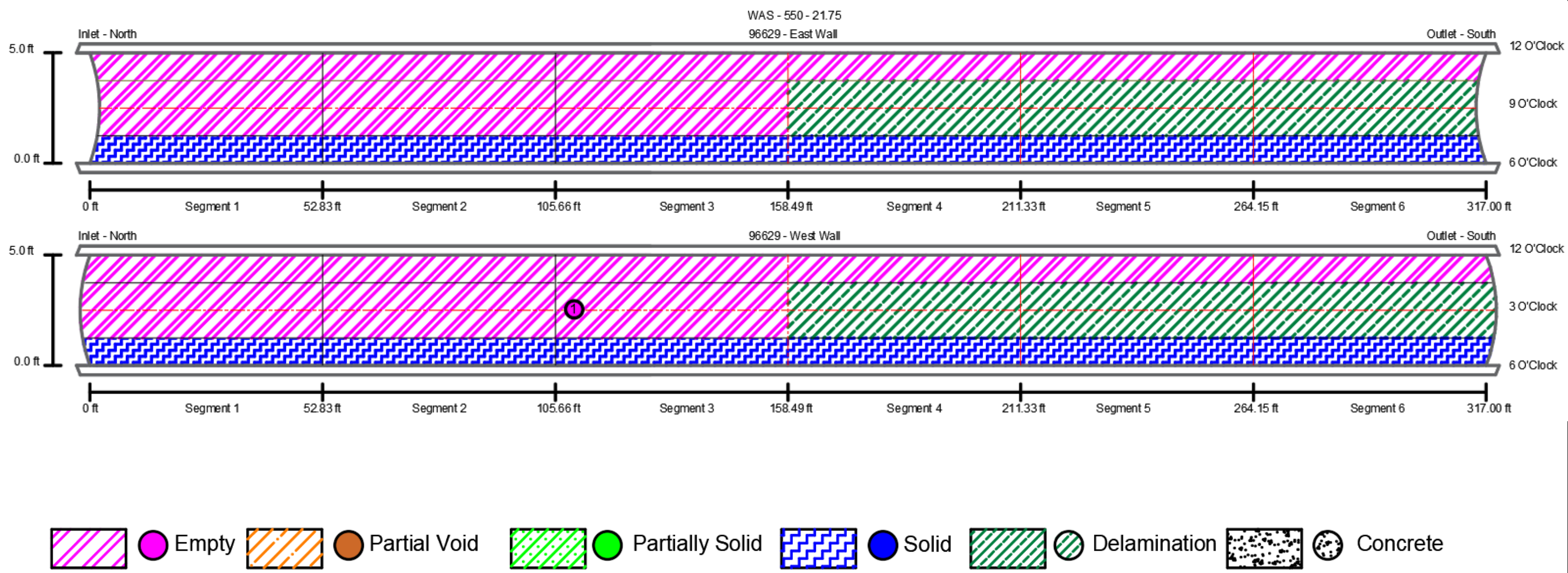


Figure C.21: Culvert Inspection and Map for WAS - 550 - 21.75 (District 10, Washington County) [Continued]

Culvert Access	Empty

Figure C.22: Culvert Inspection and Map for NOB - 285 - 3.31 (District 10, Noble County)

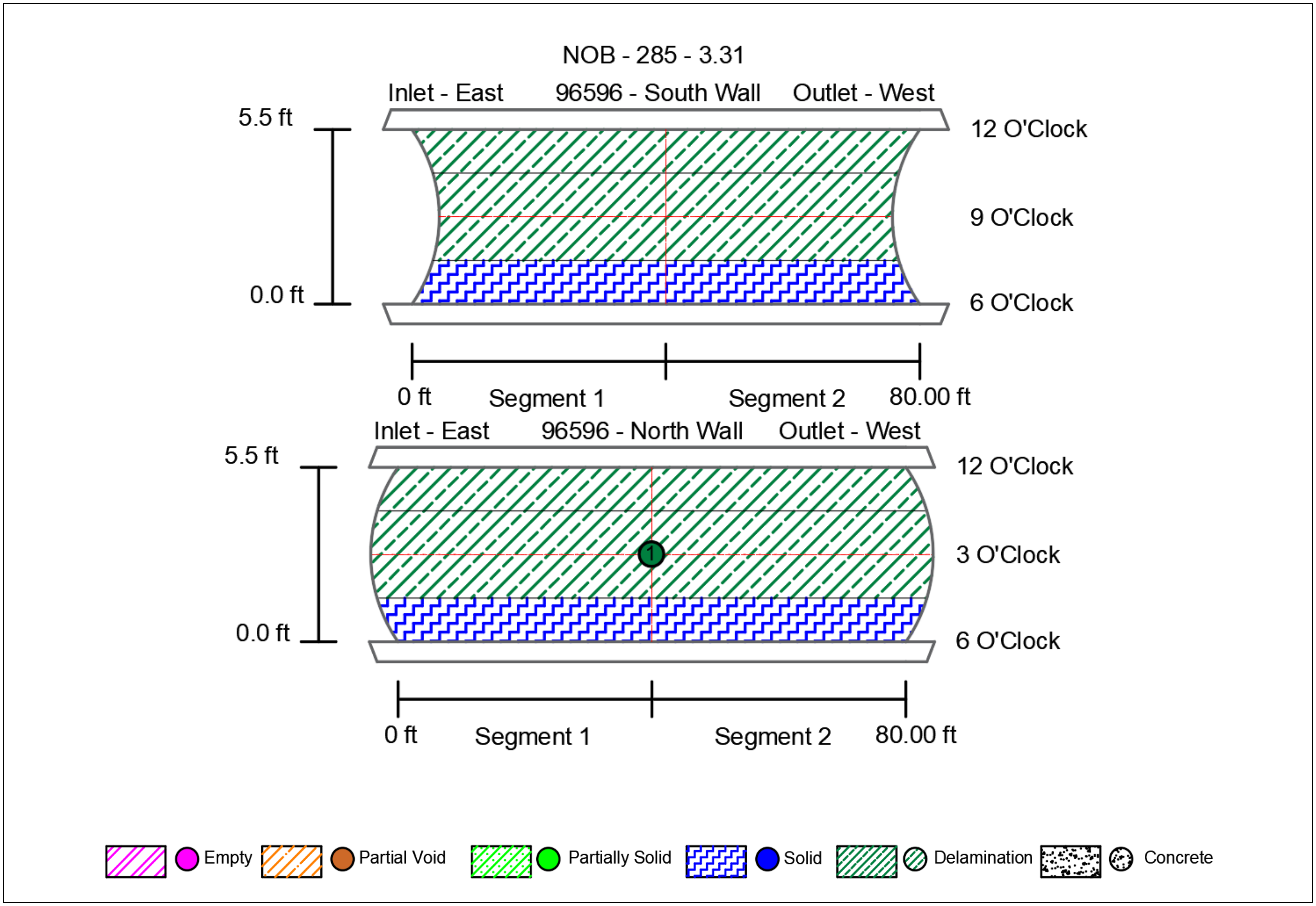


Figure C.22: Culvert Inspection and Map for NOB - 285 - 3.31 (District 10, Noble County) [Continued]

Culvert Access

Slight Delamination

Figure C.23: Culvert Inspection and Map for MRG - 266 - 2.73 (District 10, Morgan County)

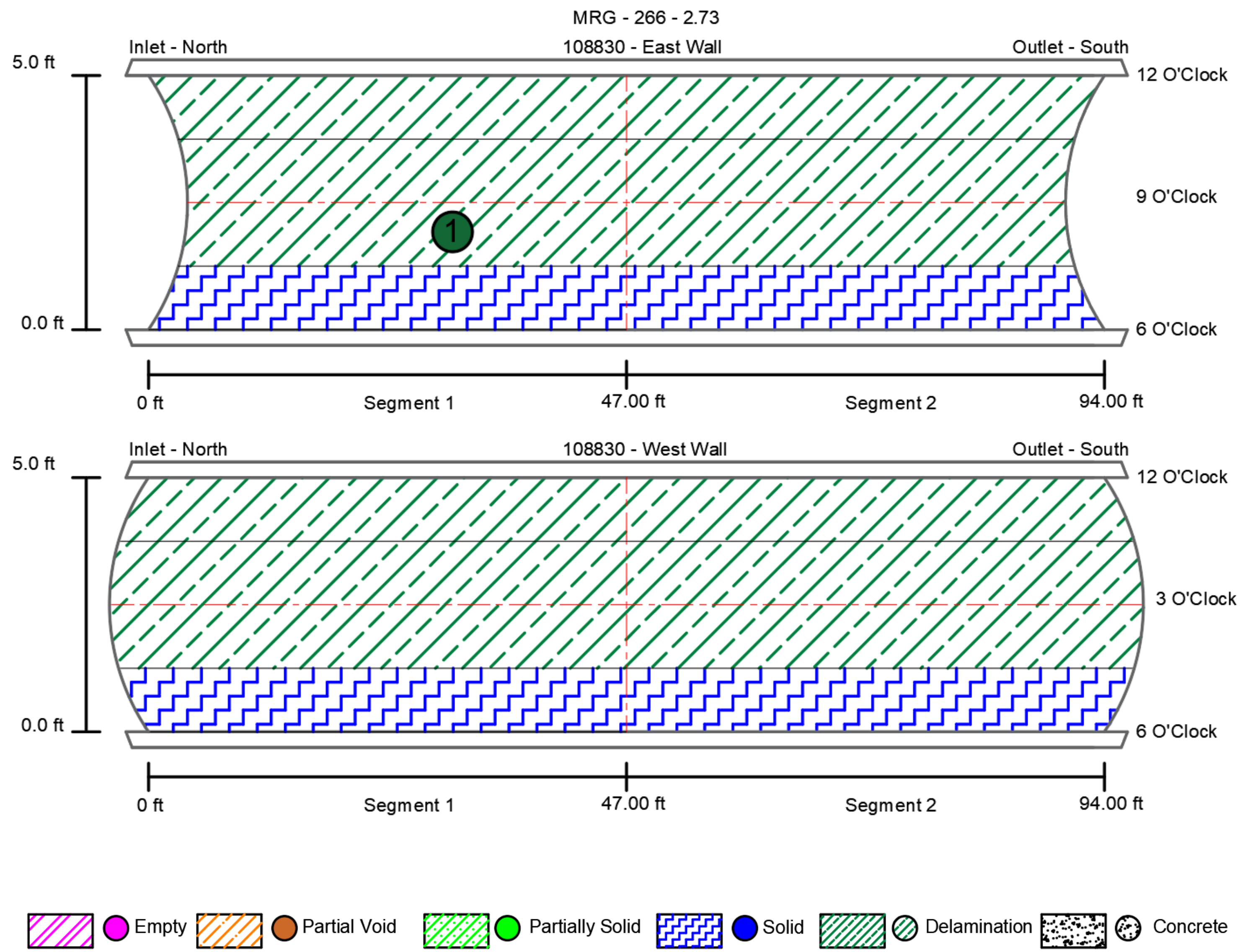
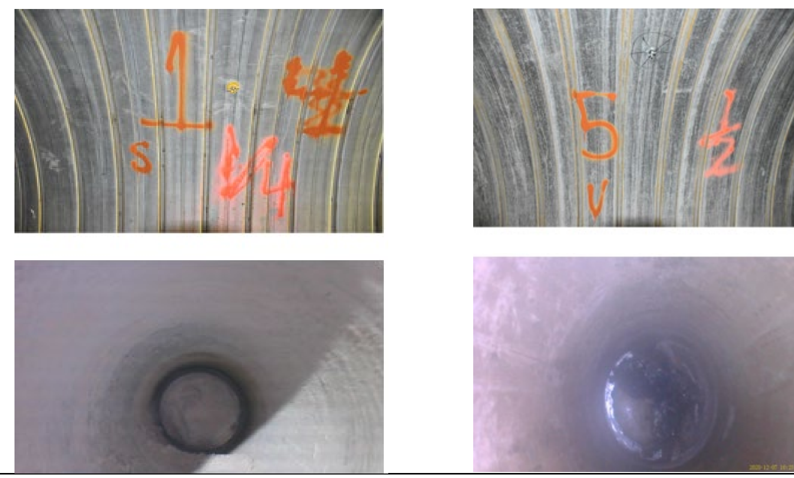


Figure C.23: Culvert Inspection and Map for MRG - 266 - 2.73 (District 10, Morgan County) [Continued]

Culvert Access

Empty



Solid

Figure C.24: Culvert Inspection and Map for JEF - 151 – 1.530 (District 11, Jefferson County)

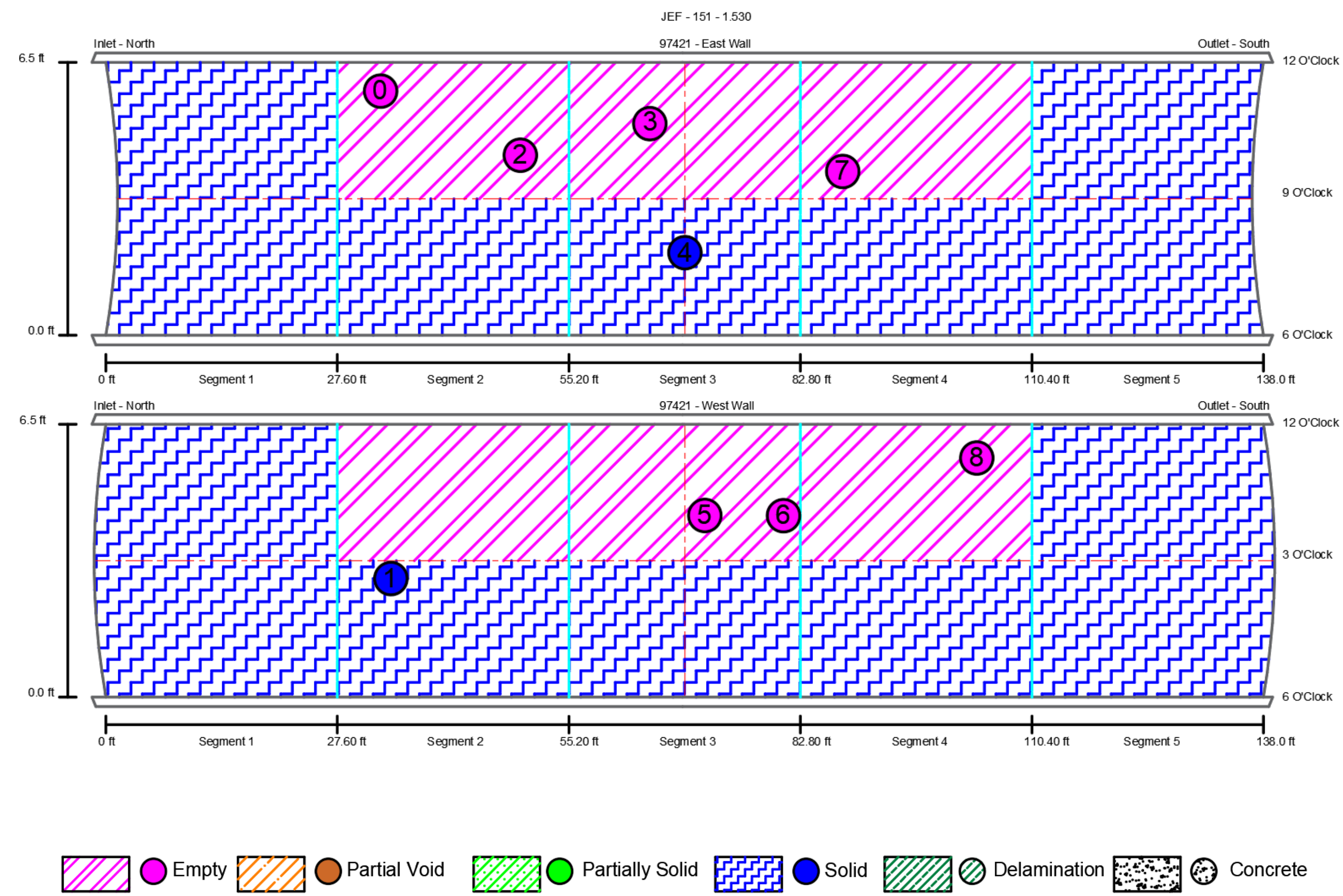


Figure C.24: Culvert Inspection and Map for JEF - 151 – 1.530 (District 11, Jefferson County) [Continued]

Marshy Land (Top), Snakes (Center). Inspection was Aborted due to safety concerns.

Figure C.25: Culvert Inspection for GUE - 70 – 13.321 (District 5, Guernsey County)

Culvert was made from corrugated steel pipe coated with bitumen (not sliplined) and exhibited tearing of the coatings at the joints.

Figure C.26: Culvert Inspection for WAR - 22 – 1753 (District 8, Warren County)

Culvert Access: High Water Level

Figure C.27: Culvert Inspection for LAW - 7– 0.27 (District 9, Lawrence County)

Culvert Access: Vegetation made it difficult and unsafe to access either side of the culvert.

Figure C.28: Culvert Inspection for MOE- 7 – 16.40 (District 10, Monroe County)

Several Cracks at the Bulkhead and Shape Distortion

Culvert Access: High Water level

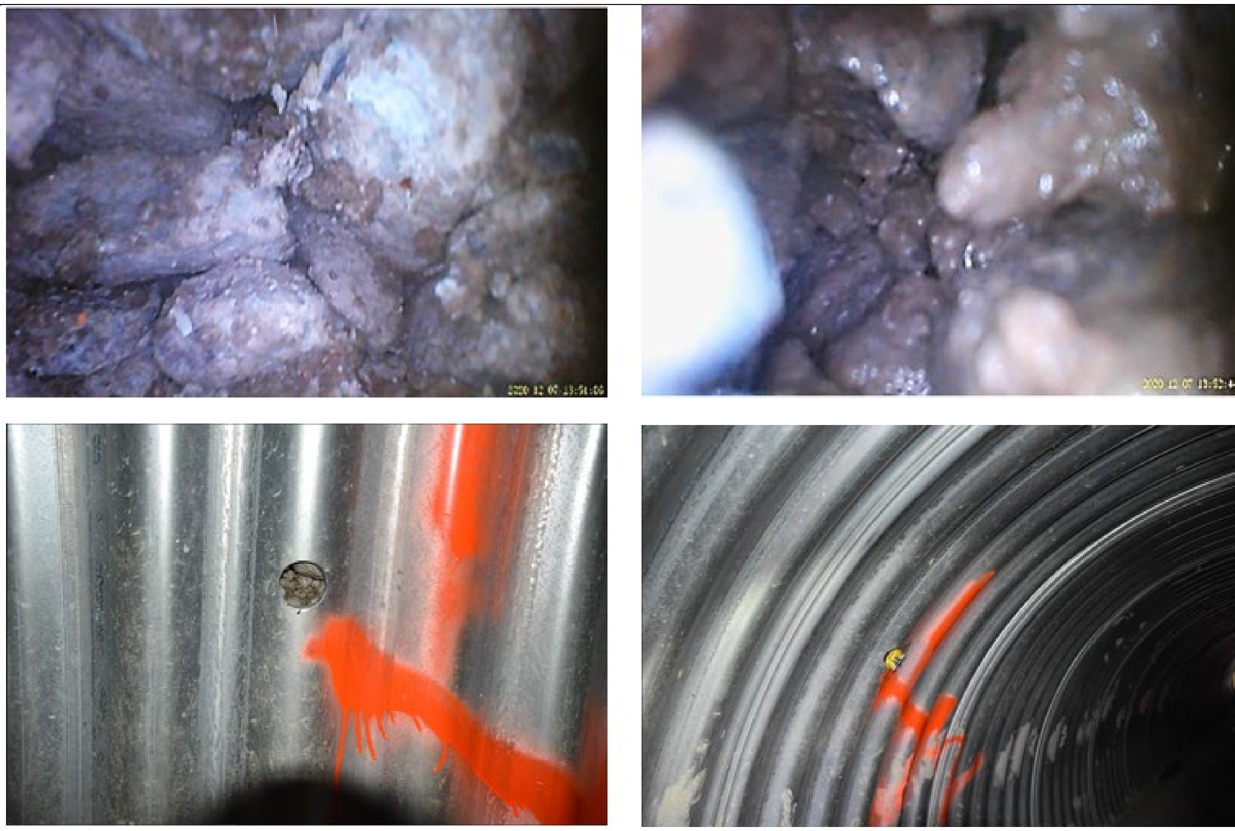
Figure C.29: Culvert Inspection for MOE - 7 – 057 (District 10, Monroe County)

Culvert Access: High water level and unsafe access prevented inspection.

Figure C.30: Culvert Inspection for WAS - 7 – 52.38 (District 10, Washington County)

Culvert Access: Inspection was aborted due to high water level and unsafe access.

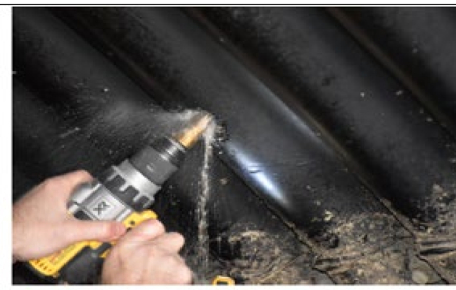
Figure C.31: Culvert Inspection for WAS - 7 – 45.40 (District 10, Washington County)



Loose limestone found at one culvert location.

Culvert Access: This culvert was not a sliplined culvert.

Figure C.32: Culvert Inspection for JEF - 150 - 4.968 (District 11, Jefferson County)


The cored void fill was very weak and crumbled easily (similar to wet soil).

Culvert Access: The culvert was not a sliplined culvert.

Figure C.33: Culvert Inspection for CUY - MK– 5.029M (District 12, Cuyahoga County)

C.5 Evaluation of Annulus Condition

The evaluation of the condition of the annulus between the host pipe and liner pipe was performed by a sounding test. The sounds made by the liner in response to being struck by a hammer will differ based on the annulus conditions and the liner material. The use of some liner materials, such as double-layered polyethylene, made it difficult to evaluate the annulus conditions. When the inspector tapped the liner, a hollow sound emanated from the space between the pipe walls. Other liner materials, such as corrugated steel pipe or steel casing pipe, made a clear sound that reflected the annulus conditions when the liner pipe was struck by the hammer, since these liner pipes have a single wall that directly touches the grout. There are potential limitations of sounding when cellular grout is used as an annulus void filler. Hammer tapping may give false hollow or partially hollow sounds even though the annulus is mostly filled with cellular grout. This is probably due to the light weight and low volume density of cellular grouts which are lightweight because of the numerous bubbles (voids) in the grout. Extra caution is warranted when evaluating and interpreting the sounding results when cellular grout is the annulus void filler. Overall, the sounds were classified into three main types.

The first type of response was either a solid sound or a semi-solid sound. A solid sound indicates that the grout filled the annulus well and remained in contact with both the host pipe and the liner pipe. A semi-solid sound indicates that the grout has remained in contact with the host pipe and liner pipe, but the annulus material was either porous or contained isolated distributed voids. For annulus voids filled with cellular grouts, it is possible to hear semi-solid sound even though the annulus is mostly filled with grout.

The second type of response is a hollow sound, indicating that the grout has not remained entirely in contact with either the host pipe or the liner pipe (or both). Hollow sounds can indicate four kinds of voids. The most common of these is delamination, where a gap between the liner pipe and the grout is present. This gap generally ranges from ⅛ inch to ¼ inch but can be narrower (like a hairline) in some culverts. As a small gap size can be difficult for an inspector to see with the naked eye, it is necessary to use the side camera of the endoscope to identify such voids. A partial void can also produce a response with a hollow sound; when an endoscope camera was inserted into a hole drilled in one liner pipe at a location where a partial void was suspected, a gap between the grout and the host pipe was discovered. Some culverts evaluated in this study had a combination of partial voids and delamination.

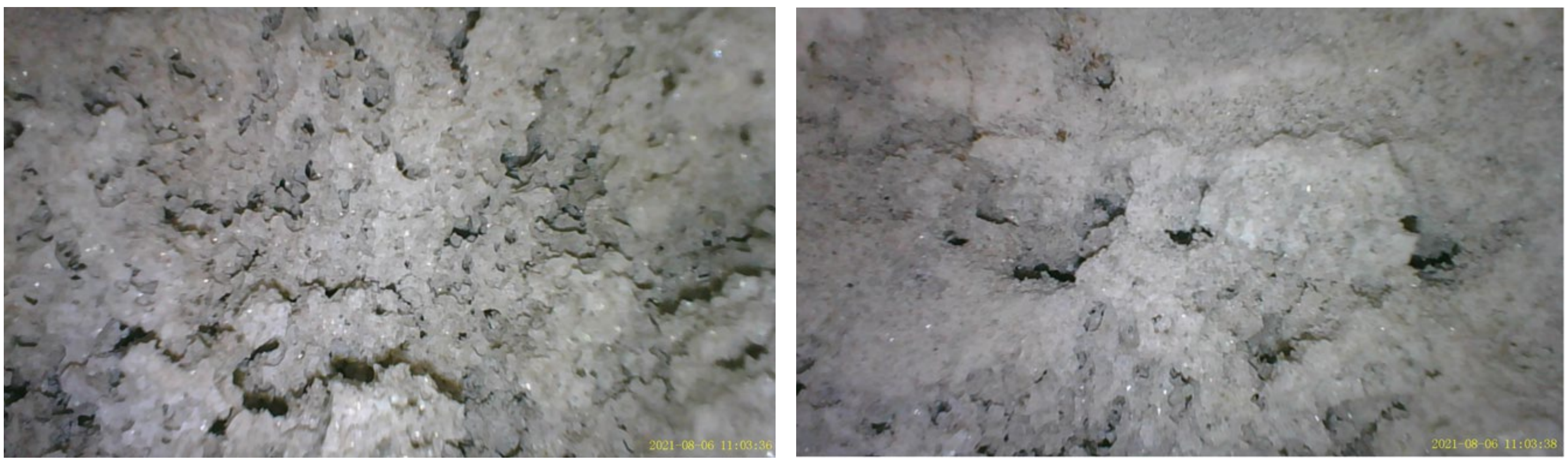
The third type of response is pure metallic sound, which indicates that there is no grout between the host and liner pipe. Figure C.34 illustrates the types of voids that were frequently encountered in the sliplined culverts that were inspected in this study. A chart showing the correlation between the void shapes and the associated sounds is provided in Figure C.35.

(a) Empty Voids

(b) Partial Voids

Figure C.34: Annulus Conditions in Sliplined Culverts

(c) Delamination (left: at the liner pipe; right: at the host pipe)



(d) Partial Voids (typical of cellular grouts)

Figure C.34: Annulus Conditions in Sliplined Culverts [Continued]

(e) Completely Solid

Figure C.34: Annulus Conditions in Sliplined Culverts [Continued]

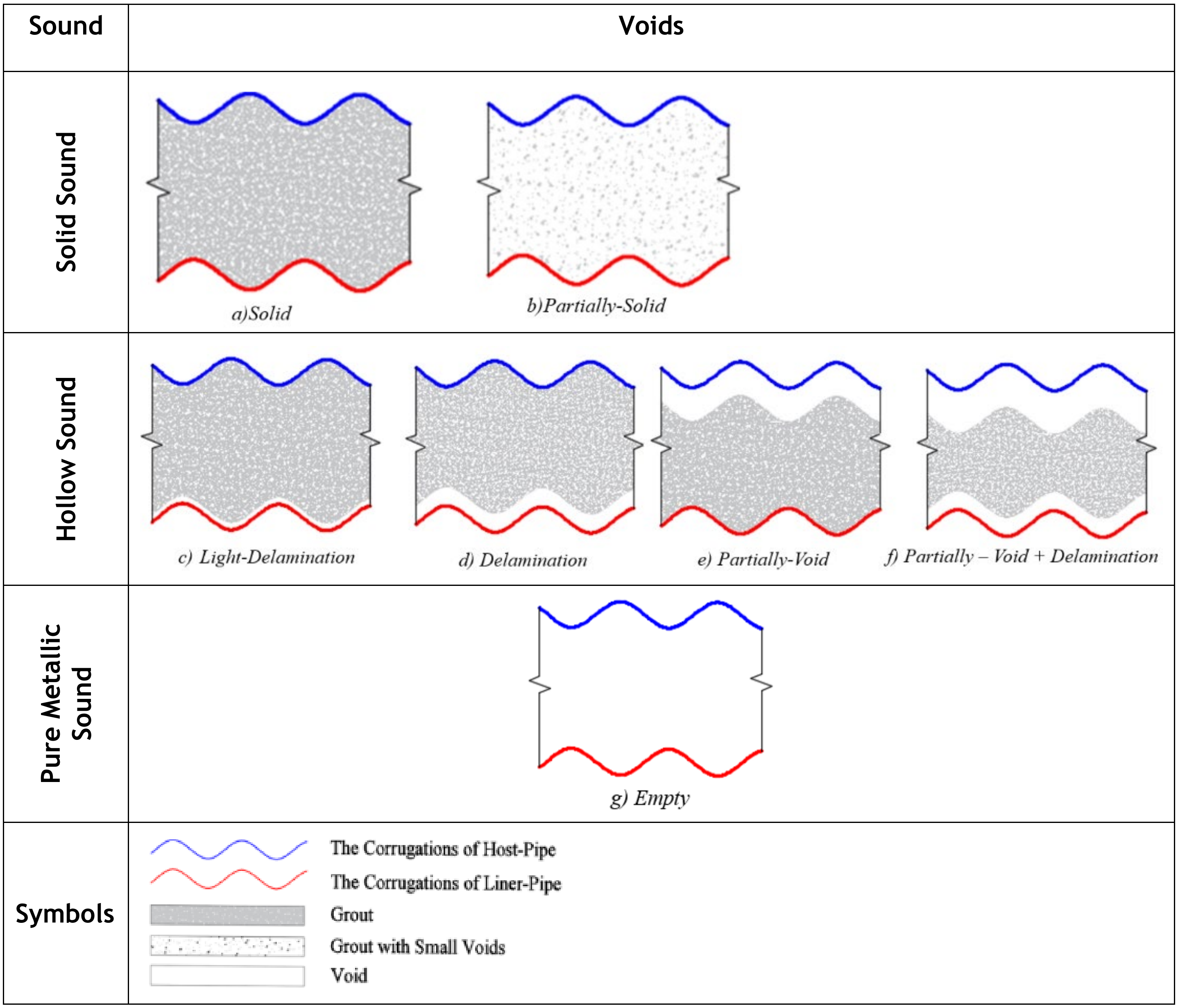


Figure C.35: Sound Classification of Voids in Sliplined Culverts.

C.6 Evaluation Results

A total of 30 culverts in various ODOT districts were shortlisted for our culvert surveys. Nine of these culverts had difficult access and were unsafe to enter. The annulus conditions of 21 culverts were mapped to record the presence and extent of voids as well as their locations in the culverts. The data obtained from the sounding tests assisted the research team in classifying the voids that were most frequently noted in the inspected culverts.

From the inspection results shown in Figures C.4 to C.33, it can be noticed that most of the voids detected behind the liner pipes are near the crown of the liner pipe (between the 10 o'clock and 2 o'clock positions through the crown). Delamination was also frequently detected at positions from 3 o'clock to 9 o'clock below the springline.

Culverts with voids at the crown (such as ATB-90-28.406 9, JEF-151-1.530) showed some deflections, as there is no grout (filler) to transfer the load coming from the host pipe. Such loads can induce distortion of a circular liner pipe, causing the pipe to become oval in shape. Water condensation was also found at the crown of the liner pipes, indicating that the annulus is not well grouted at the crown. Condensation occurred where the annulus void was completely or mostly empty.

Some differences were noted for liner pipes made from different materials. The main advantage of lining culverts with steel casing pipe is that no distortion in the liner shape will occur since the wall thickness of the casing pipe is substantially greater than the corrugated steel pipe. However, most of the steel casing pipes in the surveyed culverts showed a high degree of corrosion on the exposed surface. Culverts lined with steel spiral rib pipes were found to have some amount of corrosion at the invert.

Figure C.36 presents the frequency of voids for all culverts surveyed. Moreover, inspections in all districts are not equally represented. ODOT District 3 had only one culvert that performed very well: for this culvert, more than 60% of the culvert area was solid, with no signs of a completely empty annulus. However, this culvert still showed delamination (24%) and partial voids (15%). On the other hand, culverts in other districts seem to have more voids. For example, for the two culverts inspected in District 4, about 72% of the total area of these culverts was empty; for the culverts in ODOT District 5, delamination accounted for 51% of the total area. In addition, delamination was observed in almost every culvert surveyed, whereas responses that were partially solid were only obtained for the culverts in District 4 (maybe because of the use of cellular grouts). Overall, the results indicate that the grout in most of the inspected culverts did not completely or mostly fill the annular space between the host pipe and liner pipe.

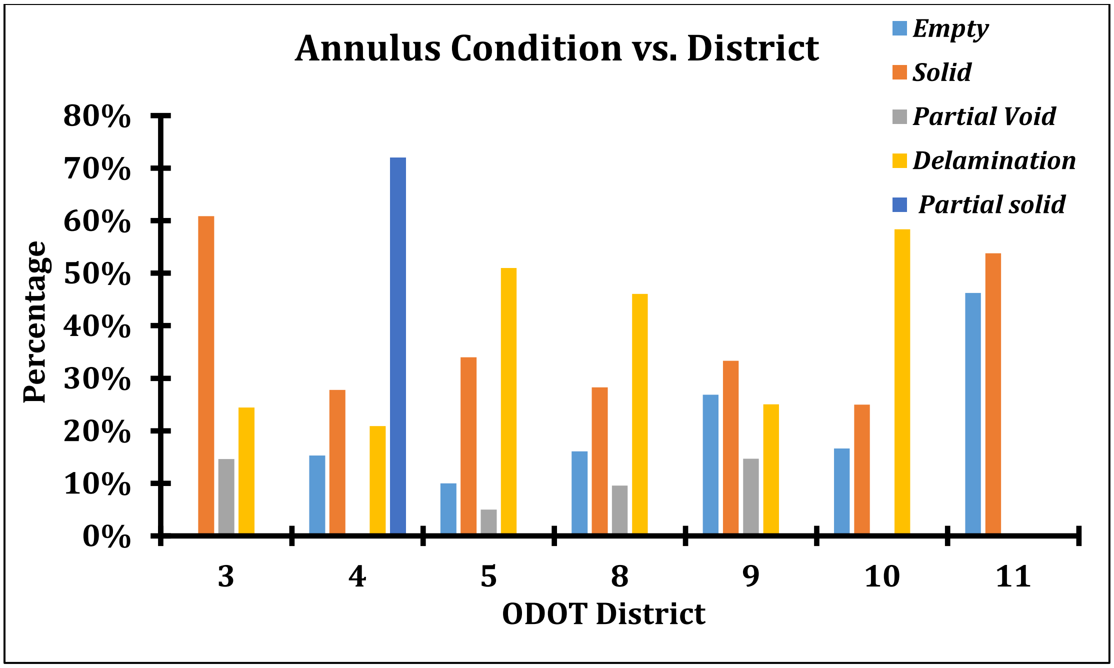


Figure C.36: Percentage of Voids in Sliplined Culverts in Different ODOT Districts.

C.7 Conclusions

Based on the findings of the inspections conducted on the culverts surveyed in this study, the following conclusions are made:

- Sounding tests and examination with an endoscope camera are simple methods that can be used to detect voids and reveal the condition of the annulus behind most liner pipes, except for liner pipes with double layers of polyethylene. The sounding results are inconclusive in double-walled plastic pipes due to the space between the two polyethylene walls.
- It is sometimes difficult to determine the extent or types of voids with sounding particularly if the fill material is cellular grout. Therefore, the sounding method can be used as a general indicator for sliplined culverts. When in doubt, the use of the liner drilling and endoscope camera is necessary to identify the severity of the voids.
- The data obtained from sounding test method assisted the research team in classifying the voids that are frequently seen in most of the sliplined culverts inspected in the study.
- The sounding test is an implementable method to detect voids. Drilling a small hole in the liner and inserting an endoscope camera is particularly useful because voids are physically seen with a camera. Therefore, it is a simpler, reliable, and inexpensive method to detect voids in the annulus of sliplined culverts.
- Our field inspections indicated that most of the grouts used in the sliplining of culverts were controlled low strength material (CLSM) or non-shrink grout. Very few culverts inspected in this study were found to contain cellular grout.

Incomplete filling to a varying degree was observed in majority of the inspected culverts regardless of what grout was used.

- From this study, it was determined that four types of liner pipes can be inspected using the sounding test method: corrugated steel pipe, steel rib pipe, solid wall high density polyethylene (HDPE), and steel casing pipe. However, caution must be exercised when the annulus void filler is a cellular grout because the sounding test may give false alerts.

Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX D

Sliplined Culverts Inspection By Non-Destructive Methods

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State Job Number 135965
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U.S. Department of Transportation
Federal Highway Administration

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APPENDIX D

INSPECTION OF SLIPLINED CULVERTS USING NON-DESTRUCTIVE METHODS

D.1 Introduction

After completing inspections on nearly 30 sliplined culverts, it was recommended by ODOT to assess the condition of the annulus void grout of the inspected sliplined culverts using an advanced technology currently available in the industry. As discussed in the literature review, no studies have been reported that examine the use of non-destructive test (NDT) methods for inspecting the annulus conditions of sliplined culverts. However, one study that involved inspecting the lack of backfill behind an original culvert wall was reported by Anderson and Bowles (2012). The authors of this study investigated the use of backscatter computed tomography (BCT) to evaluate the soil conditions behind a culvert wall, and they concluded that BCT could be used to quantify the voids behind original culvert pipes (not slip-lined culverts). For this reason, BCT was selected in this project for the inspection of the annulus void grout condition of the sliplined culverts.

Since most NDT methods are considerably more expensive than a sounding test, it was not practical to conduct NDT inspections for all culverts that were previously inspected by the research team. Therefore, a subset of eight sliplined culverts with different liner materials and grout conditions were proposed to be inspected using NDT, as the sounding test results for these culverts showed a wide range of annulus conditions—from “good” to “poor”, indicating conditions from ranging from solid to empty. Additional details about the selected culverts and the NDT methods used in the inspections are provided in Table D.1.

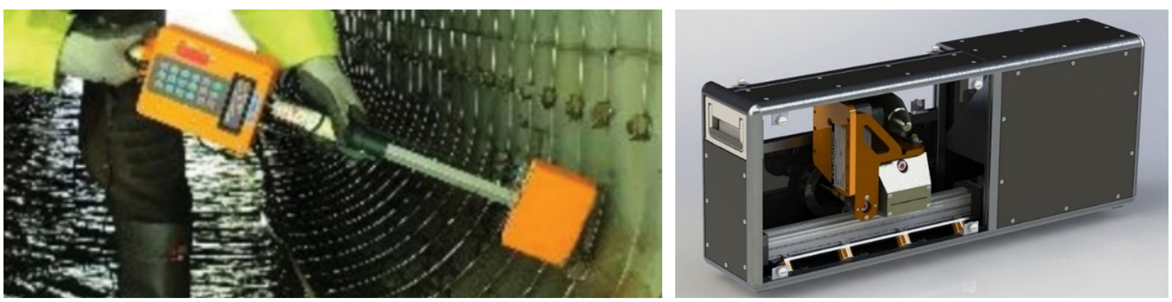
Table D.1: Sliplined Culverts Inspected using NDT

Project ID No.	County/Route/ Section	ODOT District	Length (ft)	Host Pipe Size (in)	Host Pipe Shape	Host Material	Liner Pipe Size (in)	Liner Material	Inspection Method
97421	JEF-151-1.530	11	138	96	Circular	Corrugated Metal Pipe	78	Corrugated Steel Spiral Rib Pipe	InSight™ Lite + InSight™ BCT
14018	MED-71-10.77	3	200	120	Circular	Corrugated Metal Pipe	102	Corrugated Steel Spiral Rib Pipe	InSight™ Lite + InSight™ BCT
104065	JAC-35-0.418	9	256	72	Circular	Corrugated Metal Pipe	60	Corrugated Steel Spiral Rib Pipe	InSight™ Lite
87535	FAI-37-23.09	5	282	72	Circular	Corrugated Metal Pipe	60	Corrugated Steel Spiral Rib Pipe	InSight™ Lite
85540	LCT-70-13.00	5	302	78	Circular	Reinforced Concrete Pipe	60	High-density polyethylene	InSight™ Lite
76721	SUM-8-7.81	4	202	60	Circular	Corrugated Metal Pipe	54	Corrugated Steel Spiral Rib Pipe	InSight™ Lite
25869	ATB-90-28.406	4	364	120	Circular	Corrugated Metal Pipe	108	Corrugated Steel Spiral Rib Pipe	InSight™ Lite
97228	BRO-68-4091	9	184	96	Circular	Corrugated Metal Pipe	84	High-density polyethylene	InSight™ Lite

Inversa Systems Ltd. (Fredericton, New Brunswick, Canada) was retained to perform the NDT inspection on the selected sliplined culverts using their proprietary BCT system. The following subsections outline the inspection methodology using BCT for the inspection of the annulus conditions between the host pipes and liner pipes of the selected culverts. The outcome of the BCT inspections and some conclusions that are based on the outcome of the BCT inspections are also outlined.

D.2 Methodology for Inspections using Backscatter Computed Tomography

Backscatter computed tomography (BCT) is an industrial diagnostic imaging technique that provides information in a way that is similar to computerized tomography (CT) techniques used in medical diagnostic imaging. The BCT system uses the collected information to create a relative density map, which allows inspectors to distinguish between materials of different densities and map the locations of those materials. The inspection protocol requires the use of proprietary instruments produced by Inversa Systems. Two BCT systems were used in the NDT inspections in this project: InSight™ Lite (a handheld BCT imaging device) and InSight™ BCT (a conventional BCT imaging unit). Photos of the two BCT systems are provided in Figure D.1.

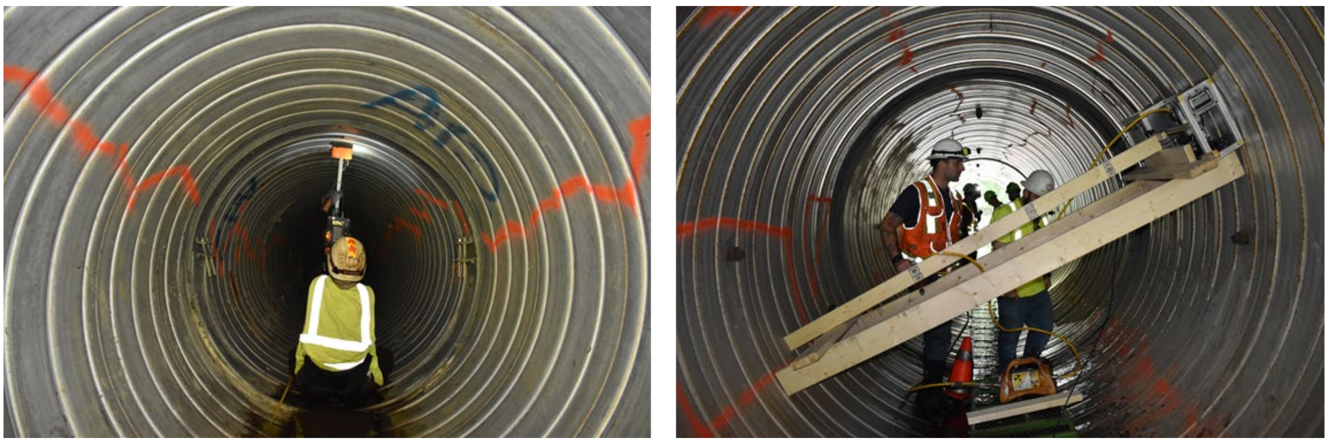


(a) InSight™ Lite (b) InSight™ BCT

Figure D.1: Inspection Equipment for NDT Evaluation.

For the culvert inspections in this study, a preliminary assessment was first made using the handheld InSight™ Lite scanner to identify locations where voids might be present, as shown in Figure D.2(a). The preliminary scanning was performed at set distances starting from the inlet and continuing toward the outlet of the culvert, with data collected at locations along the inside diameter of the liner pipe at twelve positions matching the twelve clock positions. Once InSight™ Lite data at all locations along the culvert were captured, they were uploaded to the SoilSight™ portal, where the collected data were processed and the output presented in the form of two-dimensional maps. Further details about the mapping process and the interpretation of the output maps will be provided in the following section.

At locations where the preliminary results indicated the presence of possible voids, an in-depth inspection using InSight™ BCT was performed to help the inspector visualize the conditions behind the liner pipe wall. To accomplish this, the InSight™ BCT unit was first placed in a wood frame to help stabilize the unit during scanning, as shown in Figure D.2(b). Next, the BCT scanner was positioned against the pipe wall. The scanning region covered a distance of 8 inches along the pipe wall, and the depth of the image was set to a target depth (the through thickness of the annulus) of up to 9 inches from the face of the scanner. For safety purposes, no inspectors were permitted to remain in the culvert while scanning was performed, as the InSight™ BCT unit is known to produce a certain amount of radiation during the scanning process.



(a) Preliminary inspection with a handheld InSight™ Lite

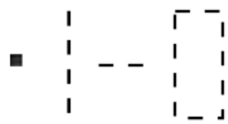
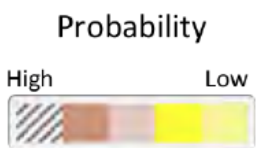
(b) Detailed inspection using InSight™ BCT

Figure D.2: Inspection Equipment for NDT Evaluation.

D.3 Results of NDT Inspection using BCT

The measurements collected in the preliminary NDT inspection of each culvert with the handheld InSight™ Lite device were imported into SoilSight™ and used to generate a two-dimensional map representing the conditions of the annulus behind the wall of the liner pipe. In these maps, areas of the annulus behind various locations on the liner pipe are characterized in terms of their probability of containing actual voids. The horizontal axis of the generated map is the longitudinal position along the culvert as measured from the inlet of the culvert, while the vertical axis indicates the clock position around the inside diameter of the liner pipe. A key to the symbols on the maps generated by SoilSight™ are presented in Table D.2. All the culvert inspection results that were generated using BCT devices, which included NDT maps, BCT scans, and the interpretation of the results were provided by Inversa Systems.

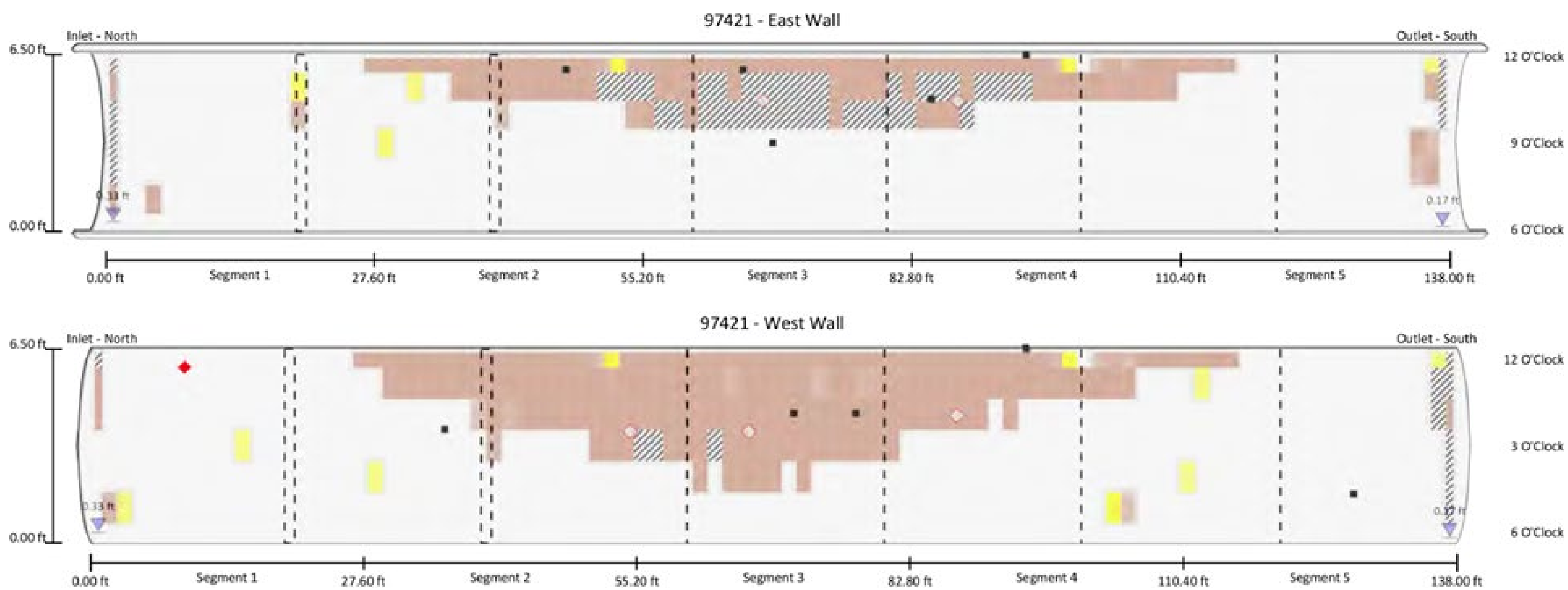
Table D.2: Symbols on the SoilSight™ Maps Provided by Inversa Systems

Symbol	Explanation
	**Acoustic anomalies** are indicated as rectangles and are assigned identification numbers. The horizontal (X) and vertical (Y) position of each anomaly is recorded and is displayed in the table for the corresponding pipe segment.
	**Visual indicators** for defects based on the flaw type are also provided and are assigned a corresponding identification number. Black squares indicate isolated defects, dashed lines indicate linear defects, and rectangles with dashed lines indicate larger areas with defects. The X and Y positions for the defects are recorded and are displayed in the table for the corresponding pipe segment. Photos are included in the visual assessment section of the inspection report.
	**InSight™ Lite anomalies** are regions detected by the InSight™ Lite scanner that may contain voids or other low-density materials. The various regions are categorized in terms of their probability of containing actual soil voids, with low probabilities indicated in shades of yellow and high probabilities indicated in shades of brown. The unburied end(s) of the culvert are represented by diagonal black stripes.
	**InSight™ BCT images** are assigned an identification number and are represented by a diamond. Once a scan is captured, it is verified as a void (a diamond with no shading) or solid backfill (a diamond with red shading). The X and Y positions are recorded and are displayed in the table for the corresponding pipe segment.
	**Waterline marks** indicate the level of water in the pipe at the time of inspection.

The results of the preliminary inspection for the eight sliplined culverts using the InSight™ Lite handheld device, which are summarized from a report provided by Inversa Systems, are shown in Figures D.3 to D.10. The map for culvert LCT-70-13.00 (Figure D.7) indicates numerous areas where potential voids could be present in the annular space between the existing culvert pipe and the sliplining pipe. The areas are located on both sides of the culvert and are primarily found between the 9 o'clock and 3 o'clock positions along the entire length of the culvert. Other culverts exhibited a similar probability of containing annular voids. For culvert JEF-151-1.530 (Figure D.3), a high probability of voids was reported at most locations over the entire length of the culvert (except for the first and last segments) at positions from 9 o'clock to 3 o'clock. Culvert BRO-68-4091 (Figure D.9) showed a high probability of voids over only half of the length of the culvert, but at the same clock positions as in culvert JEF-151-1.530. The remaining culverts exhibited lower probabilities of voids at various locations.

Images for two of the sliplined culverts, JEF-151-1.530 and MED-71-10.77, were obtained with the InSight™ BCT unit to verify if voids were present at the locations indicated in the preliminary assessment, and the results are presented in Figures D.11 to D.14. These BCT images provide a cross-sectional view behind the pipe wall. The lower portion of the image indicates the front (accessible) side of the pipe wall, while the area perpendicular to the lower portion of the image indicates the depth behind the wall. The BCT image presents the results in white, gray, and black: white represents high-density materials (such as the wall of a pipe that could be either the host pipe or the liner pipe); black represents voids, which have a lower density than the grout or pipe; and gray represents the grout, which has an intermediate density (lower than that of a pipe and higher than that of a void).

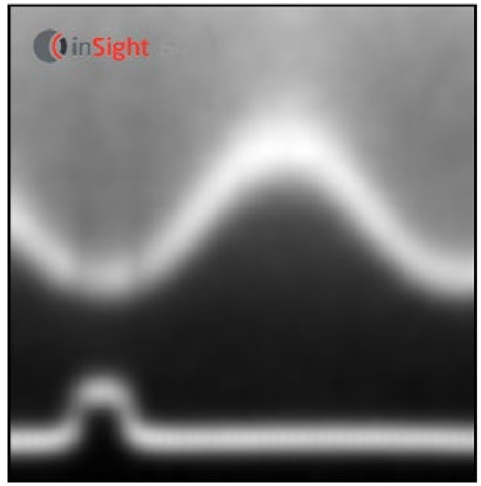
To better understand the maps of possible voids generated from the data collected by the InSight™ Lite unit, a comparison was made to aid in translating the probability of voids from the InSight™ Lite maps and the images obtained by InSight™ BCT. A comparison between the InSight™ Lite maps and the InSight™ BCT images was performed for two of the culverts from the preliminary inspections. In Tables D.3 and D.4, a comparison is made between the InSight™ BCT images and the corresponding InSight™ Lite maps from specific segments of culverts JEF-151-1.530 and MED-71-10.77, respectively. It can be seen from these tables that when the InSight™ Lite map indicates diagonal stripes or dark brown, the annulus of the sliplined culvert is completely empty at the specific location behind the pipe wall; if the map indicates light brown or yellow, the annulus is solid with no sign of voids.



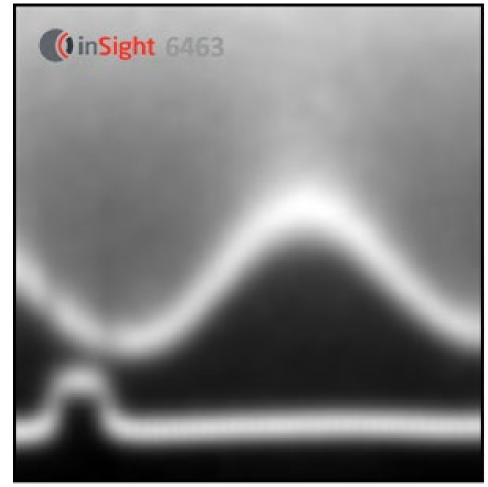
InSight™ Lite Map

Figure D.3: NDT Map and BCT Scans for Culvert JEF-151-1.530.

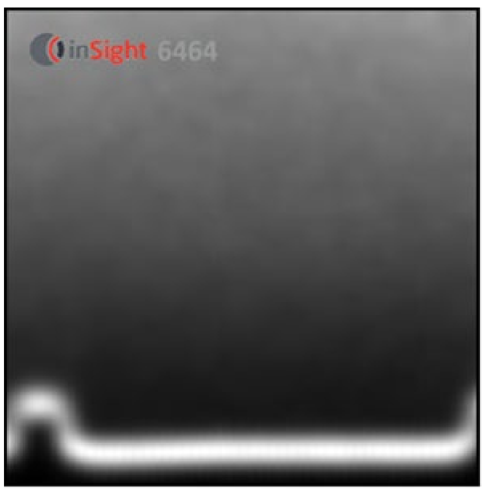
BCT-1 (Scan ID: 6461)
No void. Control point



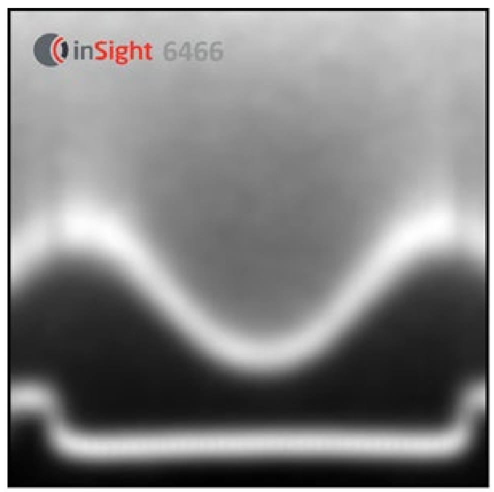
BCT-2 (Scan ID: 6462)
Full annular void



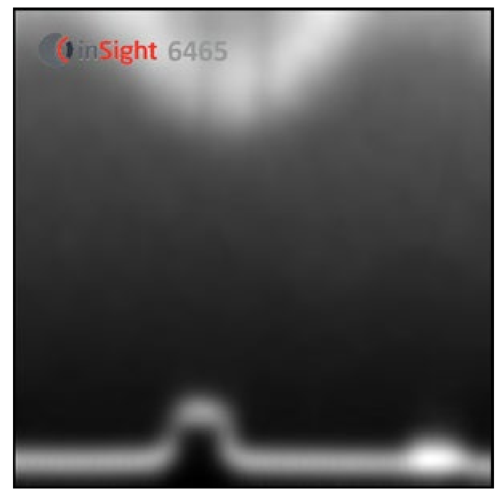
BCT-3 (Scan ID: 6463)
Full annular void



BCT-4 (Scan ID: 6464)
Full annular void

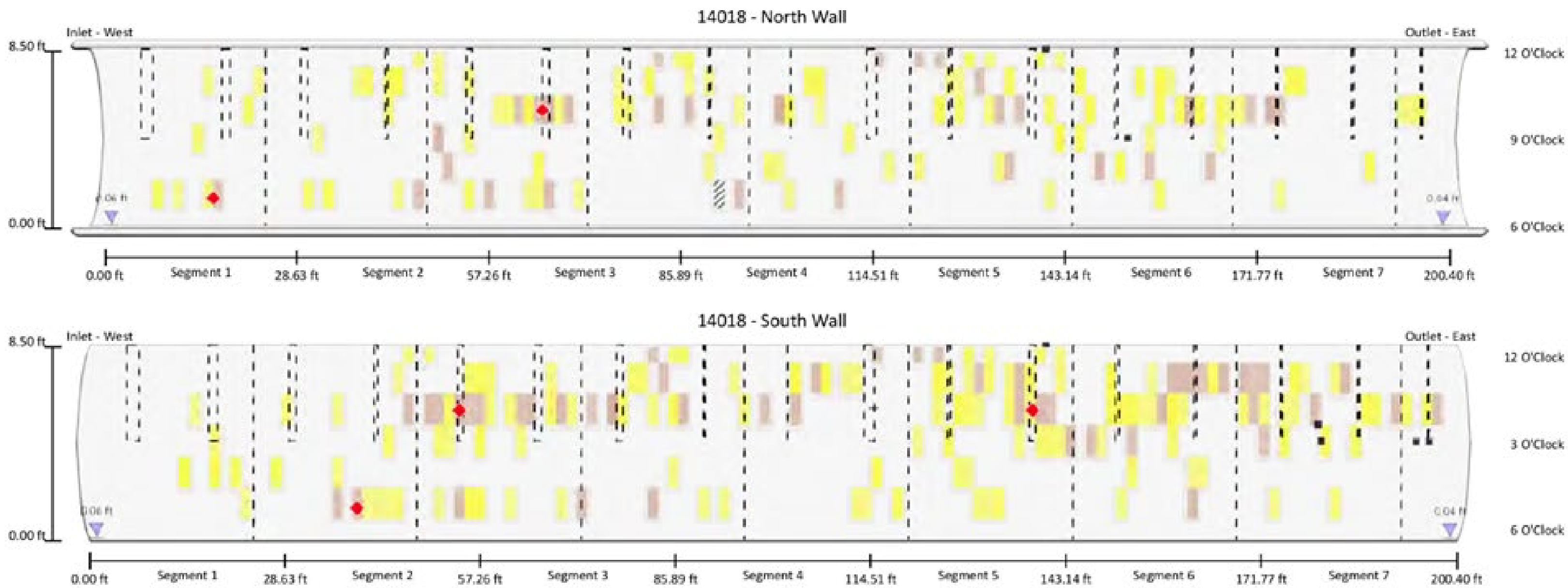


BCT-5 (Scan ID: 6466)
Full annular void



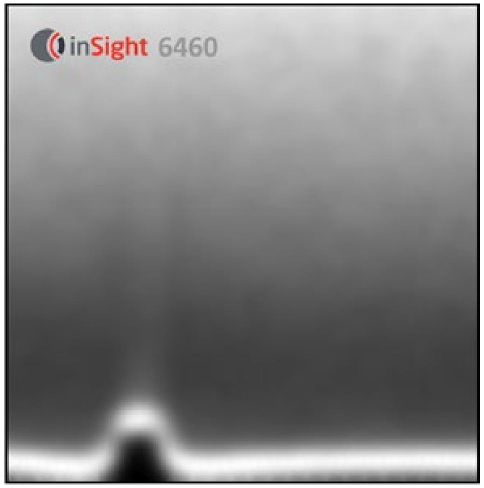
BCT-6 (Scan ID: 6465)
Full annular void

Figure D.3: NDT Map and BCT Scans for Culvert JEF-151-1.530. [Continued]

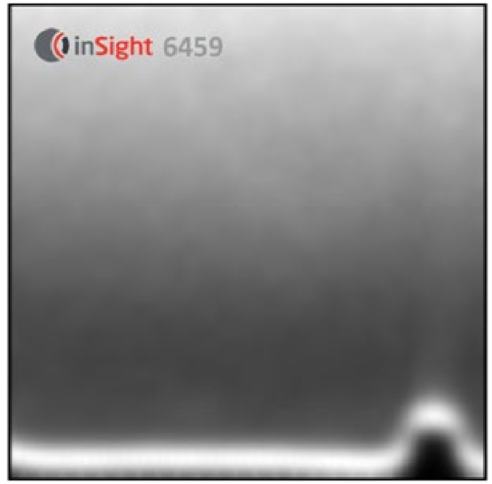


InSight™ Lite Map

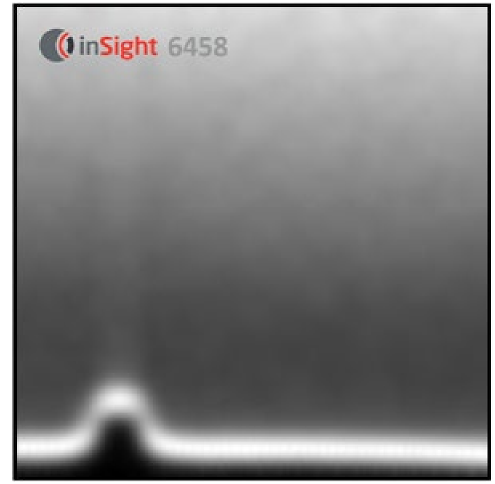
Figure D.4: NDT Map and BCT Scans for Culvert MED-71-10.



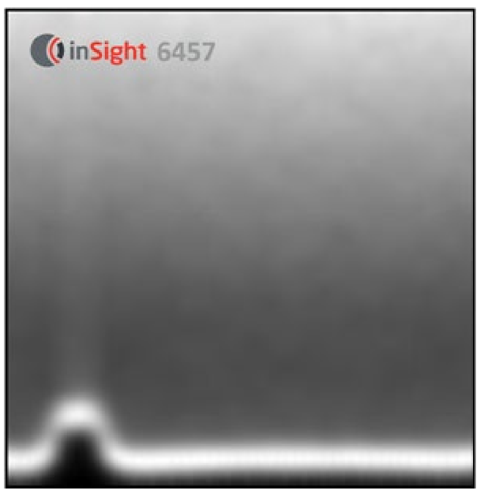
BCT-1 (Scan ID: 6460)
No void. Control Point



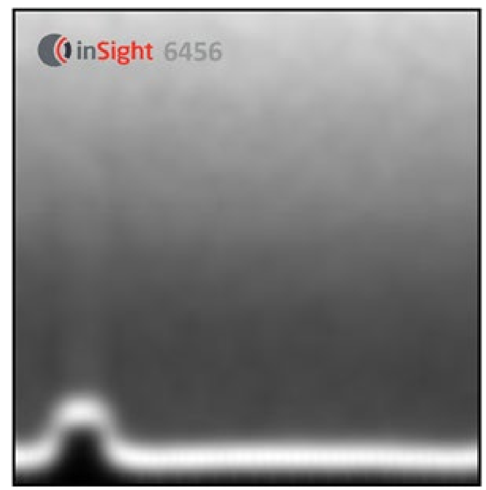
BCT-2 (Scan ID: 6459)
No void



BCT-3 (Scan ID: 6458)
No void

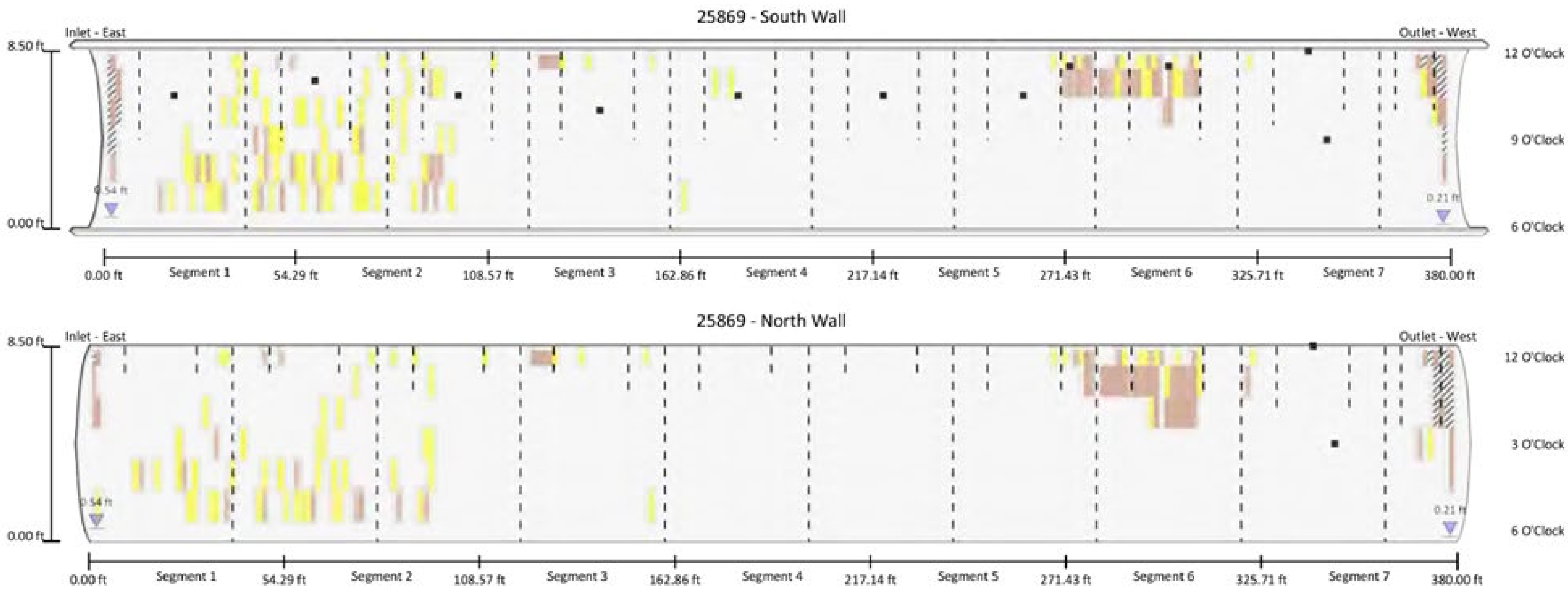


BCT-4 (Scan ID: 6457)
No void



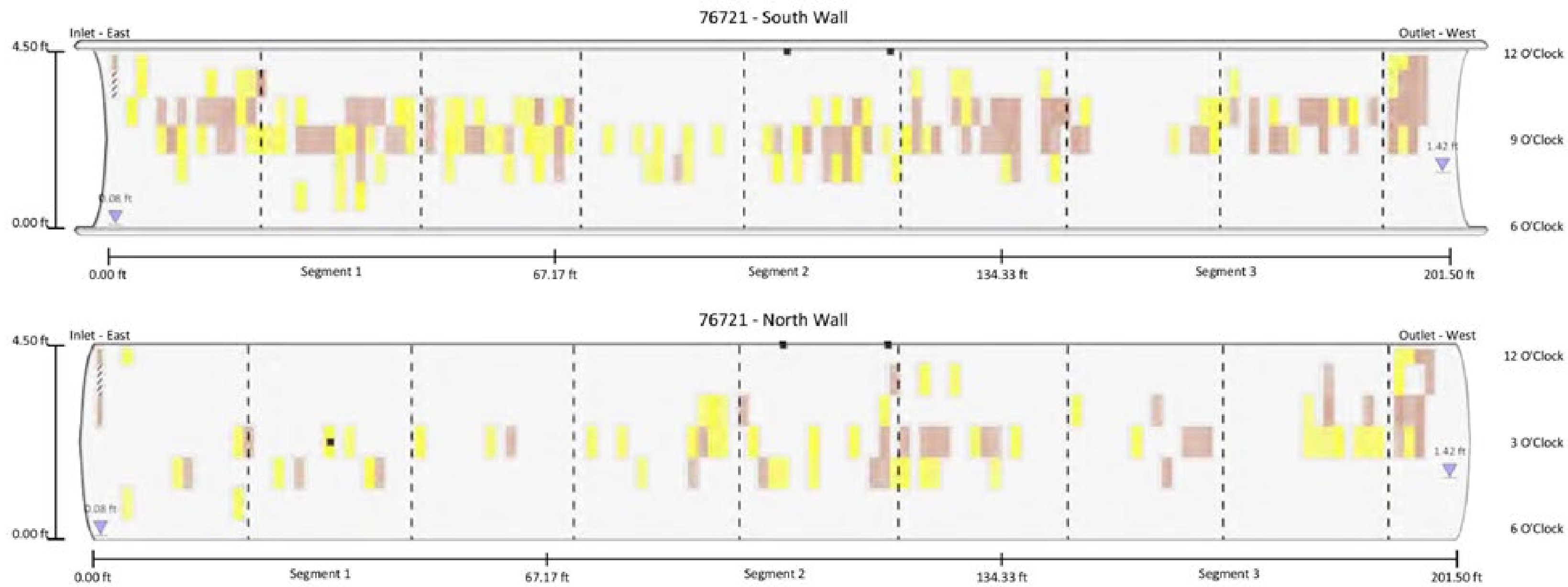
BCT-5 (Scan ID: 6456)
No void

Figure D.4: NDT Map and BCT Scans for Culvert MED-71-10. [Continued]



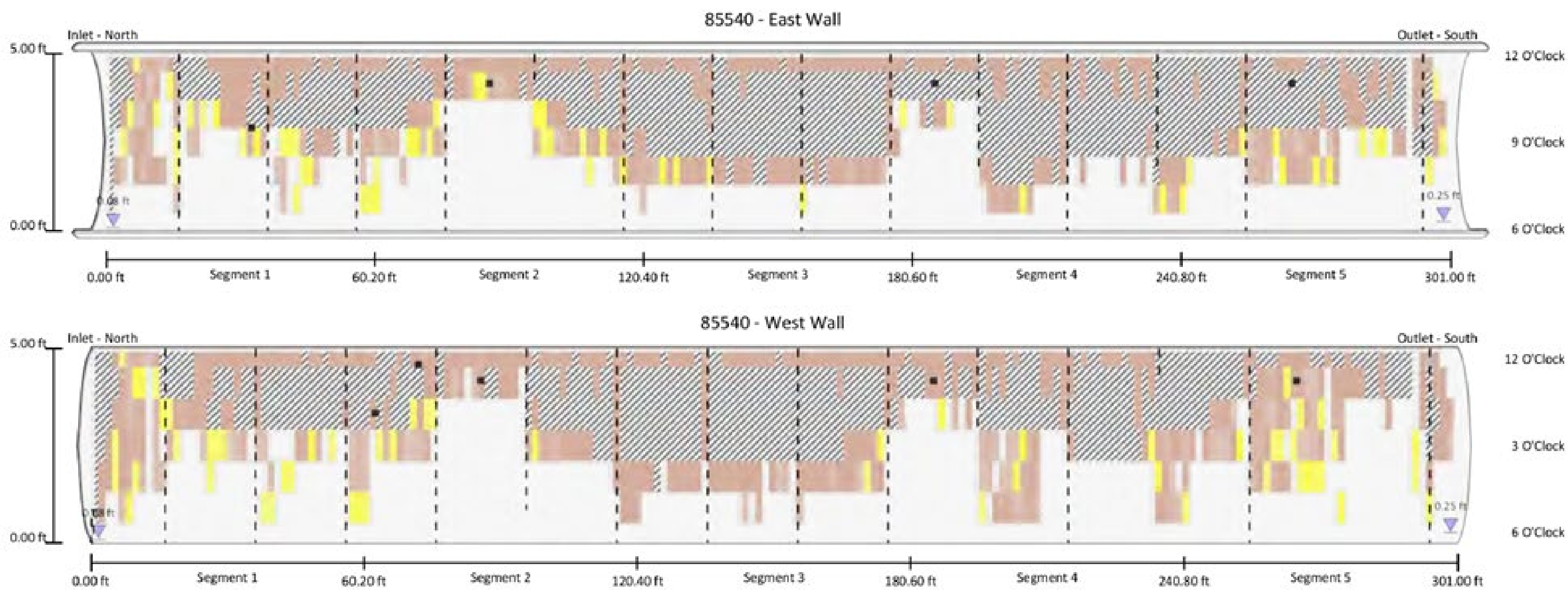
InSight™ Lite Map

Figure D.5: NDT Map for Culvert ATB-90-28.406.



InSight™ Lite Map

Figure D.6: NDT Map for Culvert SUM-8-7.81.



InSight™ Lite Map

Figure D.7: NDT Map for Culvert LCT-70-13.00.

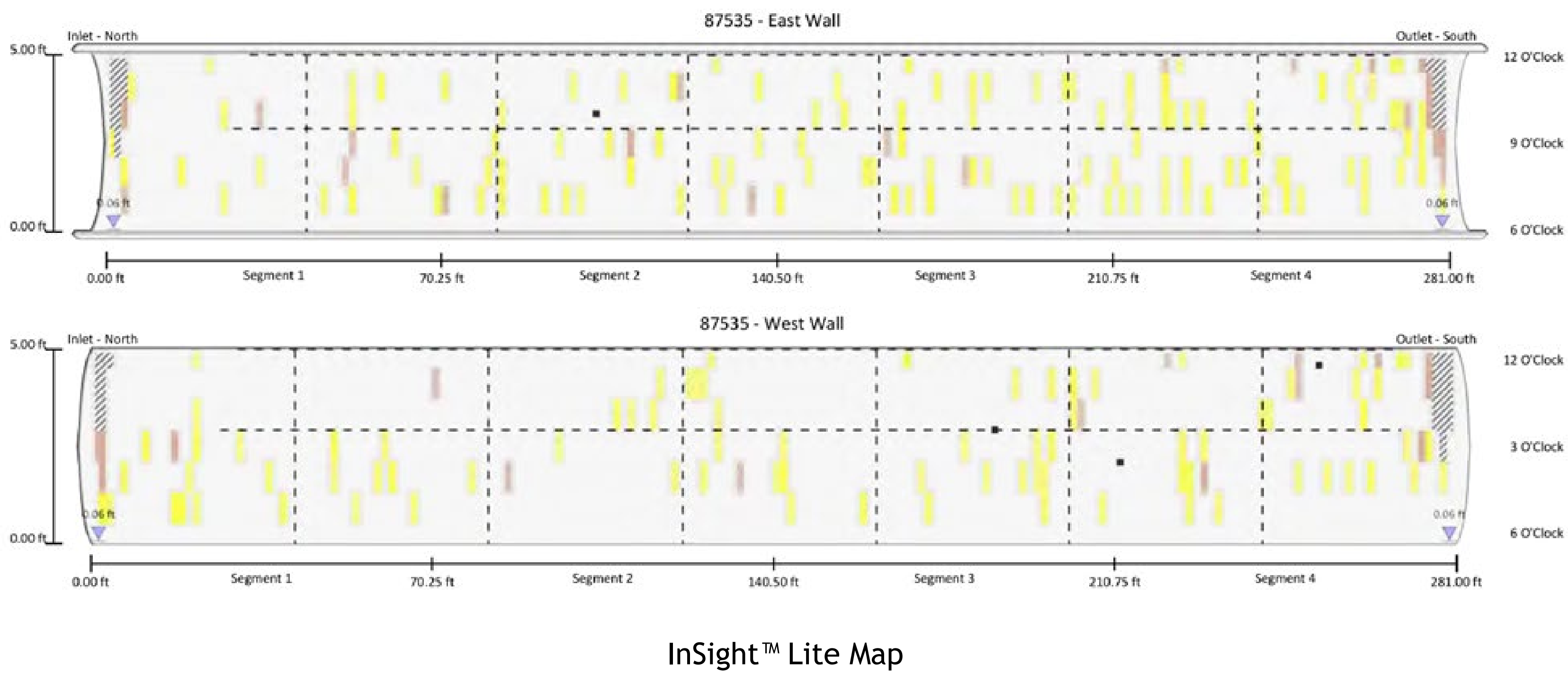
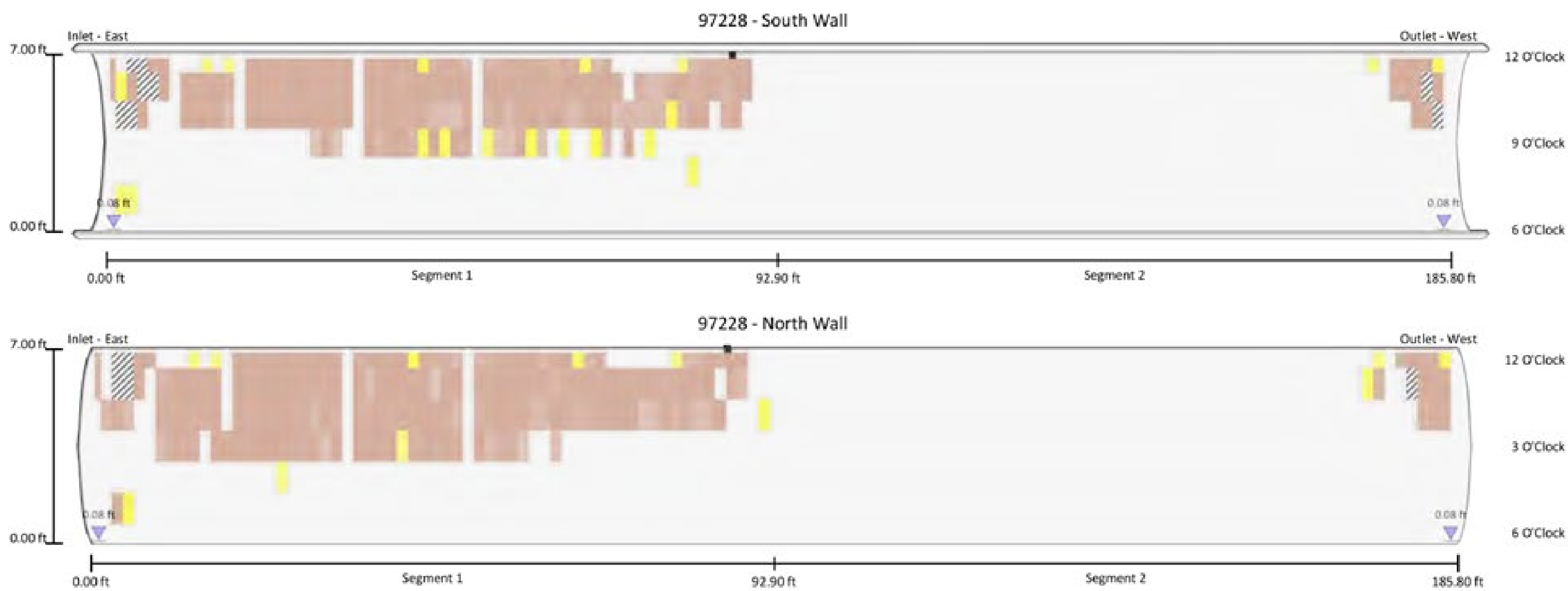
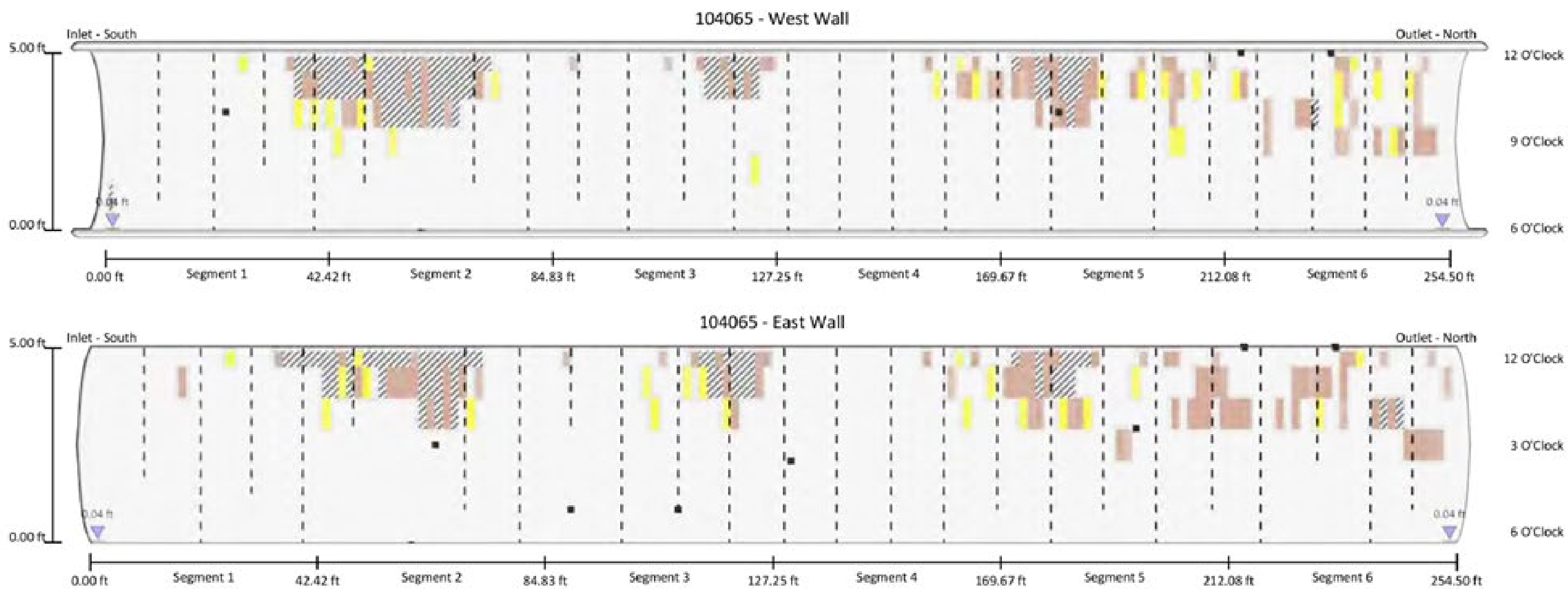


Figure D.8: NDT Map for Culvert FAI-37-23.09.



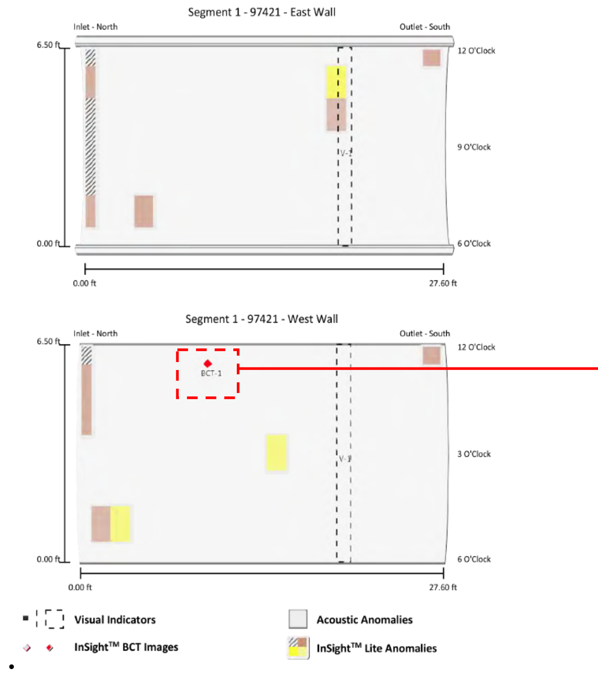
InSight™ Lite Map

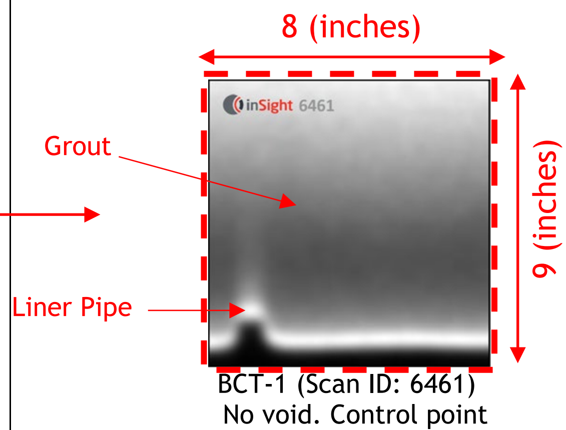
Figure D.9: NDT Map for Culvert BRO-68-4091.

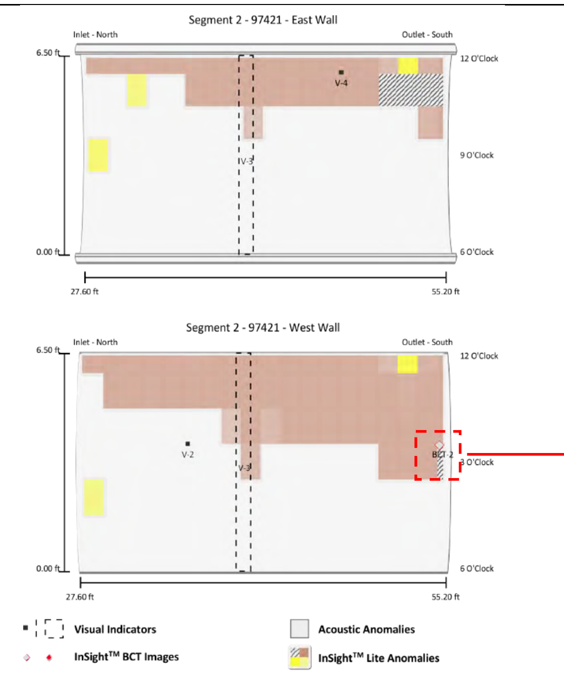


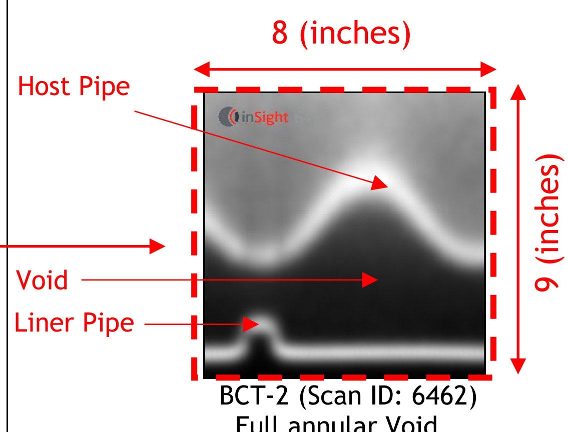
InSight™ Lite Map

Figure D.10: NDT Map for Culvert JAC-35-0.418.









InSight^{TM} Lite Map	InSight^{TM} BCT Image

Figure D.11: NDT Map and BCT Scans for Segments 1 and 2 of Culvert JEF-151-1.530.

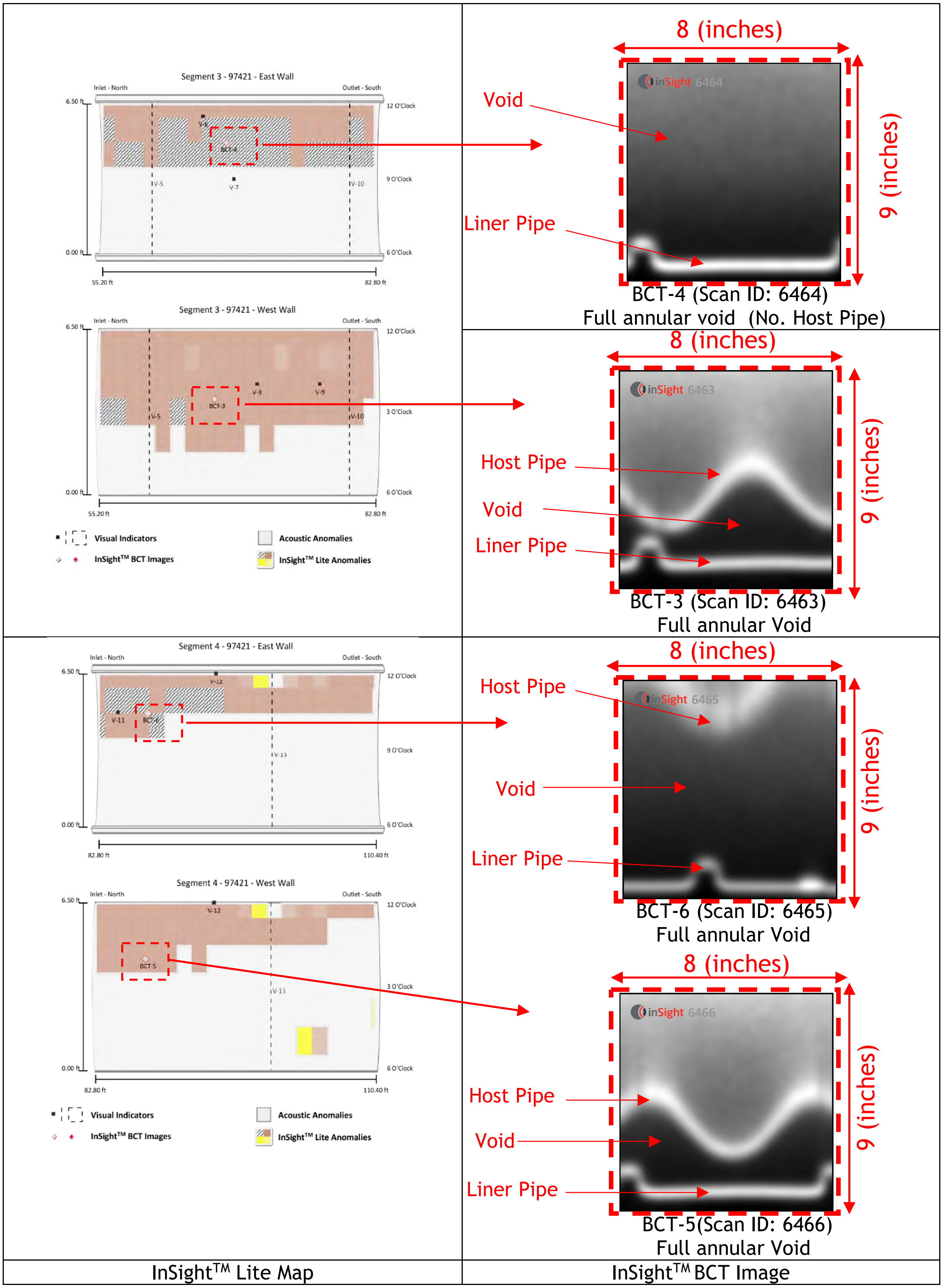


Figure D.12: NDT Map and BCT Scans for Segments 3 and 4 of Culvert JEF-151-1.530.

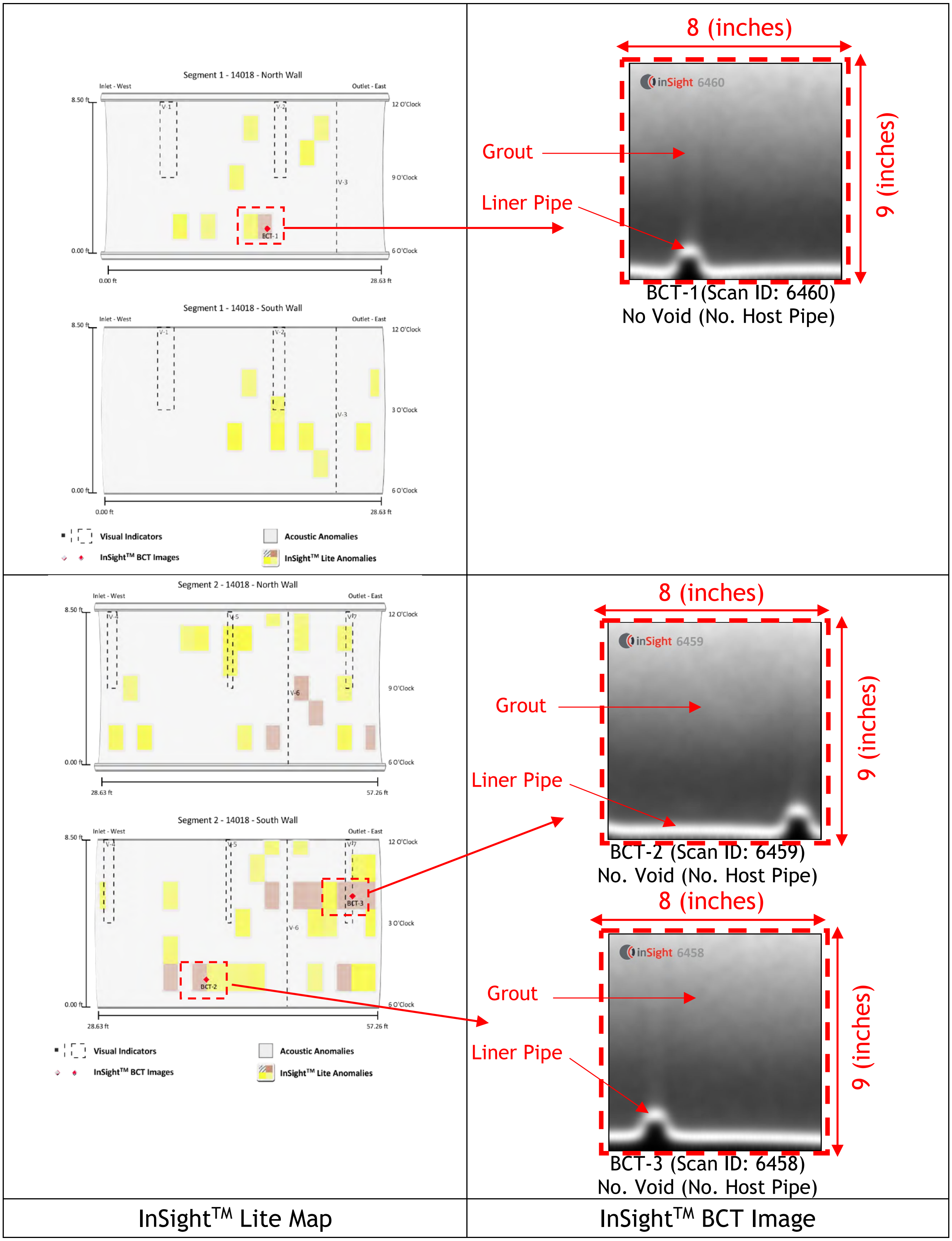
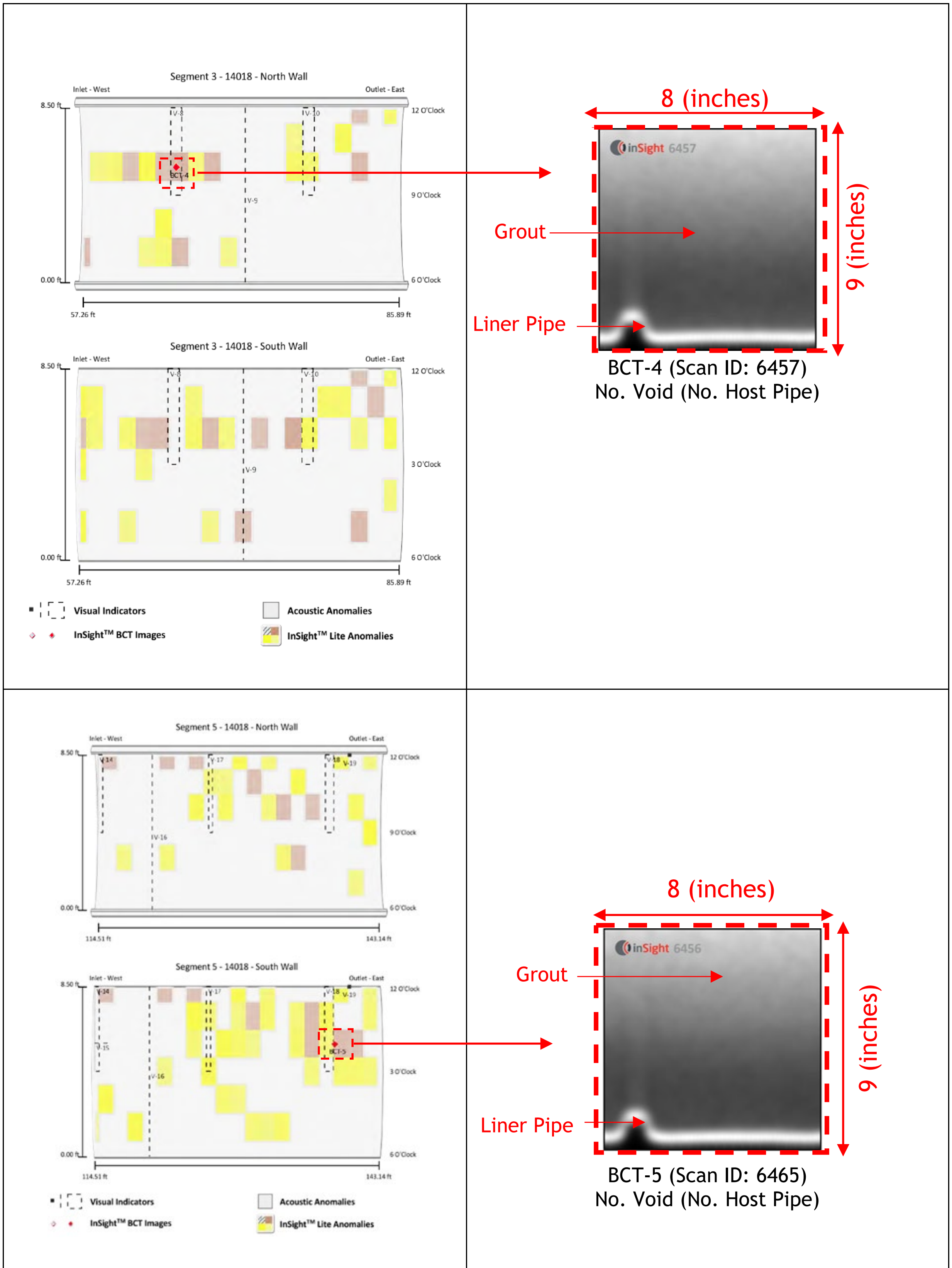


Figure D.13: NDT Map and BCT Scans for Segments 1 and 2 of Culvert MED-71-10.77.



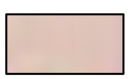
InSight™ Lite Map	InSight™ BCT Image

Figure D.14: NDT Map and BCT Scans for Segments 3 and 5 of Culvert MED-71-10.77.

Table D.3: Comparison between InSight™ Lite and InSight™ BCT Results for Culvert JEF-151-1.530

InSight™ Lite 	InSight™ BCT ◇ Void ◆ No void.
	BCT-1: No void detected. (Control point)
	BCT-2: Full annular void
	BCT-3: Full annular void
	BCT-4: Full annular void
	BCT-5: Full annular void
	BCT-6: Full annular void

Table D.4: Comparison between InSight™ Lite and InSight™ BCT Results for Culvert MED-71-10.77

InSight™ Lite 	InSight™ BCT ◇ Void ◆ No void.
	BCT-1: No void detected
	BCT-2: No void detected
	BCT-3: No void detected
	BCT-4: No void detected
	BCT-5: No void detected

D.4 Discussion

A total of eight sliplined culverts were initially inspected by NDT using backscatter computed tomography. The annulus conditions for all eight culverts were mapped using InSight™ Lite, and two of the eight culverts were subsequently inspected using InSight™ BCT. Based on the findings of the inspections conducted on the surveyed culverts in this study, the following conclusions are drawn:

- InSight™ Lite indicates a probability of having voids in some culverts at positions from 9 o'clock to 3 o'clock (above the springline) to the crown of the culvert (as 12 o'clock).
- Using InSight™ BCT in two culverts gave a clearer understanding of the meaning of the colors indicated in the InSight™ Lite maps, which provides a more objective assessment than simply relying on the probabilities that can lead to subjective interpretations by different inspectors.
- The results from InSight™ BCT showed that the annulus conditions in the two sliplined culverts were either solid or completely empty, while the sounding test results presented in Appendix C indicated areas of partial voids and delamination.
- As the depth of the InSight™ BCT is limited to 9 inches, it does not show the host pipe wall but only shows the liner pipe. This might suggest that no host pipe is present, even though all of the inspected culverts have a host pipe.
- The culverts inspected using the NDT method (handheld BCT device) in this study had only two liner materials: corrugated steel and high-density polyethylene. In future research, it is recommended to investigate the performance of this NDT for inspecting sliplined culverts that have liner pipes made from other materials in order to verify the effectiveness of BCT for inspecting culverts with other liner types.

D.5 References

1. Anderson, B., and Bowles, J. (2012). Backscatter Computed Tomography (BCT) Pilot Project for Culvert Integrity Analysis in the City of Toronto. In 2012 Conference and Exhibition of the Transportation Association of Canada-Transportation: Innovations And Opportunities. Available at http://www.tac-atc.ca/english/annualconference/tac2012/docs/session7/anderson.pdf.

Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX E

Cellular Grout

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Prepared for:
The Ohio Department of Transportation,
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U.S. Department of Transportation
Federal Highway Administration

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APPENDIX E

CELLULAR GROUT

E.1 Introduction

Non-cellular and cellular grouts have been used to fill the annular spaces of rehabilitated culvert systems. However, in recent years, many transportation agencies have installed sliplined culverts using cellular grout, which consists of cement, water, and foam. However, as discussed in the literature review reported in Appendix A, there have only been a limited number of studies on the fresh and hardened properties of cellular grout materials, and very few studies that have focused on the use of such grout materials for sliplined culverts. Laboratory testing of cellular grout is useful for identifying the primary features that influence the performance of cellular grout when used as an annulus void fill material for sliplined culverts. This appendix presents the in-depth analysis performed in this project to examine the material components that were used for cellular grout materials (including a variety of foaming agents) as well as the mix design, mixing technique, sample preparation, and testing procedures that were employed. This appendix also presents the results of laboratory-scale parallel plate loading tests of sliplined culvert segments that were used to assess the performance of cellular grout.

E.2 Materials and Mix Design

Cellular grout is a low-density material with a uniform void or cell structure. This structure can be created either by adding prepared foam to a cement mixture or by producing foam inside the mixture. In most cases, the cast-wet density can vary from 20 to 120 lb/ft^3. The density of the cementitious slurry may be controlled by varying the quantity of foam that is added to the mixture, and this can be accomplished with or without the addition of sand or other ingredients. The foaming process results in the formation of air bubbles, which may make up as much as 80% of the total volume of the material.

Cellular grout can be classified into three types based on its density and composition. The first is a type of cellular concrete known as *neat cement concrete*, which is made from Portland cement, water, and prepared foam; it can have a cast-wet density of up to 50 lb/ft^3 and does not include any additional fine aggregates. The second type, known as *sanded cellular concrete*, contains sand as a fine aggregate in addition to water, cement, and prepared foam. Sanded cellular concrete is often made in cast-wet densities ranging from 50 to 120 lb/ft^3. The third type, *lightweight aggregate cellular concrete*, is very similar to sanded cellular concrete but includes low-density aggregates (such as perlite or vermiculite) instead of sand (Pielert 2006).

Considering that any grout used for filling annulus voids needs to be able to flow inside a polyvinyl chloride (PVC) pipe of about 2-inches in diameter over long distances, the grout design should not include the addition of any material that could potentially clog the PVC pipe while the grout is being placed. As a result, the primary emphasis of this research was placed on the process of placing a cellular grout that does not include any fine or coarse aggregate in the fresh mixture (i.e., most of the mix is made up of cement and water). Several different foaming agents were investigated to find agents that would improve both the fresh and hardened properties of cellular grout. The following subsections discuss the characteristics of the different materials used in this investigation.

E.2.1 Cement

The Type III Portland Cement used in this project originated from the Fairborn Cement Company (Xenia, Ohio) and was supplied by the W. L. Tucker Supply Company (Cuyahoga Falls, Ohio). The Type III Portland cement was examined by Fairborn Cement and was found to be in compliance with AASHTO M85 (AASHTO 2020) and ASTM C150/C150 M-12 standards (ASTM 2015). The chemical composition and the physical characteristics of Type III Portland cement are listed in Table E.1 and Table E.2, respectively. The supplier stated that the provided cement fully satisfies all standards outlined in the AASHTO and ASTM specifications.

Table E.1: Standard Composition Requirements for Type III Portland Cement

Chemical Composition (ASTM C 114)	Specification	ASTM C 150	AASHTO M85	Percentage
Silicon dioxide (SiO_2), %	--	--	--	19.4
Aluminum oxide (Al_2O_3), %	--	--	--	4.4
Ferric oxide (Fe_2O_3), %	--	--	--	3.1
Calcium oxide (CaO), %	--	--	--	61.5
Magnesium oxide (MgO), %	Maximum	6.0	6.0	4.3
Sulfur trioxide (SO_3), %	Maximum	3.5	3.5	4.4
Loss on ignition (LOI), %	Maximum	3.5	3.5	2.3
Insoluble residue, %	Maximum	1.5	1.5	0.52
Free calcium oxide, %	--	--	--	0.6
Alkalies (Na_2O equivalent), %	--	--	--	0.77
Tricalcium silicate (C_3S), potential %	--	--	--	56
Dicalcium silicate (C_2S), potential %	--	--	--	13
Tricalcium aluminate (C_3A), potential %	Maximum	15	15	7
Tetracalcium aluminoferrite (C_4AF), potential %	--	--	--	9
CO_2, %	--	--	--	1.1
Limestone, %	Maximum	5.0	5.0	2.5
$CaCO_3$ in limestone, %	Minimum	70	70	97

Table E.2: Standard Physical Requirements of Type III Portland Cement

Physical Requirements	Specification	ASTM C 150	AASHTO M85	Result
Blaine fineness (per ASTM C 204), m^2/kg	--	--	--	628
Initial time of setting (Vicat; per ASTM C 191), minutes	Minimum	45	45	99
Final time of setting (Vicat; per ASTM C 191), minutes	Maximum	375	375	200
Air content (per ASTM C 185), %	Maximum	12	12	8
Autoclave expansion (per ASTM C 151), %	Maximum	0.80	0.80	0.10
Expansion in water (per ASTM C 1038), %	Maximum	0.02	0.02	0.004
Normal consistency (per ASTM C 187), %		--	--	28.9
1 day compressive strength (per ASTM C 109), psi	Minimum	1740	1740	4470
3 day compressive strength (per ASTM C 109), psi	Minimum	3480	3480	5533
7 day compressive strength (per ASTM C 109), psi		--		6368
28 day compressive strength (per ASTM C 109), psi		--		7285

E.2.2 Water

The water utilized in the grout mixture laboratory tests was tap water with a pH ranging from 3.8 to 7.0. Because the tap water was not salty or briny, it is ideal to use for cellular grout. For most mixtures, the water temperature was maintained at 65 ^oF to 70 ^oF. However, the examination of stability included consideration of using hot water at a temperature of 100 ^oF.

E.2.3 Foam

The primary role of a foaming agent in a cellular grout is to reduce the overall weight of the mixture while significantly increasing the volume of the grout. Foaming agents accomplish this by producing tiny air bubbles that are completely encapsulated when the foam is added to the base mix. The increase in volume of the mixture is related to the amount of foam added to the base mix.

In the manufacture of cellular grout, numerous foaming agents are used; however, the typical foaming agent used for a cellular grout is either a surfactant or a synthetic or protein foaming agent. According to research on various foaming agents that was reported by Sun et al. (2018), a synthetic foaming agent spreads 10.2 in., while plant-based and animal-based surfactants spread 7.8 in. and 7 in., respectively.

According to their research findings, spread can be enhanced by up to 30% when a synthetic foaming agent is used, even when the target density is the same.

Four foaming agents were used in this investigation. Aerix Industries (Allentown, Pennsylvania) supplied three distinct types of foaming agents: two were synthetic-based and one was protein-based. The fourth foaming agent was a surfactant, which was acquired from the Drexel Chemical Company (Memphis, Tennessee). The physical-chemical characteristics of these materials, along with other relevant information, are listed in Table E.3.

The density and quality of the produced foam affects how stable the grout will be. According to ASTM C796 (ASTM, 2019) and ACI 5283.3R-14 (ACI, 2014), foam density will typically fall somewhere in the region of 2 to 5 lb/ft^3. The setup for the foam generator used by Richway Industries (Janesville, Iowa) and shown in Figure E.1.a can be used to produce both low- and high-density foam using a simple process. First, a foam concentrate and water are added to the pressure container of the foam generator, and the mixture is stirred constantly. The foam generator, which uses electrical power, is then used to generate pressure within the container and produces foam.

The scope of the investigation in this project was restricted to manufacturing cellular grouts with a wide range of densities and identifying a cellular grout with a specific density that can be used as a grout in sliplined culverts.

In order to generate foam with a density that is suitable for an annulus void grout, the tests in this project were conducted on foams produced using all four types of foaming agents. A stable foam was produced by combining 4 oz. of foaming agent with 5 gallons of water. The densities of the generated foams were then obtained by weighing a predetermined amount of foam. The density was measured using three plastic graduated cylinders with a capacity of 1000 ml each, as illustrated in Figure E.1.b, and the average density was reported.

According to ASTM C796 and ACI 5283.3R-14, the minimum foam density standard can be satisfied by using a foam with density falling between 4.5 and 5.5 lb/ft^3. The average densities of all foams produced in this study were found to fall within this range.

Table E.3: Properties and Composition of Foaming Agents

Product Name	**DREXEL F.M.160™**	**AERLITE™**	**AERLITE-iX™**	**AERLITE-R™**
Type of foaming agent	Anionic/ non-ionic surfactant	Protein concrete foam concentrate	Synthetic concrete foam concentrate	Synthetic concrete foam concentrate
Physical State	Liquid	Liquid	Liquid	Liquid
Appearance/Color	Colorless to Yellow	Brown	Straw yellow	Straw yellow
Odor	Mild odor	Bland	Mild, pleasant	Mild, pleasant
pH	6.0 – 7.5	7.1	7.3	7.3
Freezing point (°F)	<32	2	N/N	N/N
Boiling point (°F)	212	No data available	No data available	No data available
Flashpoint (°F)	>200	128	126	126
Relative density (lb./gal.)	8.6	N/N	N/N	N/N
Specific Gravity	N/N	1.06	1.04	1.04
Water content	N/N	40% – 50%	45% – 55%	N/N
Anionic surfactant content	N/N	10% – 20%	15% – 25%	N/N
Amphoteric surfactant content	N/N	5% –15%	5% –15%	N/N
Anionic/non-ionic surfactant content	100%	N/N	N/N	N/N
Detergent content	N/N	1% – 5%	1% -5%	N/N
Isopropanol content	N/N	1% – 5%	1% – 5%	1 - 5%
Hexylene glycol content	N/N	1% – 5%	1% – 5%	1 - 5%
Glycerin content	N/N	<2%	<2%	1 - 5%
Ferrous sulfate content	N/N	0.1% – <1.0%	N/N	N/N
Zinc oxide content	N/N	0.1% – <1.0%	N/N	N/N
Ammonium alcohol (C6-10) ether sulfate content	N/N	N/N	N/N	10% – 30%
Cocamidopropyl betaine content	N/N	N/N	N/N	7% – 13%
Sulfonic ccids, C14-16-alkane hydroxy and C14-16-alkene, sodium salts	N/N	N/N	N/N	1% – 5%
Viscosity	No data available	No data available	No data available	No data available

Note: *N/N* = Not mentioned in the material data sheet.

(a) Setup for Foam Generator (b) Measuring Foam Density

Figure E.1: Preparation of Foam.

E.3 Foam stability

The stability of foam is influenced by a wide variety of factors, including the ambient temperature of the laboratory, the temperature of the mixing water, and the humidity. Due to the limited quantities of foam that were obtained for this project, only Drexel surfactant foaming agent was considered, and the stability test was conducted according to ASTM C940 (ASTM, 2016). As can be seen in Figure E.2, the tests involved filling three graduated cylinders with a capacity of 1000 mL with foam and obtaining the height of the foam at the start of the experiment, as denoted by (V_{fi}). Measures of the height were subsequently obtained at intervals of 5 minutes until the foam was dry (V_{ft}), which occurred after a total duration of 60 minutes). The volume of drain water (V_w) gathered at the bottom of the cylinder was also measured. The test scenarios for the stability tests are listed in Table E.4, and a schematic diagram showing the parameters measured in the tests is presented in Figure E.3.

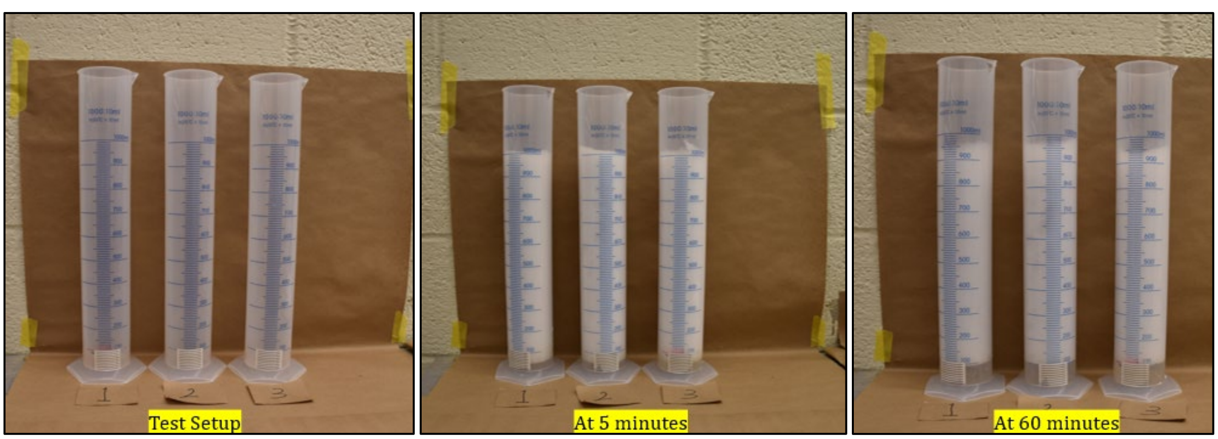


Figure E.2: Foam Stability Test: Test Setup, Foam Level at 5 Minutes into the Test, and Foam Level and Drain Water Present at 60 Minutes into the Test (*left to right*).

Table E.4: Different Conditions for Foam Stability Tests

Plan Test	**Description**	**Water Conditions**	**Storage Condition**
LL_4	Ambient Lab Conditions	Lab Temperature Water (68 °F to 72 °F)	Lab Temperature (68 °F to 72 °F)
LL_{16}	Ambient Lab Conditions	Lab Temperature Water (68 °F to 72 °F)	Lab Temperature (68 °F to 72 °F)
LC_4	Ambient Lab Conditions + High Humidity	Lab Temperature (68 °F to 72 °F)	Curing Room (68 °F to 72 °F, 99% Humidity)
LC_{16}	Ambient Lab Conditions + High Humidity	Lab Temperature (68 °F to 72 °F)	Curing Room (68 °F to 72 °F, 99% Humidity)
HL_4	Hot Solution + Ambient Lab Conditions	Hot Water (100 °F)	Lab Temperature (68 °F to 72 °F)
HL_{16}	Hot Solution + Ambient Lab Conditions	Hot Water (100 °F)	Lab Temperature (68 °F to 72 °F)
HH_4	Hot Solution + Storage at High Temperature (Oven heating)	Hot Water (100 °F)	High-Temperature (100 °F)
HH_{16}	Hot Solution + Storage at High Temperature (Oven heating)	Hot Water (100 °F)	High-Temperature (100 °F)

Note: Subscript 4 = 4 (oz) of foam solution; subscript 16 = 16 (oz) of foam solution.

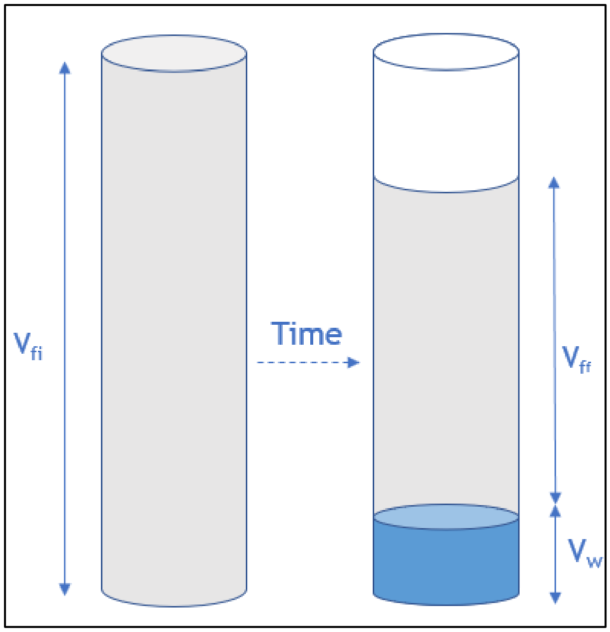


Figure E.3: Parameters Measured in the Foam Stability Test: Starting Height of the Foam (V_{fi}), Height of the Foam when Dry (V_{ft}), and Volume of Drain Water (V_w).

E.4 Mix Design

Since there are no standard guidelines for mixing cellular grout, mix proportioning begins with the selection of the unit weight or wet density for the mixture, the quantity of cement, and the water–cement ratio (w/c). Initially, some parameters for the material, such as the foam density, also need to be determined. It was found that the density of the foam might vary from one type of foam to another: the densities of foams made using DREXEL F.M.160™, AERLITE™, AERLITE-iX™, and AERLITE-R™ are 5.4 lb/ft^3, 4.6 lb/ft^3, 5.5 lb/ft^3, and 5.5 lb/ft^3, respectively. According to ACI 523.3R-14 (ACI, 2014), the air yield per volume of foam (ΦA) is typically around 0.95, the specific gravity of Type III cement is assumed to be 3.15, and the density of water is 62.4 lb/ft^3 at a typical room temperature.

To perform a proper calculation, it is necessary to obtain both the design density and the water-cement ratio (w/c). The design density of the cellular grout for this project was selected to be as low as 10 lb/ft^3 and as high as 75 lb/ft^3. Destiny increments were supposed to occur every 10 lb/ft^3 up to 40 lb/ft^3; above that, the density increments were increased by 15 lb/ft^3 because the quantity of foam added was smaller than 4 lb/ft^3. The water–cement ratio suitable for cellular grout was reported by Nambiar and Ramamurthy (2006) to vary between 0.2 and 0.6. Research on the influence of the performance — as indicated by the w/c ratio — on foamed concrete indicates that a low w/c (0.25 and below) may make the mixture too stiff, which in turn would cause the grout to not flow properly when placed in the annulus of the sliplined culvert. Conversely, a water-to-solids ratio that is too high, such as 0.6 or above, may cause the foam to separate from the mixture because the slurry becomes too thin to maintain the bubbles created by the foaming agent. According to Ruiwen

(2004), using a water-to-solids ratio of 0.5 in the mix design assures that the foam will be well combined with the cement slurry mixture. As a result, a value of 0.5 was selected to be used for the grout mixture in this project.

The following example demonstrates how to calculate the theoretical mixture proportions for a cellular grout mix prepared using C40 concrete (a commercial grade concrete mix with a wet density of 40 lb/ft^3) and DREXEL F.M.160™ foaming agent.

1) **Obtain material information**

   Specific gravity of Type III Portland cement (C_G) = 3.15

   Water density (γ_W) = 62.4 lb /ft^3

   Foam density (γ_f) = 5.4 lb /ft^3

   Air yield per volume of foam (ΦA) = 0.95

2) **Obtain other inputs**

   Target wet density of cellular grout (γ_c) = 40 lb /ft^3

   Water–cement ratio (w/c) **=** 0.5

3) **Perform calculations**

   Cement content $(C) = \frac{\gamma_c}{(1+(w/c))}$ = 26.7 lb /ft^3

   Water Content *(W)* = C × (w/c) = 13.3 lb /ft^3

   Air content **(*Av*)** $= 1 - \left(\frac{C}{(Gc \times \gamma_w)} + \frac{W}{(\gamma_w)}\right)$ = 0.7 ft^3

   Volume of foam $(V_F) = \left(\frac{Av}{\Phi A}\right)$ = 0.68 ft^3

   Weight of foam $(F) = V_F \, x \, \gamma_f$ = *3.7 lb*

   Adjusted weight of water $(W_{adj}) = W - F$ = *9.6 lb*

   Total density (γt) = $W_{adj} + C + F$ = 40.0 lb

4) **Verify that the total density (γt) is equal to selected wet density (γ_c): $\gamma t = \gamma_c$**

In the findings section (Section E 9.2.1.1), the theoretical mix design proportions in ACI 523.3R-14 (ACI, 2014) are compared to the mix proportions in the trial batch prepared as a part of this project.

E.5 Mixing Procedure

As illustrated in Figure E.4, the components were mixed in a 20-gallon plastic drum bucket. Initially, water and cement were mixed together using a handheld concrete mixing drill. This process continued until the lumps of cement were completely broken up and were mixed well with water. Next, the required amount of preformed foam was added to the wet cement slurry and mixed. This process continued until there were no visible signs of the foam on the surface of the slurry, indicating that the foam has been evenly dispersed and integrated into the mixture. It is essential, however, to avoid excessive mixing following the addition of foam, as excessive mixing has the potential to alter the density by removing foam bubbles and changing the consistency of the cellular grout.

Figure E.4: Addition of Foam to a Cement Mixture:
Before (*left*) and After (*right*) Addition of Foam.

E.6 Mix Proportions of Trial Concrete Cement Mixtures

Trial batches of cellular grout mixtures were prepared as a part of this project for properties testing. The mix proportions of mixtures with different densities are presented in Table E.5.

Table E.5: Mix Proportion for Cellular Grout Mixes

Mix Component	C10	C20	C30	C40	C55	C65	C75
Cement content Type III (lb/ft^3)	3	10.2	17	24	34	41.5	48
Water content (lb/ft^3)	1.5	5.1	8.6	12	18	21	25
Foam* (lb/ft^3)	5.5	4.7	4.4	4	3	2.5	2
Resulting design Density (lb/ft^3)	10	20	30	40	55	65	75

**Foam is defined as the theoretical amount of foam that is produced using a foam generator.*

E.7 Properties of Cellular Grout

In the laboratory, a number of different tests were conducted for each cellular grout mixture to determine the fresh and the hardened properties of the grout. The fresh properties included density, fluidity (efflux time), flowability, air content, and stability. Properties of the hardened grout included compressive strength, splitting tensile strength, shrinkage, water absorption, and oven-dry density. These tests were carried out in accordance with the applicable ASTM standards, as shown in Table E.6.

Table E.6: Methods for Testing Cellular Grout Mixtures

	Test	Test Standard
Fresh Grout Properties	Fresh density	ASTM C138
	Fluidity	ASTM C939
	Flowability/slump	ASTM D6103
	Air content	ASTM C138
	Stability test	ASTM C940
Hardened Grout Properties	Compressive strength	ASTM D4832
	Splitting tensile strength	ASTM C496
	Shrinkage	ASTM C596
	Water absorption	ASTM C796
	Oven dry density	ASTM C495

E.7.1 Fresh properties

E.7.1.1 As-cast density of cellular grout

It is common practice to ascertain the as-cast density, also known as the cast-wet density, at the construction location by weighing a tared container of a known volume filled with cellular grout in accordance with ASTM C796/C796M (ASTM, 2019). The density of the cast-wet material is determined using a cylinder that is 12 inches high and 8 inches in diameter. In general, cellular grout, unlike normal weight concrete, must not be compacted or vibrated, as this would alter the density of the grout. However, ASTM C796/C796M specifies that, during molding, the sides of the molds should be lightly tapped with a rubber mallet to ensure the container is completely filled. Any excess grout on the top is then scraped off using a strike-off plate before the cast density is determined. The acceptable tolerance for the cast-wet density is the design density ± 3 lb/ft^3. Figure E.5 shows a standard metal container filled with a test mixture of grout prepared as a part of this project.

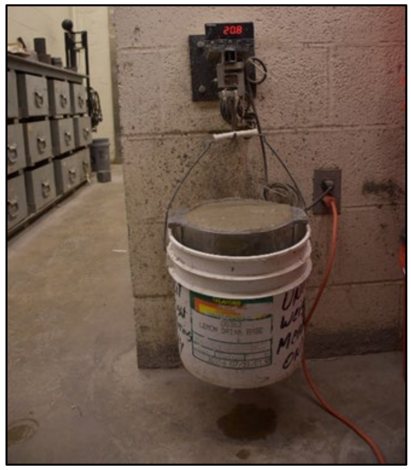


Figure E.5: A Cylinder of Grout in a Container for Measuring Wet Density.

The cast-wet density of the grout mixture can be calculated using Equation (E.1):

$$D = \frac{Mc - Mm}{Vm} \quad \text{(E.1)}$$

where D is the density of the cellular grout (in lb/ft^3), M_c is the mass of the cylinder filled with cellular grout (in lb), M_M is the mass of the cylinder only (in lb), and V_M is the volume of the cylinder (in ft^3).

E.7.1.2 Flowability of cellular grout

The flowability of cellular grout mixtures prepared as a part of this project were measured using flow consistency tests, which were conducted in accordance with ASTM D6103-17/D6103-17 (ASTM, 2017). In this test, the consistency of the cellular grout is evaluated both before and after the foam is added to the cement slurry in a plastic cylinder with a diameter of 3 inches and a height of 6 inches that is placed on top of a smooth, non-porous base measuring 36 inches × 36 inches × 0.5 inches, as shown in the setup in Figure E.6. After filling the cylinder with grout up to its top edge (brim), a rigid metal straightedge is used to strike off any excess grout to ensure that the top surface is even. After striking off, any spillage is removed from the base. Next, the cylinder is lifted rapidly (removed completely within 5 seconds) to allow the fresh mix to run freely over the smooth plate. ASTM guidance strongly suggests ensuring that the entire test (beginning with the filling of the flow cylinder and ending with its removal) be carried out continuously and will last no more than 60 seconds. At the end of the test, a measuring tape is used to determine the diameter of the largest extent of resultant spread of the grout (Figure E.7). Two measurements of the spread diameter along axes that are perpendicular to one another are obtained, and the final spread is computed by taking the average of the values from the two measurements.

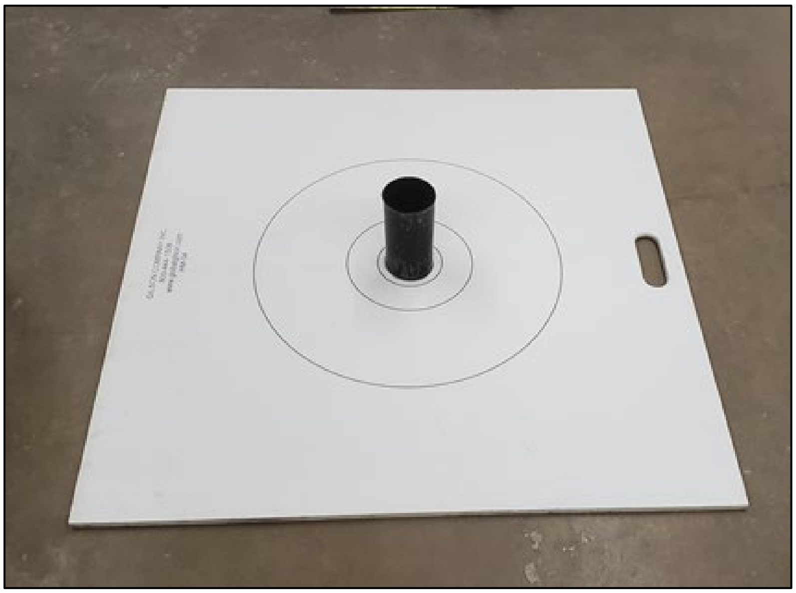
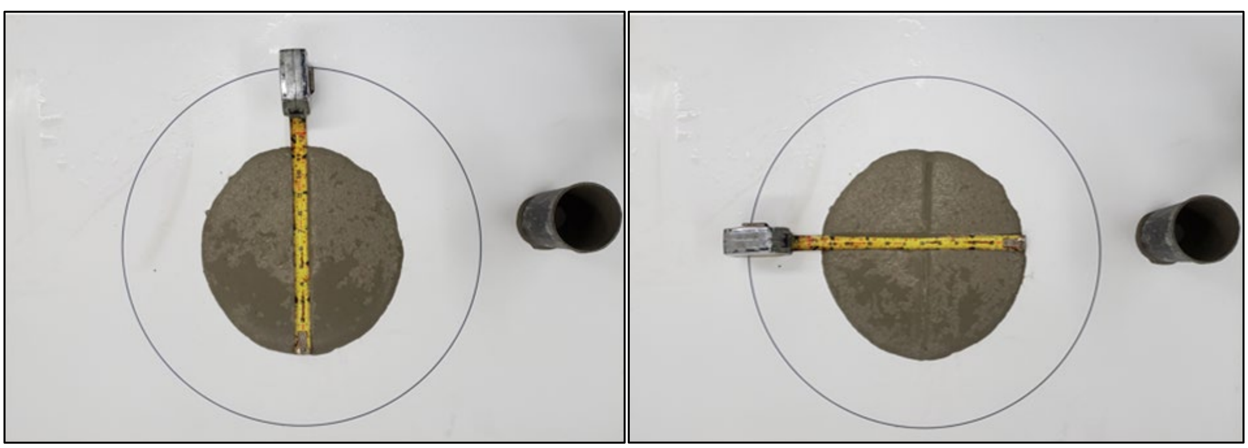


Figure E.6: Base plate for flow consistency of cellular grout.

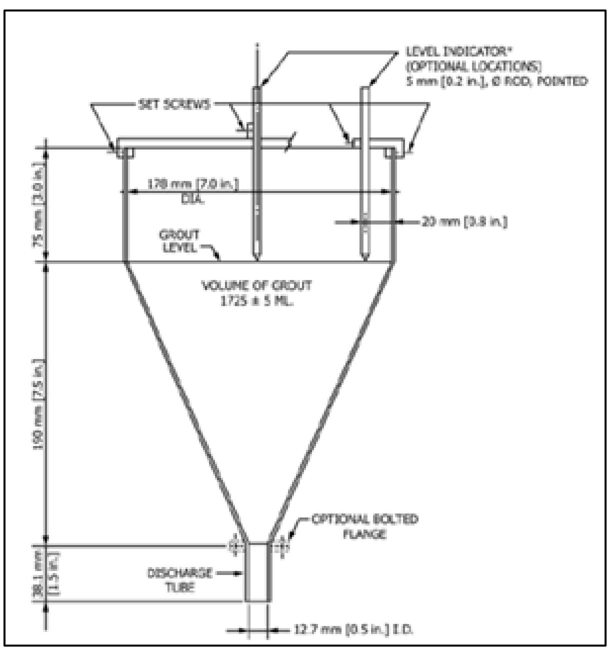


(a) Measuring spread diameter on one axis. (b) Measuring spread on second axis.

Figure E.7: Measuring spread diameters to calculate the flowability value for a fresh cellular grout.

E.7.1.3 Determining the flow of grout using the flow cone method

It is essential to monitor the flow of grout to ensure that the mix has adequate flowability, and the monitoring of the flow may be done either in the field or in the laboratory. In ASTM C939-16a "Flow of Grout for Preplaced-Aggregate Concrete" (ASTM, 2010), a standardized flow cone is used to determine the period of efflux of a given volume of cellular grout (as shown in Figure E.8.a). In the test setup, the flow cone is securely fastened to a frame to prevent vibration during the test. However, before using the flow cone for measuring grout flow, it is important to confirm that the setup yields accurate measurements. The ASTM standard requires that the length of time it takes for water to efflux as recorded by a stopwatch should be 8.0 seconds with a margin of error of ±0.2 seconds. Also, it is preferred to measure the efflux time of the water within one minute before the grout sample is poured into the cone to ensure that the flow cone would have some moisture in it. The discharge end of the tube is then blocked with a finger until the surface of the grout rises high enough to make contact with the point gage, as illustrated in Figure E.8.b, and a sample of the grout is then poured into the cone. Following that, the finger is removed at the exact moment the stopwatch is activated. The length of time that elapses after a sufficient volume of grout has flowed through the flow cone to the point where light is visible through the discharge tube is recorded; this time duration is referred to as the *efflux time* of the grout. While an efflux time of less than 35 seconds is acceptable for the purposes of the ASTM test, there is no standard guidance regarding the range of efflux time that should be utilized to indicate good flow or acceptance.



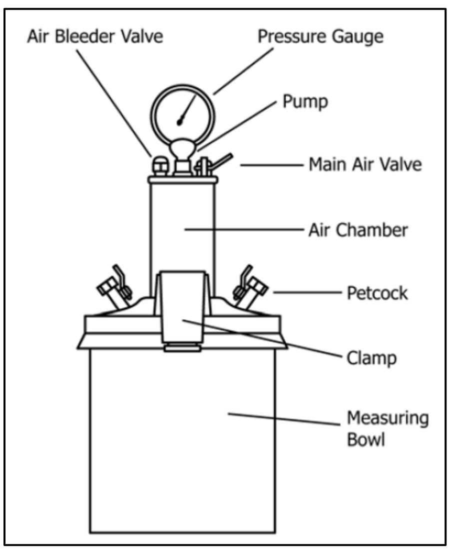
(a) Flow Cone Test Setup.

(b) Photo of Flow Cone Test.

Figure E.8: Flow Test for Cellular Grout per ASTM C939-16a (ASTM 2010).

E.7.1.4 Determining the air content

The air content of the freshly mixed cellular grout was determined according to ASTM C231-22a (ASTM, 2022). Figure E.9 depicts an air meter that meets ASTM specifications. The vertical air chamber was equipped with a measuring bowl and cap. The operational principle of this meter is to equalize a known volume of air at a known pressure in a sealed air chamber with the unknown volume of air in the cellular grout sample, with the dial on the pressure gauge calibrated in terms of percent air for the observed pressure at which equalization occurs. The measuring bowl was filled with cellular grout; no rodding was required for these fluid mixes. The measuring bowl's lid was then attached to the bowl. Next, the primary air valve between the air chamber and the measurement bowl was closed, and both cover holes were opened. Water was added through one petcock until water emerged from the opposite petcock. Next, the air chamber's air bleeder valve was closed, and the air was pumped into it until the gauge needle reached the beginning pressure line. The gauge hand was stabilized at the starting pressure line by pumping or bleeding out air as needed and lightly tapping the gauge. Finally, the main air valve between the air chamber and the measurement bowl was opened. The air content of cellular grout was displayed on the dial of the pressure gauge as a percentage of air. The pressure was released by opening both petcocks and removing the cap.



(a) Vertical Air Chamber.

(b) Conducting Air Content Test.

Figure E.9: Air Content Test of Cellular Grout per ASTM C231.

E.7.1.5 Assessing the stability of the cellular grout

The stability of a cellular grout refers to the grout's capacity to maintain its initial form or volume without collapsing even after it has reached its hardened state. Figure E.10 shows a photo of cellular grout that became unstable 24 hours after field casting. There are two main factors that can influence the stability of cellular grout: external factors such as the temperature of the surrounding environment and internal factors, which include the density and temperature of the fresh grout.

Considering that there is no universally accepted method for determining the stability of cellular grout, the test used to verify the foam stability, ASTM C940-16 (ASTM, 2016) with some modifications, was used to evaluate the stability of the grout mixture. In the modified method, cellular grout mixture was poured into a 1000-mL graduated cylinder until it reached a volume of 800 ± 10 mL (as shown in Figure E.11). Immediately after pouring, the initial volume of the grout specimen was measured and recorded. Measurements were also obtained at 60 minutes after placing the grout in the graduated cylinder and at 120 minutes after grout placement, and a final reading was taken at 24 hours after placement. The test plan for the stability tests conducted as part of this study, which is outlined in Table E.7, shows the specific mixing and curing conditions for each test.

Figure E.10: Cellular Grout Instability on Site (Jones et al., 2016).

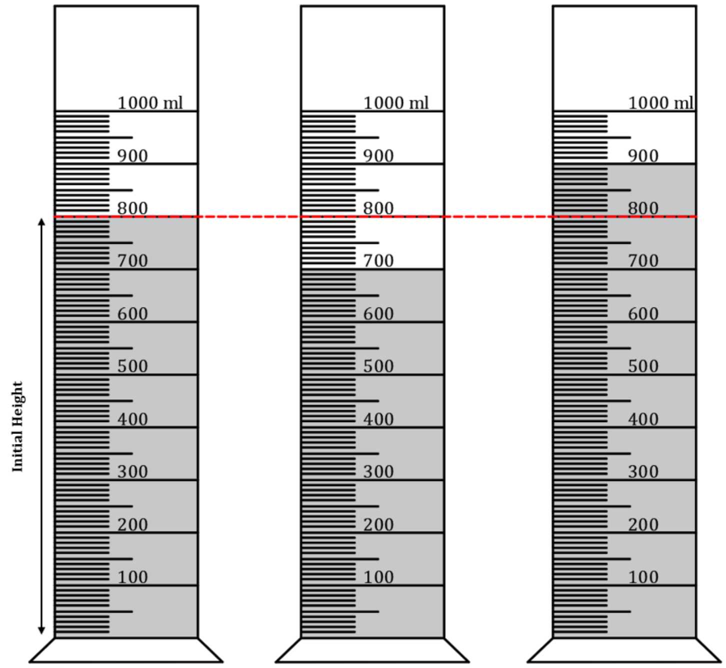


Figure E.11: Diagram Showing Stages of the Cellular Grout Stability Test: Initial Height of Grout, Collapse of Grout, and Grout Expansion (*left to right*).

Table E.7: Cellular Grout Stability Test Plan

Test Set ID	Mixing Conditions	Curing Conditions (24 hours)
CL	Cellular grout with cold water (65 ^{o}F)	Specimen cured at room temperature (70 ^{o}F)
CH	Cellular grout with cold water (65 ^{o}F)	Specimen cured at high temperature (100 ^{o}F)
HL	Cellular grout with hot water (100 ^{o}F)	Specimen cured at room temperature (70 ^{o}F)
HH	Cellular grout with hot water (100 ^{o}F)	Specimen cured at high temperature (100 ^{o}F)

E.7.2 Hardened Properties of Cellular Grout

The following subsections describe the tests used in this project to determine the hardened properties of the cellular grout.

E.7.2.1 *Casting and demolding of test specimens*

Proper casting of cellular grout specimens is essential for obtaining accurate results. To ensure that the specimens were properly produced, the cylinders and molds were sprayed with releasing oil before casting to prevent the grout from sticking to the mold. No vibration was necessary after pouring of the grout due to the self-leveling and self-compacting properties of the grout mixture. After pouring, the grout surface of each specimen was leveled to provide a smooth finish, and the specimens were allowed to set for 24 hours. After 24 hours, the specimens were removed from the molds using the appropriate tools and were placed in a curing chamber to complete the curing process.

E.7.2.2 *Water absorption and oven-dry density*

To determine the oven-dry density of cellular grout, three specimens are required. The grout specimens are first cured in the curing chamber for the standard amount of time for concrete, which is 28 days. After completing the curing process, the specimens are removed from the curing chamber and left at room temperature for at least an hour until the specimens are dry. The dried specimens are then placed in an oven heated to 230 ± 41 °F, as shown in Figure E.12.a. Weight measurements were made every 24 hours until the weight loss did not exceed 1% of the specimen weight over a 24-hour period. Once the weight had stabilized, the mass and dimensions of the oven-dried specimens were recorded. The density is determined by averaging the available data for the three specimens according to the procedure outlined in ASTM C495 (ASTM, 1999).

The following is a relationship that was proposed between the as-cast density and the oven-dry density by ACI 523.3 R-14 and Neopor (2012):

$$\gamma_D = \left[\gamma_f - 7.8\right] \tag{E.2}$$

where γ_D is the oven-dry density (in lb/ft^3) and γ_f is the cast-wet density (in lb/ft^3).

After determining the density of the oven-dried specimens, the specimens were cooled to room temperature. Once cooled, the specimens were immersed under water for at least 24 hours, as shown in Figure E.12.b. The temperature of the water was maintained at around 70 °F during the entire process. After that, the test specimens were removed after 24 hours and weighed to determine the wet mass. This process continued until the loss in weight did not exceed 1% per 24 hours. The water absorption and oven-dry density were determined by applying the following equations to the data:

$$Oven\ dry\ density\ \left(\frac{lb}{ft^3}\right) = \frac{Dry\ mass\ of\ the\ specimen\ (lb)}{Volume\ of\ specimen\ (ft^3)} \tag{E.3}$$

$$Water\ Absorption\ (\%)\ by\ volume = \frac{Volume\ of\ water\ absorbed\ in\ 24\ h}{Volume\ of\ specimen} \times 100 \qquad (E.4)$$

(a) Oven-drying of Cylinder Specimens.

(b) Specimens Immersed in Water.

Figure E.12: Oven Drying and Water Absorption of Cellular Specimens.

E.7.2.3 *Compressive strength*

ASTM D4832-16 “Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders” (ASTM, 2016) was used to determine the unconfined compressive strength of the cellular grouts in this project. Molds were used to create 3-inch × 6-inch specimens of cellular grout. In order to determine the compressive strength of each mixture, at least three specimens were evaluated. After 24 hours of casting, the specimens were removed from the molds and placed in the curing room to complete the drying process. As the relative humidity in the curing room was at least 95%, the samples were taken out of the curing chamber after 28 days and allowed to dry for 24 hours before testing. The unconfined compressive strength test was carried out with the assistance of an Instron 5569 universal testing machine (Figure E.13). Compressive loading at a rate of 10 lb/sec was applied to the cylinder specimens to meet the standards of ASTM D4832-16 and guarantee that the cylinder would not fail in under 2 minutes. This was accomplished by applying compressive loading to the specimens in a cylinder. The following formula was used to determine compressive strength:

$$C = \frac{P}{\frac{\pi D^2}{4}} \qquad (E.5)$$

where *C* is the compressive strength (psi), *D* is the nominal diameter of the cylinder (in.), and *P* is the maximum load applied to the specimens (lbs.).

Figure E.13: Test Setup for the Unconfined Compressive Tests.

E.7.2.4 *Splitting tensile test*

ASTM C496-17 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM, 2017) was used to perform tensile tests on the cellular grout. For this test, standard cylinders with a diameter of 6 inches and a length of 12 inches are used. At 24 hours after casting, the cellular grout specimens were removed from the molds and placed in a curing room with a relative humidity level of at least 95% to complete curing. After curing for 28 days, the specimens were removed from the curing room and were allowed to dry for 24 hours before being tested.

Specimens were placed in a horizontal position in a split tensile test frame (as shown in Figure E.14). Tests were performed to ensure that the specimens were positioned in the middle of the frame. Using an Instron 5569 universal testing machine, load was applied to one of the long sides of the specimen in order to generate tensile stress that was consistent throughout. The load was delivered in a steady manner at a uniform rate with no sudden shocks, using a loading rate of 10 pounds per second.

After measuring and recording the maximum load during the split tensile test, the following formula was used to determine the tensile strength for each specimen at the point of failure:

$$f_t = \frac{2 \cdot P}{\pi \cdot L \cdot D} \tag{E.6}$$

where f_t is the splitting tensile strength (psi), *P* is the maximum applied load (lbs.), *L* is the length of the cylinder (in.), and *D* is the diameter of the cylinder (in).

Figure E.14: Setup for Split Tensile Test.

E.7.2.5 *Drying shrinkage*

Tests were conducted following ASTM C596-18 “Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement” (ASTM, 2018) and ASTM C157-17 “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete” (ASTM, 2017) to determine the length changes of prism samples of cellular grout mixtures. For each test combination, four prism samples measuring 1 inch by 1 inch by 10 inches were prepared, as shown in Figure E.15. The prism samples were removed from their molds after a casting time of 48 hours.

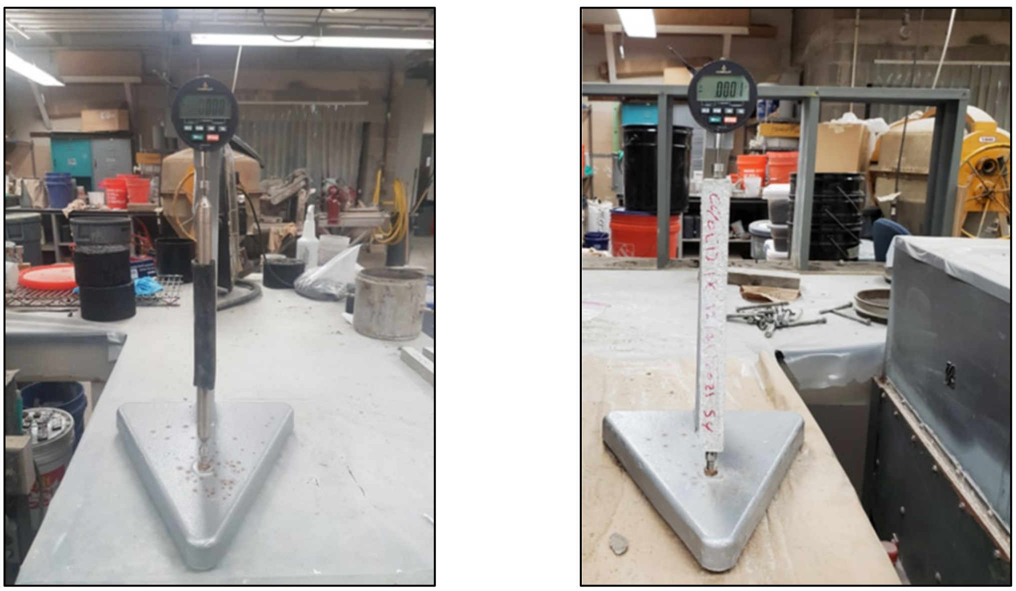
(a) Prism samples in molds. (b) Air curing of prism samples.

Figure E.15: Prism Samples used for Drying Shrinkage Measurements.

Due to the low strength and fragile nature of the material, several of the specimens broke as they were being removed from the molds, and the gauge studs did not attach to the samples as well as they should have. As a direct consequence, the shrinkage samples were allowed to cure for a full week before the first comparative measurements were obtained. After the first set of measurements, the samples were kept in a drying chamber at a relative humidity of 50% and a temperature of 73 °F. A length comparator equipped with a digital indicator (shown in Figure E.16) was utilized to collect data on a weekly basis throughout the next 28 days. After 28 days, there was no discernible change in any of the dimensions of the samples. Therefore, after taking the first reading from the comparator, the following formula is used to calculate the length change or overall net shrinkage of any specimen, regardless of its age:

$$\Delta L_x = \frac{CRD - initial\ CRD}{G} \times 100 \quad \text{(E.7)}$$

where ΔL_x is the length change (shrinkage) of specimen at any age (%), *CRD* is the difference between the comparator reading of the specimen and the reference bar at any age, and *G* is the gage length (which is 10 in).



(a) Invar Bar in Length Comparator. (b) Length Comparator with Grout Sample.

Figure E.16: Determination of the Change in Length of a Cellular Grout Sample per ASTM C157-17.

E.8 Parallel Plate Loading Tests

The primary objective of this experimental investigation is to examine how the use of a cellular grout mixture will impact the structural behavior of a sliplined corrugated steel culverts under loading. The structural load-carrying capacity of a sliplined culvert can provide evidence of the effectiveness of annual void grout. Consequently, several parallel plate loading tests on sliplined corrugated steel pipes with various grout formulations — including conventional grout made from controlled low-strength material (CLSM) and cellular grout — were carried out as part of this project. In addition, to investigate the effect of the presence and location of voids on sliplined culverts, parallel plate loading tests were conducted on a selection of sliplined culvert test specimens that had voids introduced at the crown or springline locations. This section includes details about these tests, including the preparation of the sliplined culvert test specimens, the setup for the parallel plate loading test, the testing equipment, and the materials used for the tests.

In this investigation, parallel plate loading tests were performed on six sliplined culvert test specimens. The host pipe and the liner materials were tested independently and separately to determine their individual load-carrying capacities. The load-deflection behavior for sliplined culverts, metal, and plastic pipes can be determined using standard test method ASTM D2412-21 "Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading" (ASTM, 2021). This evaluation can reveal various characteristics, including the load at a certain deflection, the pipe stiffness, and the stiffness factor. The sliplined culvert in this research was subjected to a vertical load using a universal testing machine with a load capacity of 300 kips, which satisfies the requirements of the ASTM D2412-21 standard. Initially, the host and liner pipes were tested separately using the same equipment. The travel speed of the crosshead was set to 0.25 inch per minute. The test setup for the parallel plate loading tests (shown in Figure E.17) included two parallel steel bearing plates that were used to apply the load to the specimen. The plates were 6 inches wide, 1/2 inch in thickness, and 15 inches in length parallel to the specimen, and they met all the requirements for flatness and smoothness required by the ASTM standard. During the test, the changes to diameters of the specimens were measured using digital dial gauges that were either parallel to or perpendicular to the loading direction. These gauges conform to ASTM D2412-21 and have a range from 0 to 2 inches with a precision of 0.0005 inches (as per the ASTM standard, the instrument needed to be accurate to the nearest 0.010 inch).

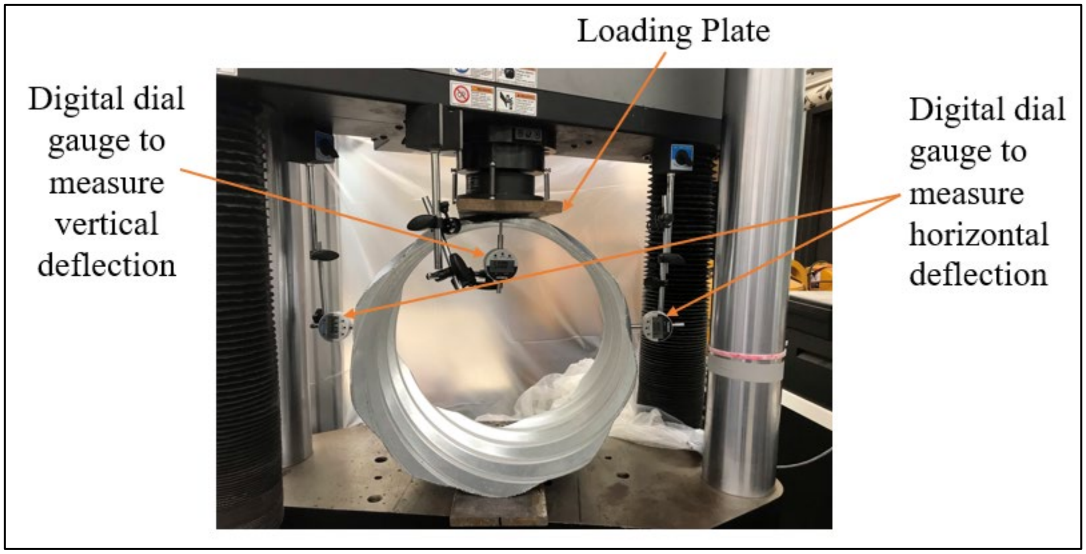


Figure E.17: Parallel Plate Loading Test of a Corrugated Steel Pipe.

E.8.1 Pipe and Grout Materials

E.8.1.1 *Host Pipe and Liner Pipe*

The host pipe and the liner pipe used for the sliplined culvert test specimens (shown in Figure E.18) were made from zinc-coated (galvanized) corrugated steel pipe that satisfied the specifications for corrugated steel pipe as specified in ASTM A929-18 (ASTM, 2018) and AASHTO M 218 (AASHTO, 2003). The host pipe had a nominal diameter of 18 inches, while the liner pipe had a nominal diameter of 12 inches. The pipes had a wall thickness of 14 gage (2 mm), and the nominal corrugation dimension was $2\text{-}{}^{2}/_{3}$ inches with a spiral pitch of ½ inch. The pipes were made from a flat steel sheet with a tensile strength of 45 ksi, a yield strength of 33 ksi, and an elongation of over 2 inches (about 20%). The pipe was sourced from a local company, WinWater of Akron; the pipe was supplied in a length of 20-foot in each diameter. The host pipe and the liner pipe were cut into 12-inch-long segments, which satisfied the requirements set out by the ASTM D2412-21 standard for the parallel plate loading tests.

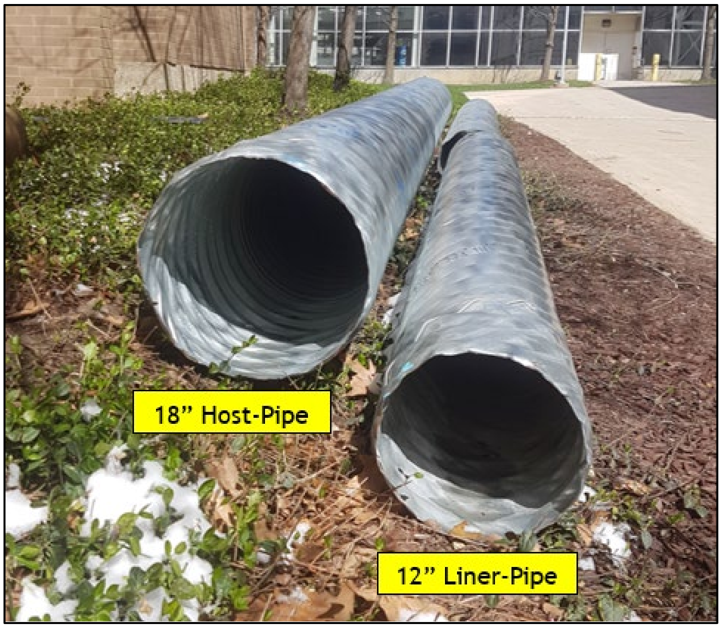


Figure E.18: Galvanized Corrugated Steel Pipes used as a Host Pipe and a Liner Pipe.

E.8.1.2 *Grouts*

Two types of grouts were employed in this experiment. The first, Mix A, is a typical ODOT CLSM grout. The second grout is a cellular grout made from a C40 mix that was developed during this project. The mix proportions and the mechanical properties of both grouts are presented in Table E.8. The parallel plate loading tests were performed on sliplined culvert specimens grouted with these grouts in order to examine the influence of compressive strength, shrinkage, and voids at various locations on the culverts.

Table E.8: Grouts Mix Design for Parallel Plate Test

CLSM (Mix A)								
Cement (lb/ft^3)	**Fly Ash**	**Fly Ash (lb/ft^3)**	**Fine Aggregate Type**	**Fine Aggregate (lb/ft^3)**	**Water (lb/ft^3)**	**Water/ Binder**	**Density (lb/ft^3)**	**Compressive Strength (psi)**
1.85	Class F	9.25	No. 4 (100% Passing)	107.7	18.5	1.67	123	92

Cellular Grout (C 40)					
Cement (lb/ft^3)	**Water Content (lb/ft^3)**	**Foam (lb/ft^3)**	**Water/ Cement**	**Design Density (lb/ft^3)**	**Compressive Strength (psi)**
24	12	4.4	0.5	40	479.3

E.8.2 Parallel Plate Test Configuration

In this project, three types of sliplined culvert test specimens were studied (Figure E.19). The first is a sliplined culvert that is completely solid with no voids (Type I). The second sliplined culvert type has a void at the crown location with a gap of about 2 inches between the host pipe at the crown and the liner pipe at the crown (Type II). The third culvert type has 2-inch voids at the springline positions (Type III). Table E.9 presents summary of the specimens tested, including the grout mixture type and the void status.

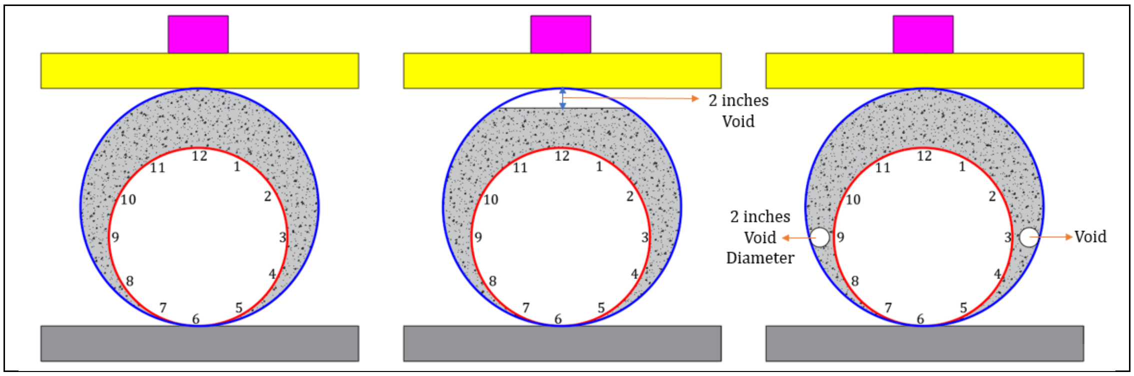


Figure E.19: Illustration of Parallel Plate Test Configurations:
Type I: No Voids (*left*), Type II: Void at the Crown Position (*center*),
and Type III: Voids at the Springline Positions (*right*).

Table E.9: Configuration of Parallel Plate Tests on Rehabilitated Pipe

Void Status	Grout Mix	No. of Samples
No Voids	Mix A	2
No Voids	C 40	2
Voids at Crown	C 40	1
Voids at Springline	C 40	1

E.8.3 Sliplined Culvert Test Specimen Preparation

The method for preparing the host pipe and liner for the sliplined culvert is shown in Figure E.20. First, 20-foot-long corrugated metal pipes were cut into 1-foot lengths. Next, one end of the host pipe was covered in plastic to prevent grout from leaking, and the host pipe was placed in an upright position with the test specimen's end wrapped with plastic at the bottom. The liner pipe was then installed in the host pipe in the same configuration as in an actual culvert, with the liner pipe located close to the wall of the host pipe at the 6 o'clock clock position. Lastly, sand was placed into the liner pipe to stabilize it when filling the annular area between the host pipe and liner pipe. Once the liner pipe was stabilized, the annular space was filled using the selected grout mix (Figure E.21).

(a) Cutting the host pipe.

(b) Wrapping the pipe end with plastic.

(c) Prepared host and liner pipe.

Figure E.20: Preparation of Host Pipe and Liner for Grouting.

Figure E.21: Filling Annulus Voids with C40 Cellular Grout: Pouring the Grout (*left*) and Smoothing the Grout at the Surface (*right*).

Voids in the samples were simulated by attaching a 2-in.-thick piece of Styrofoam at the crown of the host pipe (Figure E.22) and/or attaching two 2-in.-diameter cardboard tubes with a length of 12 in. to the host pipe at the springline (Figure E.23).

Three days after casting, the Styrofoam and tubes were removed from the test specimens to create the necessary void(s) (Figure E.24). The culvert specimens were then moved to a curing chamber with a minimum of 95% relative humidity, where they were left to cure for 28 days (Figure E.25). After 28 days of curing, parallel plate load tests were conducted on each culvert test specimen.

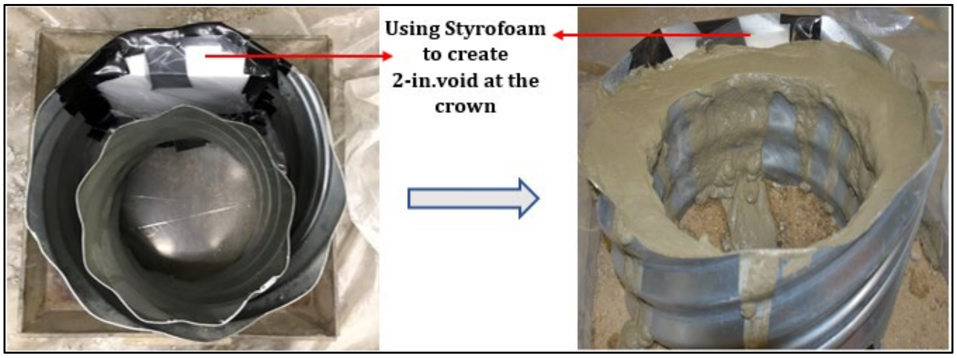


Figure E.22: Preparation of Crown Void in the Sliplined Culvert Test Specimen.

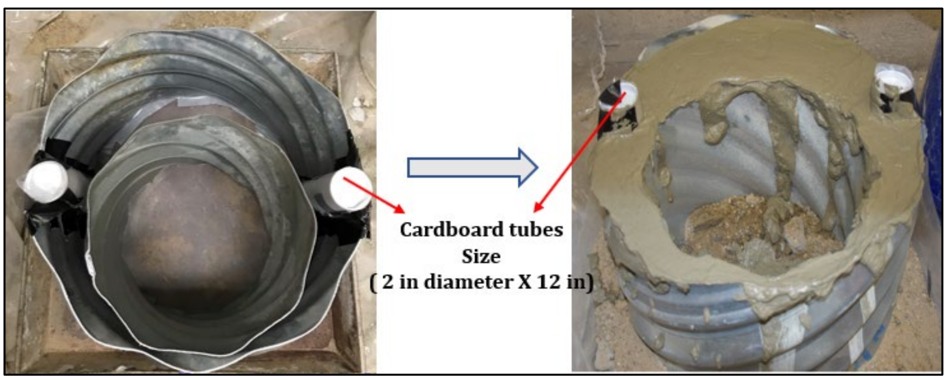


Figure E.23: Preparation of Springline Voids in the Sliplined Culvert Test Specimen.

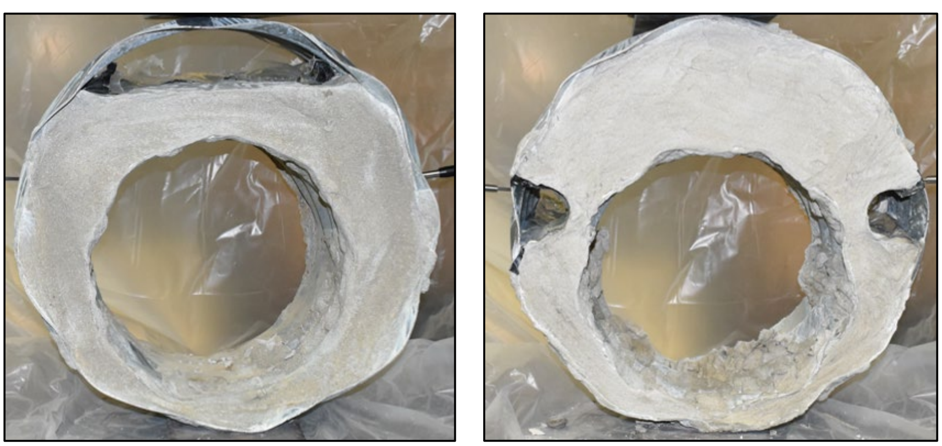


Figure E.24: Culvert Samples with Voids at the Crown (*left*) or Springline (*right*).

Figure E.25: Sliplined Culvert Samples in the Curing Room.

E.9 Results of Tests to Determine the Properties of Fresh Cellular Grout

This section describes the laboratory results of tests to identify the properties of the cellular grout mixture as well as a discussion of the test results, focusing primarily on the fresh and hardened properties of the grout material. The findings of these tests were subsequently used for identifying the optimum mix proportions for a cellular grout mixture. In addition, the results of parallel plate tests carried out on the sliplined culverts are also provided in this section. The parallel plate test results aided in providing an understanding of the effect of grout strength and the position of the voids within the annulus on the load-carrying capacity of sliplined culverts.

E.9.1 Foam results

E.9.1.1 *Foam Density*

The foam density results for the four foaming agents considered in this project are shown in Figure E.26. The foaming agents have different properties, as two are a synthetic base, one is a protein base, and one is a surfactant. Therefore, it was necessary to fix the dosage of the agents used in producing the foams. Through trial and error, it was found that mixing 4 oz. of a foaming agent with 5 gallons of water in the foaming machine would provide a foam with a density ranging from 4.6 to 5.5 lb/ft^3. The minimum densities of the resulting foams were found to satisfy the foam density requirements for producing cellular grout given in ASTM C796 and ACI 5283.3R-14. AERLITE™ has a density of 4.6 lb/ft^3, which is 16.4% lower than that of AERLTE- iX™ and AERLITE-R™. This lower density might be due to differences in water content (as indicated in Table E.3): AERLITE™ has a water content of about 40–50%, while AERLTE-iX™ has a water content of about 45–55%.

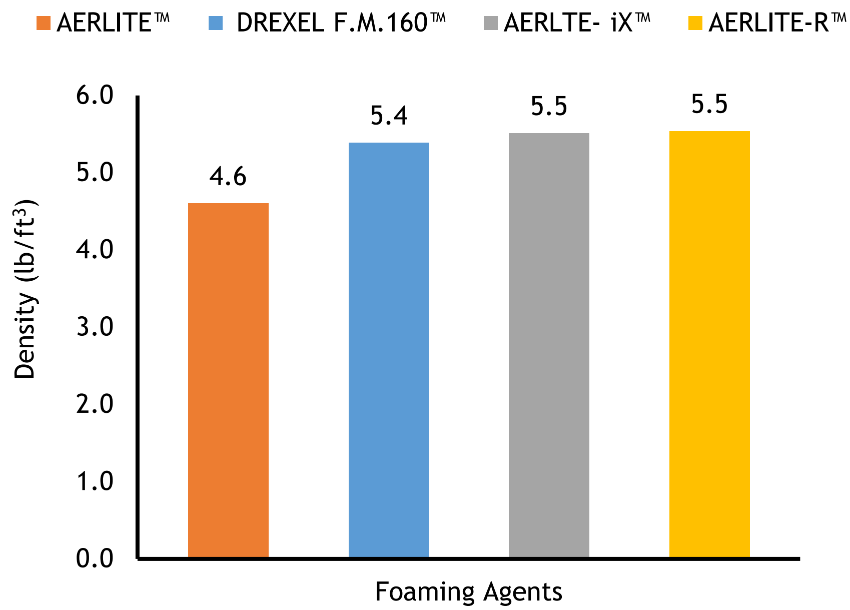


Figure E.26: Foam Density for Four Foaming Agents

E.9.1.2 *Foam Stability*

The tests results for the stability of the foams produced using the four foaming agents in various environments are presented and discussed in this section. When foam is poured into a cylinder that holds 1,000 milliliters, the foam will have an initial volume, denoted as Vf_i, that occupies about 1,000 milliliters (Figure E.27). As water drains from the foam and collects at the bottom of the graduated cylinder, the volume of the foam is reduced. The findings regarding the stability of the foam are described by two measures: the volume of drained water (Vw) produced under various scenarios and the final volume of the foam without drain water (Vf_f).

The drain water may be seen during the first five minutes of the experiment (see Figure E.28a). Cases HH4, HH16, HL4, and HL16 were found to have the greatest amount of water drain. The amount of drained water varied between 77 and 88 milliliters. This is because the foam was either prepared or maintained at a high temperature, which would reduce the foam's total volume by about 9% in just 5 minutes despite the fact that the foam dosage was increased from 4 oz to 16 oz. However, raising the foam dose from 4 oz to 16 oz has far less of an impact on the drain water, and this is especially true when the temperature is high. In other instances, when the foam was not exposed to high temperatures, the amount of drain water collected was much lower. For example, in case LC4, it was seen that the drain water was around 50 mL, while raising the foam dosage to 16 oz (as in case LC16) appears to help in reducing drain water (to 40 mL). This increase in drain water may relate to putting the prepared foam in a humid environment where spray water increases the foam's water content. Figure E.28 (b) shows that the volume of drain water may grow dramatically when the prepared foam is left for more than 15 minutes. Cases LL4 and LL16, for example, had between 33%

and 43% more drain water when compared to 5 minutes. Cases LC4 and LC16 demonstrate only a 27% and 31% increase, respectively, in the total volume of drain water. On the other hand, the drain water proportion was lower in HL4, HL16, while for HH4 and HH16, it was less than 13%. When performing the test for 60 minutes, as indicated in Figure E.28(c), it can be seen that HL4, and HL16 had less drain water (which had 8% on average) as compared to LL4, LL16, and LC4 (which had 14% on average).

Not only does the drain water (Vw_f) have the ability to reduce the volume of the foam, but the foam's initial height (Vf_i) may also alter the foam volume over time and under different situations. Figure E.29 shows the foam volume as a function of time. After the test had been conducted for 5 minutes, HL4 had a decrease in foam volume of 112 mL, but HL16, in which the foam dosage was raised to 16 oz, only had a reduction in foam volume of around 100 mL. On the other hand, when the foam was heated to a high temperature, as in HH4 and HH16, the volume was reduced by an average of 104 mL. This value is very similar to the average value found in HH4 and HH16. Other instances have a volume less than 60 milliliters. At 15 minutes after completion of the test, the foam volume decreased from 1,000 mL to an average of 579 mL, as shown in Figure 29(b), which shows that HH4 and HH16 exhibited the most significant decline of all the instances when the reduction occurred. In addition to this, after 60 minutes, HH4 and HH16 show a significant decrease, to the point where there is essentially no foam visible in the graduated cylinders (as seen in Figure E.30(c)). The inference that can be made from this particular experiment is that managing the temperature throughout the preparation of the foam may be more effective in maintaining the original volume than increasing the dose of foam. Therefore, it is essential to avoid preparing the foam at high temperatures (e.g., 100 ^{o}F) or mixing the foam dosage with high-temperature water, and/or storing the prepared foam at high temperatures to avoid further collapse of the foam volume before mixing it with the cement slurry. Avoiding high temperatures in foam preparation and adding foam to a slurry which is at a low temperature will ensure that the foam remains stable.

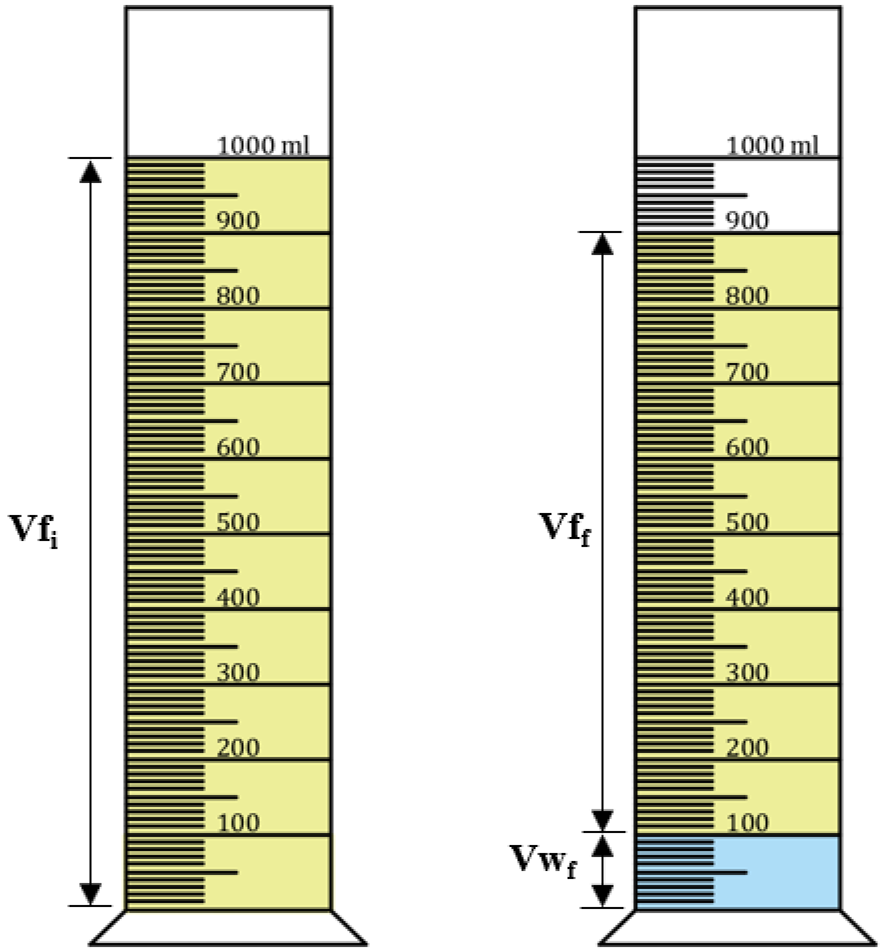
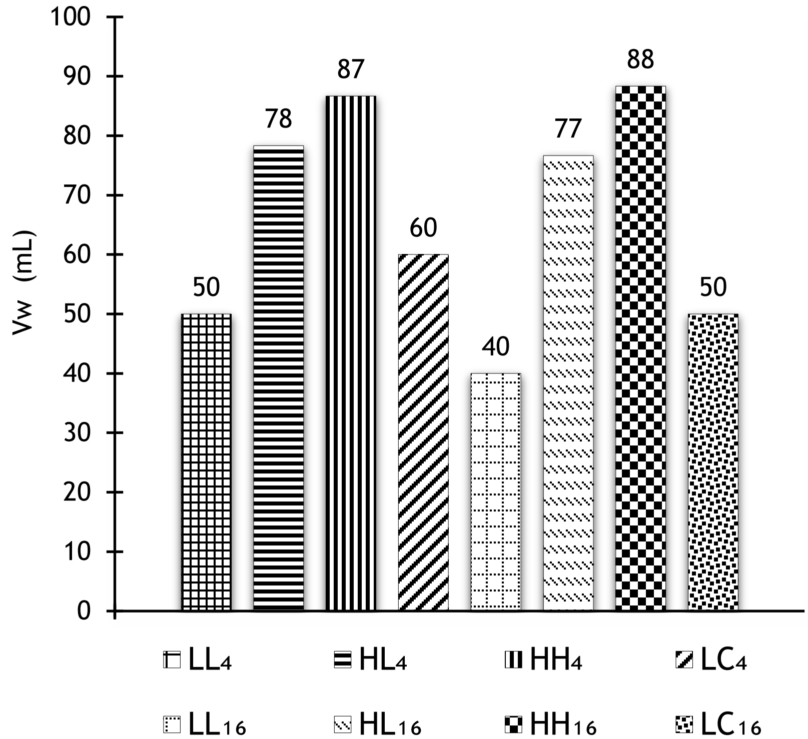
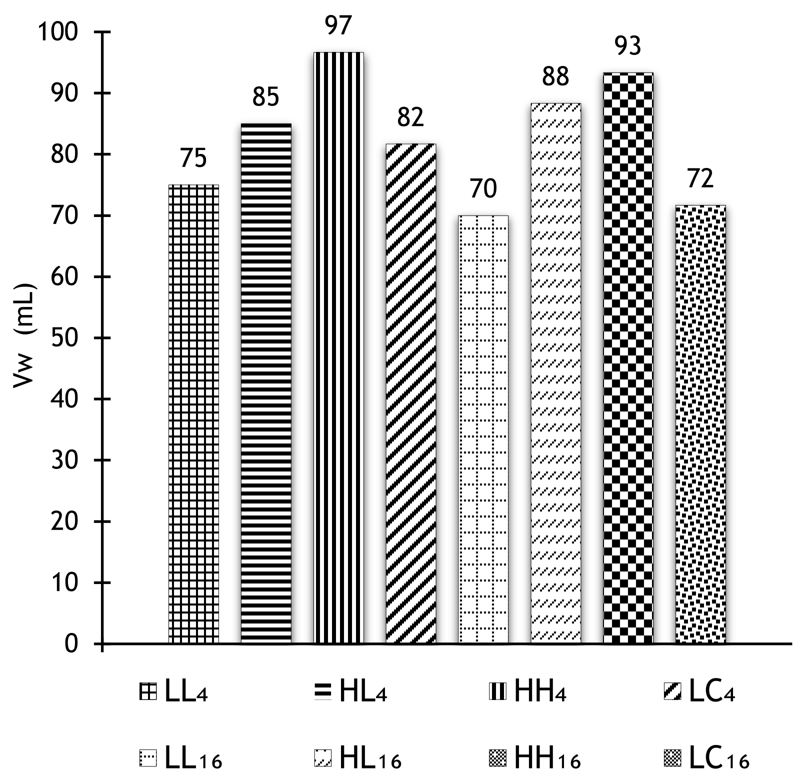


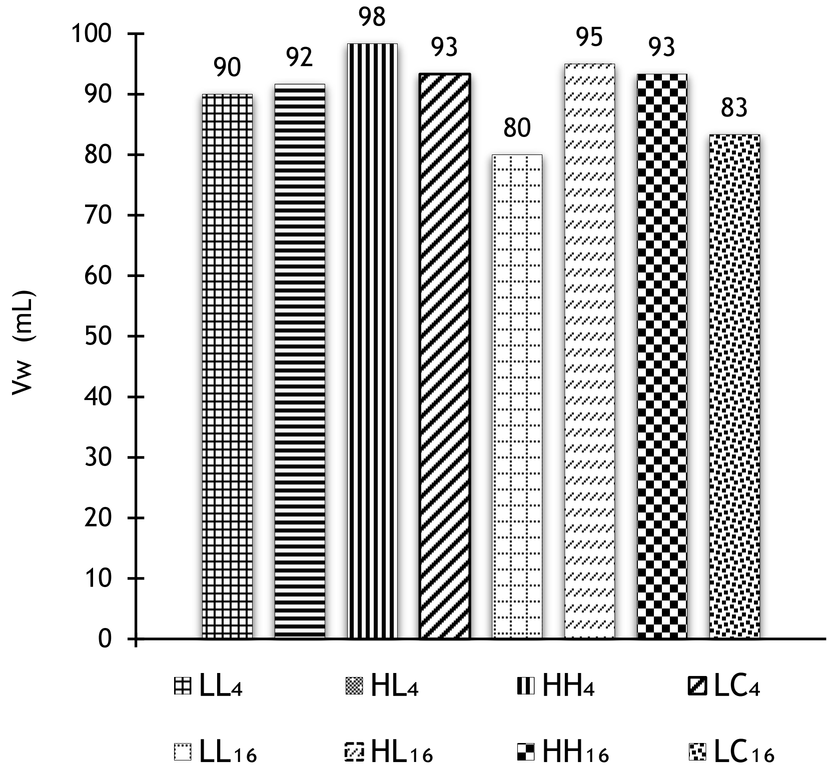
Figure E.27: Foam Stability Measurements:
Initial Volume (*left*), Final Volumes of the Foam and Drain Water (*right*).



(a) : 5 Minutes

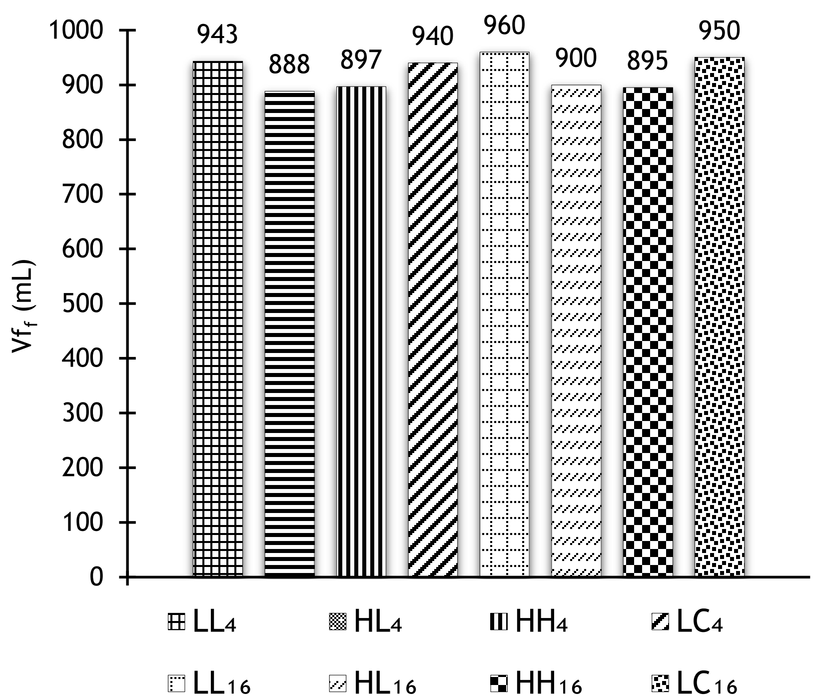


(b) : 15 Minutes

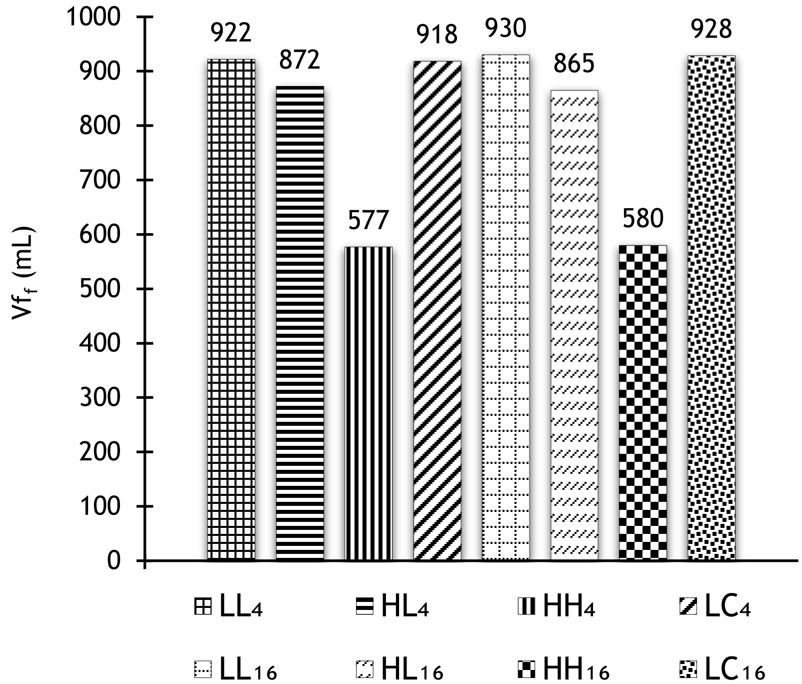


(c) : 60 Minutes

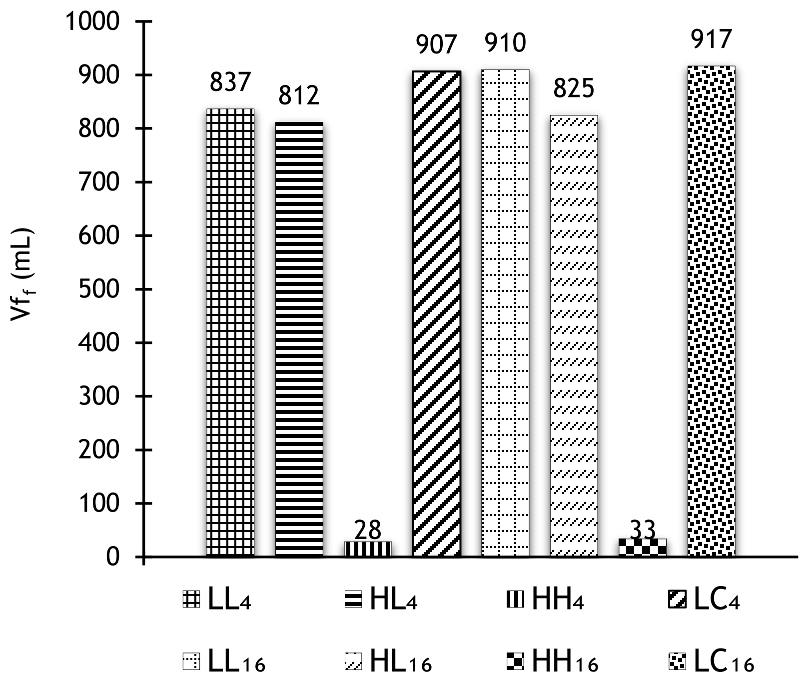
Figure E.28: Volume of Drain Water Over Time.



(a) : 5 Minutes



(b) : 15 Minutes



(c) : 30 Minutes

Figure E.29: Volume of Foam Over Time: (a) at 5 min, (b) at 15 min, (c) at 60 min.

(a) 15 minutes (b) 30 minutes (c) 60 minutes

Figure E.30: Progress of Foam Collapse Over Time for Case 3:
(a) at 15 min, (b) at 30 min, (a) at 60 min.

E.9.2 Test results for properties of cellular grout

After mixing all the ingredients of the cellular grouts, wet and hardened grout tests were done on the cellular grouts to ensure the grouts satisfy the ASTM requirements. These tests can be classified into fresh and hardened properties, and their results are discussed in the following sections.

E.9.2.1 *Fresh Properties*

E.9.2.1.1 Mix proportions

At the beginning of the cellular grout mix design process, mix proportions following ACI 523.R-14 were used to determine the mix proportions of the cellular grout. Therefore, according to ACI, the mix proportion can begin with selecting the unit weight (cast-wet density), the cement content, and the water-cement ratio (w/c). However, it was found that after preparing mixes with different densities (from C10 to C20 lb/ft^3), the cast-wet densities were outside of the upper limits and lower limits, as shown in Figure E.31(a). ASTM C869/C869M standard requires that the cast-wet density be within ± 3 lb/ft^3 of the design density). Therefore, some adjustments were made to the ACI mix proportions to make the cast-wet density fall within the recommended range. The adjustment was made by changing the mix proportion (particularly the w/c). Figure E.31(b) shows that the modified mix proportions fall within the acceptance limits. By comparing the w/c ratios for the mixes prepared using the ACI 523.R-14 design with those when using batch mix design (Figure E.32), it can be seen that a w/c ratio of 0.5 would lead to acceptable results.

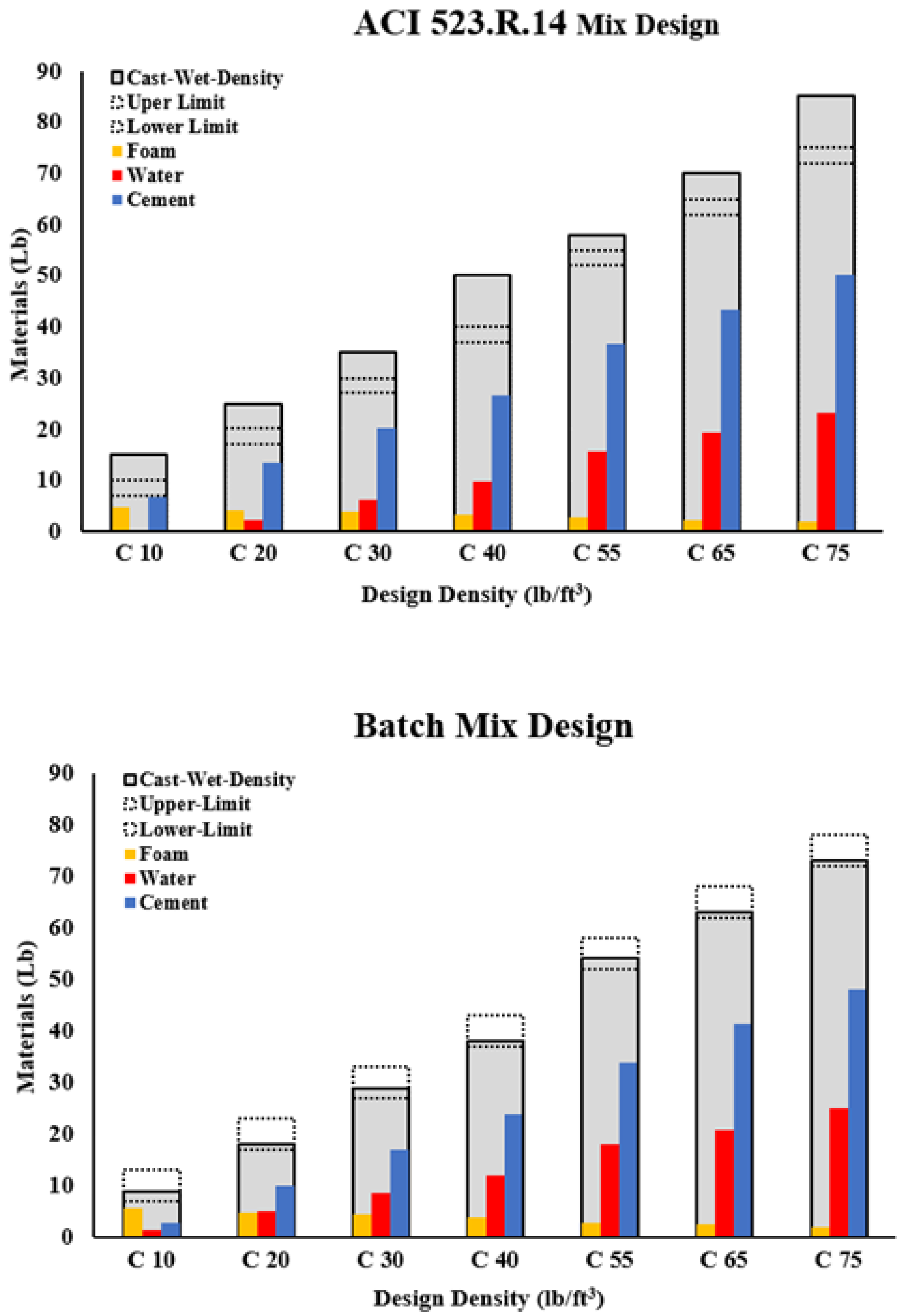


Figure E.31: Mix Design Proportions of Cellular Grout Mixtures When using ACI 523.R.14 (*top*) and Batch Mix Design (*bottom*).

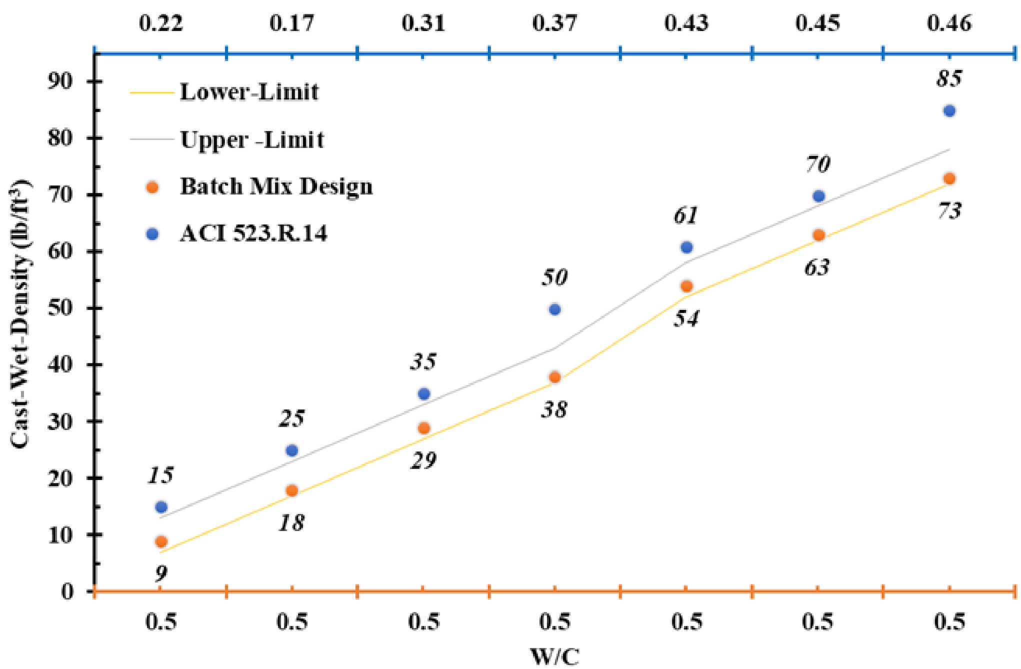


Figure E.32: Comparations of Water/Cement ratio vs. Cast-Wet Density for Grout Mixtures Produced using ACI 523.R.14 and Batch Mix Design.

E.9.2.1.2 Volume change

In general, when foam is added to a cement slurry, it increases the volume of the mix. However, there is a need to quantify the volume of the mix before and after adding the foam to facilitate comparisons between foaming agents. The volume of the slurry mix can be calculated using the dimensions of the mixing container, measuring the height of the slurry mix in the container (before adding foaming agents), and measuring the height of the mixture after the foam is added to the slurry mix. Figure E.33 shows the volume of each mixture before and after the addition of foam, from a low density of 10 lb/ft^3 to a high density of 75 lb/ft^3. It can be observed that adding foam to the slurry mix can increase the mix volume from 0.1 ft^3 to 1.51 ft^{3,} as in the case of C10. At high density (75 lb/ft^3), the increase in volume seems to be lower since a smaller quantity of foam is added to the slurry mix. Even though various foaming agents were considered, the influence of the foaming agent seems to be negligible, since the results are almost identical after the foams were added to the slurry mix.

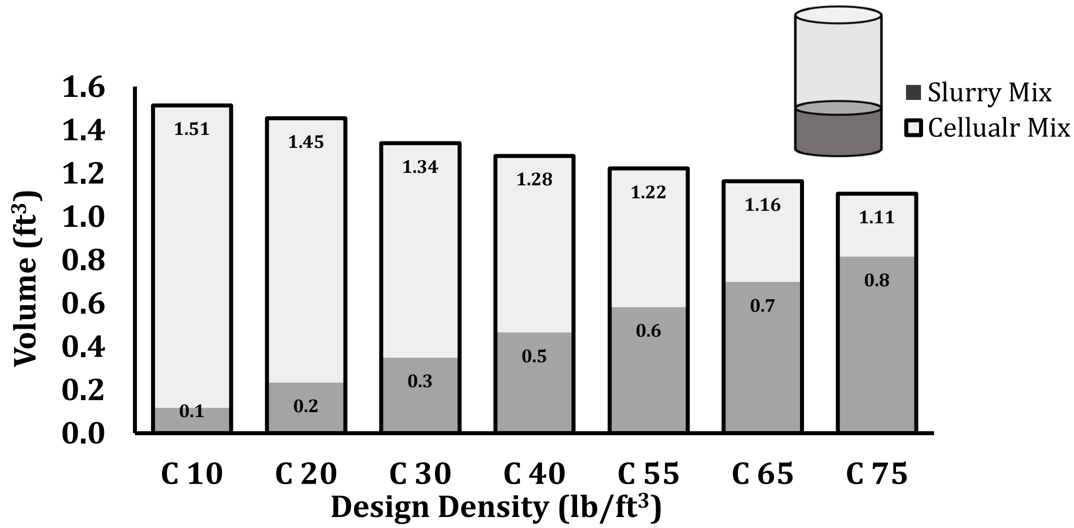


Figure E.33: Volume Change of Cellular Grout.

E.9.2.1.3 Air content test

The foam contents of cellular grouts with densities ranging from 10 lb/ft^3 to 75 lb/ft^3 can range from 87% to 36%. Figure E.34 depicts the plastic density (cast-wet density) on the y-axis versus plastic air on the x-axis, and another x-axis represents the foam percentage. The trend line can be generated from the collected data from foams of various densities and different types of foam. The trend line represents a linear relationship between plastic density, air content, and foam percentage ($y = -0.9594x + 104.74$). The trend line can represent a linear equation with an R^2 value of 0.965. The results show that the plastic air content of cellular grout as measured using a vertical air chamber appears to have a reasonable correlation with the foam volume of the cellular grout, even though at a high percentage of foam, such as 10 lb/ft^3, the foam accommodates approximately 87% of the total volume of the mix. Moreover, mixing cellular grouts with various foaming agents (such as synthetic-based agents, protein-based agents, or surfactants) has only a minimal effect on the plastic air content of cellular grouts at the same plastic density. This minor difference may be due to the experimental accuracy of the dial gauge of the air meter device. In general, it can be concluded that as the plastic density increases, the air content decreases.

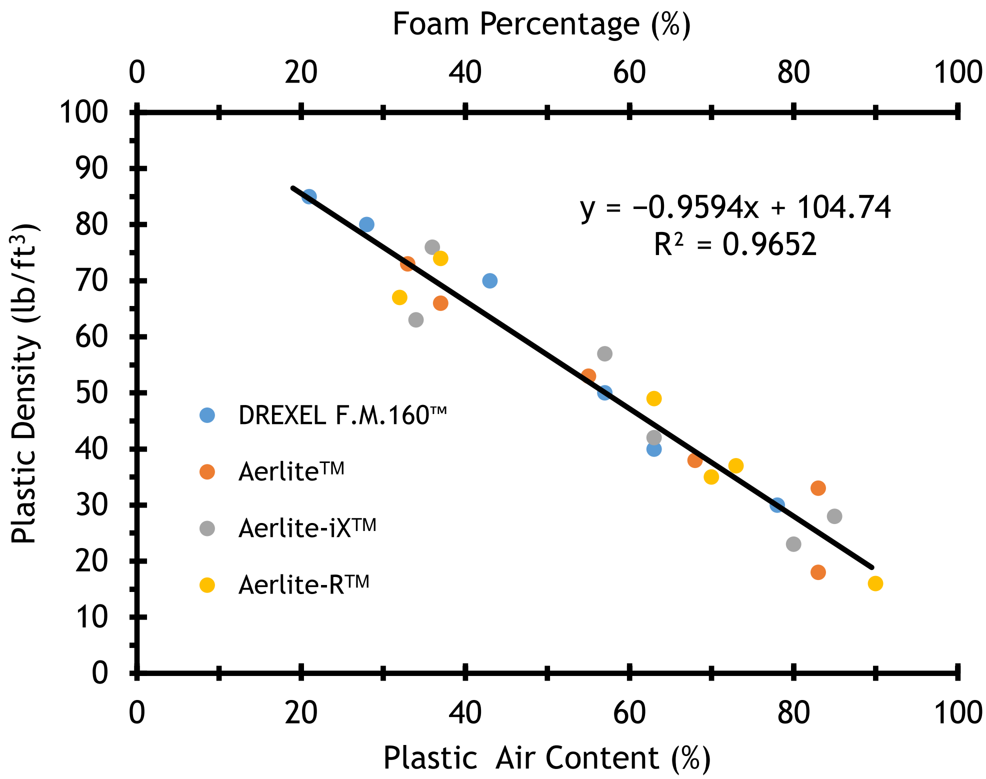


Figure E.34: The Influence of Foam Type on Plastic Air Content.

E.9.2.1.4 Flowability

Casting cellular grouts with the same density but different foaming agents can result in different spreading behaviors, as shown by the results presented in Figure E.35. The graph shows that adding a foaming agent to the slurry mix can enhance the spread of the mix regardless of the type of foaming agent. For example, C40 slurry mix (before adding foam) showed a spread of only 6.25 inches, whereas the spread increases to 8 inches by adding 69% of foam to the slurry mix using a surfactant (Drexel F.M.160TM) as a foaming agent. Figure E.36 shows the spread before and after adding foam to the C40 mix. Further improvement of spread can be observed using synthetic foaming agents (Aerlite-iXTM and Aerlite-RTM) or a protein foaming agent (AerliteTM), leading to a better spread (10.25, 10.5, and 11.25 inches, respectively). Nearly the same trend in overall densities and a better spread were observed for these foaming agents than for the surfactant. ACI Committee 229 (2013) suggests that meeting a spread diameter of at least 8 inches will allow good grout flow. All foaming agents considered in this project satisfy the minimum requirements of spread except for C30 and C20 mixed with surfactants. However, the spread effect seems less extensive when the cellular grout density is greater than 65 lb./ft^3, since the foam amount in the mix design is less than 45%.

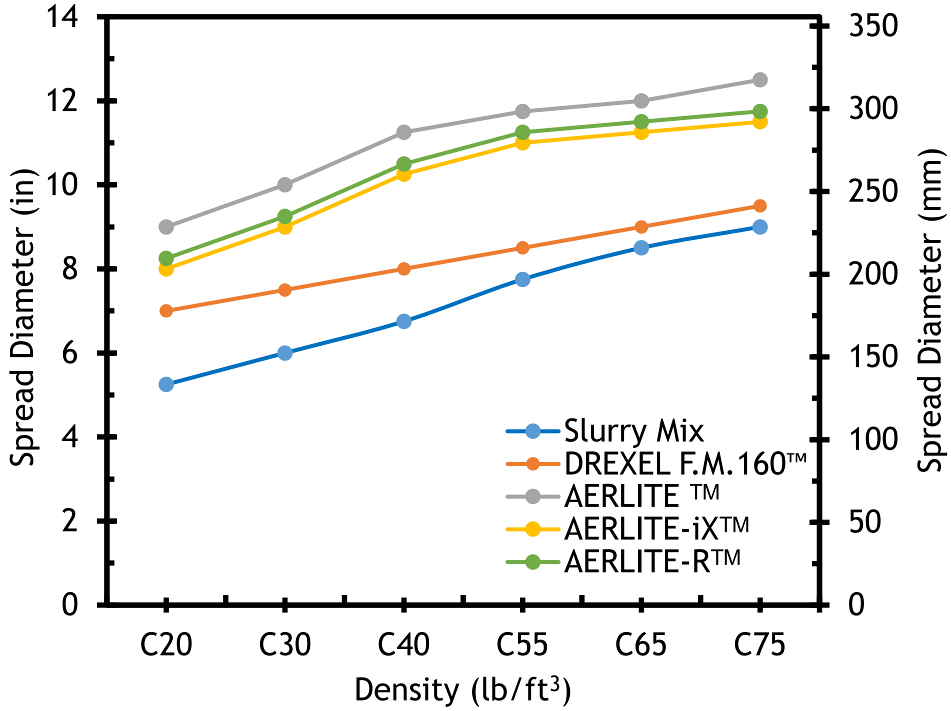
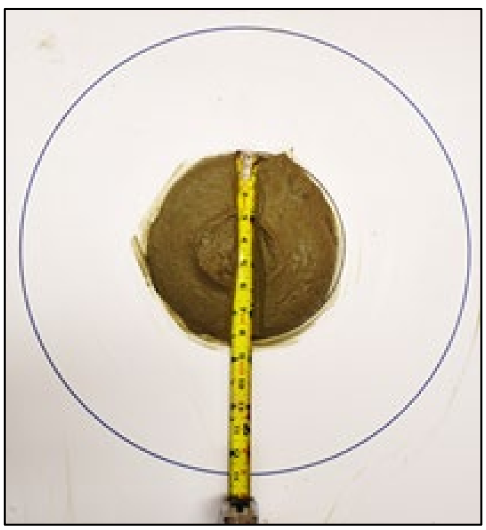
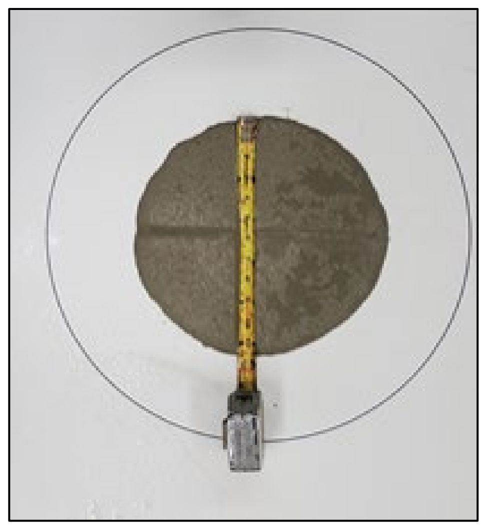


Figure E.35: Flowability of Slurry and Cellular Grout Mixes

(a): C40 Slurry Mix (no Foam)



(b) C40 Drexel F.M.160™



(c) C40 AERLITE ™

Figure E.36: Spread of Cellular Grout Before and After Adding Foam.

E.9.2.1.5 Flow of grout (flow cone method)

Figure E.37 presents results for the flow of cellular grout as measured following ASTM C939-16a. These results indicate the efflux time required for the cellular grout mixtures to pass through the flow cone. Although there are no recommendations on the range of efflux times required to demonstrate good flow, ASTM C939 recommends a maximum efflux time of 30 sec. The efflux times for the cellular grout mixes considered in this project were in the range of 36 sec to 175 sec. Using a surfactant (i.e., Drexel F.M.160™) foaming agent in the cellular grout mix was found to lead to a longer efflux time than for mixes using other foaming agents. In particular, when the density of the cellular grout ranged from 20 lb/ft^3 to 55 lb/ft^3, surfactant foaming agents require 175 to 121 sec, while synthetic and protein foaming agents take on average only 44 to 78 sec. Even for grouts with the same density, the differences in efflux time might result from the higher water contents in the synthetic-based and protein-based foaming agents, as discussed previously.

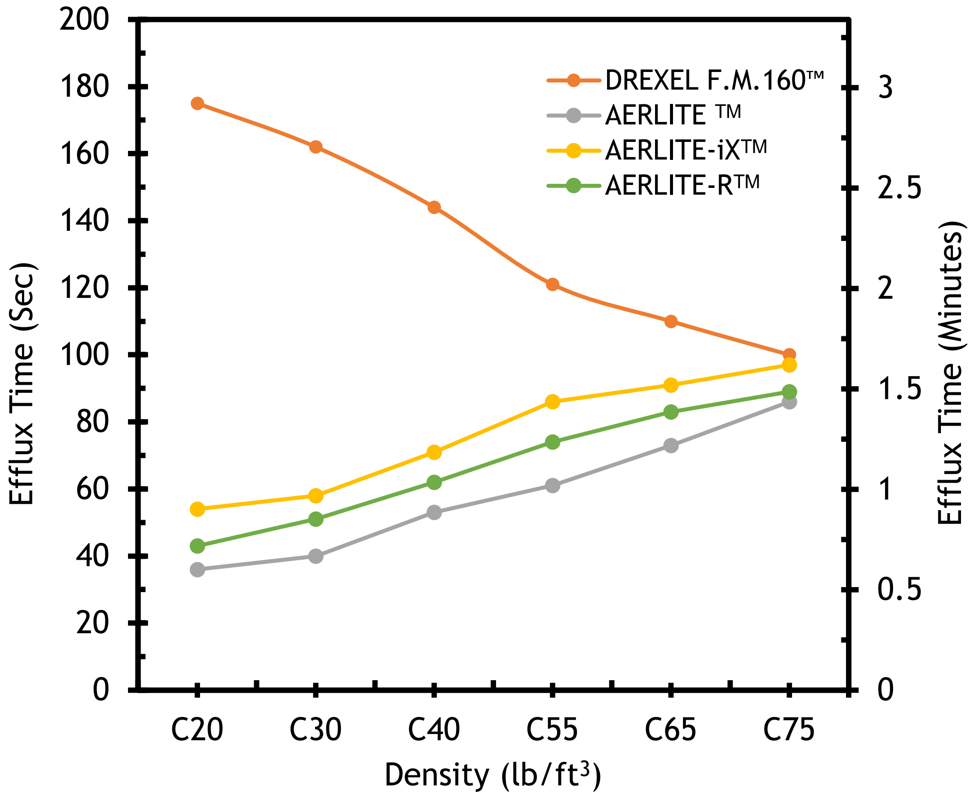


Figure E.37: Efflux Time from Flow Cone Test of Cellular Grout Mixtures.

E.9.2.1.6 Cellular grout stability

ASTM C940-16 ("Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory"; ASTM, 2016) was modified to simulate the stability of cellular grout, since no standard test is used to quantify this material. The first set of cellular grout stability tests, denoted by "CL", included mixing and curing the cellular grouts under standard conditions during the first 24 hours. Figure E.38 shows the results for the stability calculation of CL grout mixes with different densities. It is noted that most mixtures remained stable throughout the casting process (which lasted for 24 hours), except for mixture C10, which showed an average collapse of 200 mL in 800 mL for the different foaming agents. Moreover, the C10 grout mix crumbled to the point that it could be broken by hand when pressed with fingers. This is because the mix has a substantial quantity of foam, comprising about 96% of the total mix volume.

Figure E.39(c) shows the collapse in the field density of an ultra-low density cellular grout C10. The C10 collapse findings from the tests in this project seem to correspond with those of Jones et al. (2016), in that it displayed a similar collapse pattern at densities below 12 lb/ft^3. On the other hand, the cellular grout with a density greater than or equal to 20 lb/ft^3 demonstrated stability.

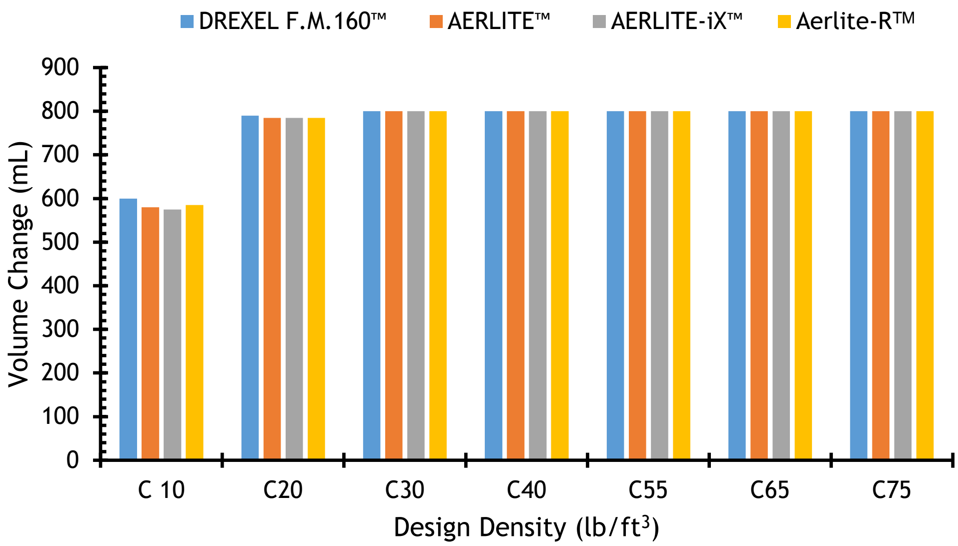


Figure E.38: Foam Stability During the First 24 Hours.

Figure E.39: Instability of Ultra-Low Cellular Grout: (a) Lab-prepared Grout from Jones et al. 2016 (*left*), (b) Lab-prepared Cellular Grout C10 (*center*), (c) and On-site Instability for Grout Reported by Jones et al. 2016 (*right*).

The stability of the cellular grout in the field may also be influenced by several other factors, and these factors can play an important role. For example, the temperature of the fresh mix as well as the temperature of the surrounding environment can also affect the mixture's stability. The influence of temperature on the stability of a cellular grout in this study is presented in Figure E.40.

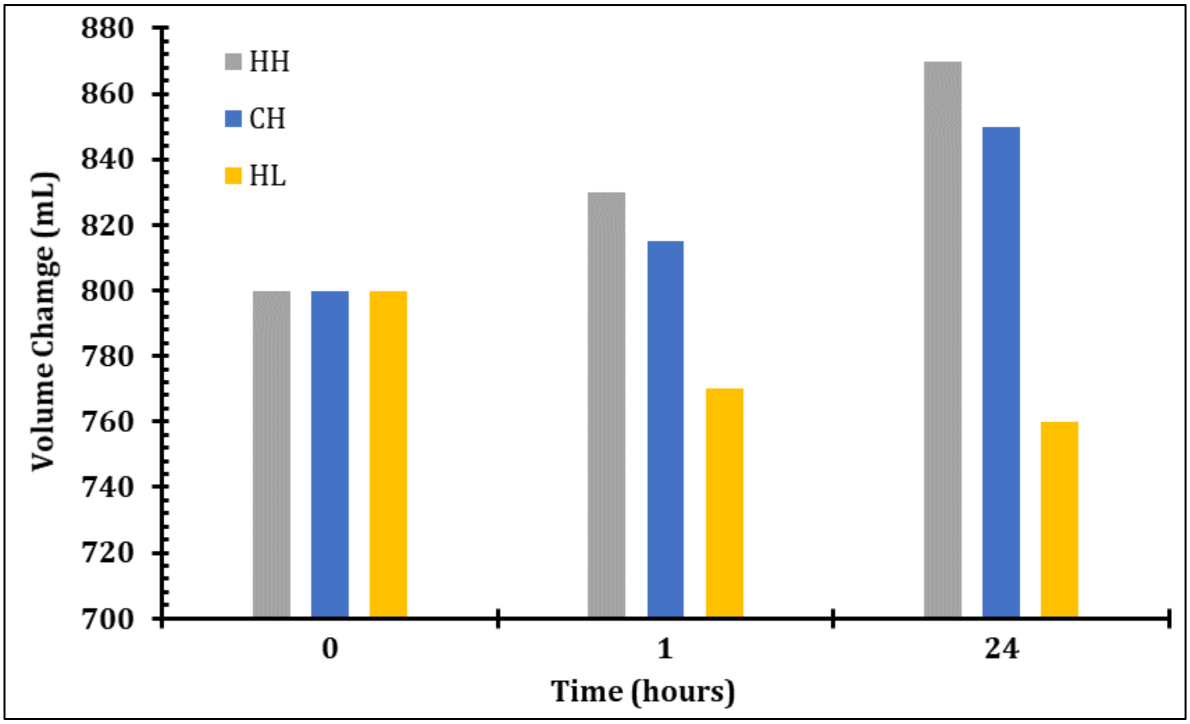
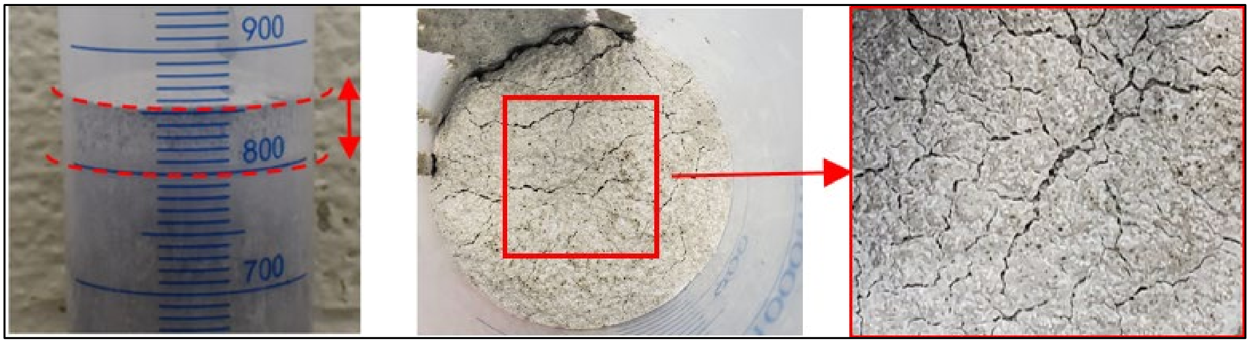


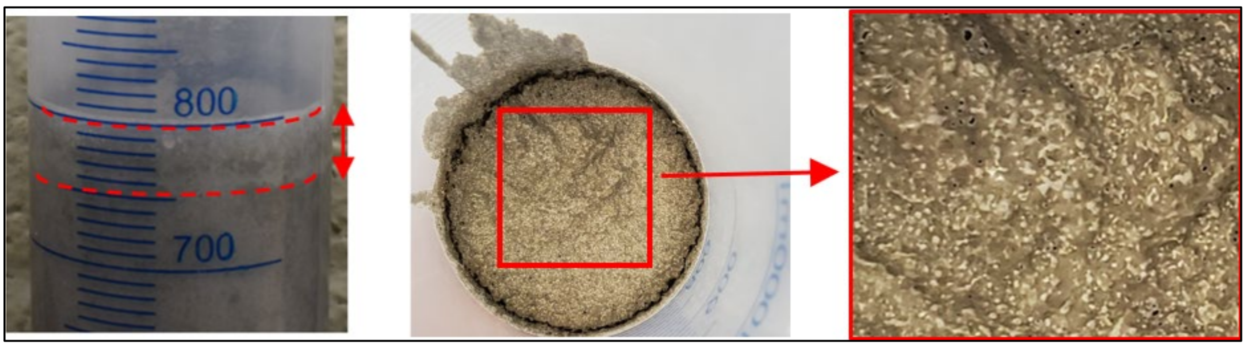
Figure E.40: Influence of Temperature on Cellular Grout Stability (Mix C40).

As cellular grouts with many densities are considered in this project, it was necessary to eliminate grouts with densities that do not fulfill the stability requirements under the usual circumstances, such as mix C10. Mix C40 was prioritized in this set of tests, since it has a density that falls somewhere in the middle of the range of densities for a cellular grout mix. Grout for each specimen was poured until an initial volume of 800 ±10 mL was reached.

Case HH demonstrated the expansion of cellular grout to a volume of 830 mL at 1 hour after casting; the volume of the grout increased to 870 mL after 24 hours, representing an increase of 8% in the volume. The high temperature (100 °F) in the environment surrounding the specimens while they were hydrating is the primary cause of the expansion. This expansion of the grout results in an increase in the volume of the test specimen, which leads to some cracking at the top surface of the specimen as shown in Figure E.41(a). This growth in volume may be reduced by 5.8% if the specimens are maintained for 24 hours at typical room temperatures (as in Case CH). In contrast, Case HL specimens drastically shrink to 770 mL just 1 hour after exposure to high temperatures, as shown in Figure E.41(b). In general, due to the sensitivity of cellular grouts to high temperatures, it is recommended that the grout be mixed and cured at normal room temperature (about 70° F) for a period of 24 hours in order to prevent any concerns related to instability after casting.



(a) Expansion of Cellular Grout During the First 24 Hours



(b) Collapse of Cellular Grout During the First 24 Hours

Figure E.41: Instability of Cellular Grout due to Temperature.

E.9.2.2 *Hardened Properties of the Cellular Grout*

E.9.2.2.1 Compressive strength

The 28-day compressive strength results for six cellular grout mixes of different densities (ranging from 20 to 75 lb/ft^3) prepared with different foaming agents (protein-based agents, synthetic-based agents, and surfactants) are shown in Figure E.42. As discussed in the previous section, Mix C10 was omitted because it is weak and easy to break.

The decrease in compressive strength and density was observed with an increase in foam content for all mixes regardless of the foam type. The loss in strength is shown to be closely connected to the decrease in density (i.e., the increase in foam content). When very large numbers of air bubbles are introduced into the mixture, the binder material volume is reduced, which can decrease the compressive strength of the cellular grout. In contrast, the compressive strength is increased substantially when the grout is prepared with a surfactant foaming agent (i.e., Drexel F.M.160^{TM}), particularly at a density of 75 lb/ft^3. The compressive strength enhancement was about 33% for this grout compared to the mix with AERLITE-iX™ and even more so when compared to AERLITE-R™ (45%) and (AERLITE™ (61%). It can be inferred that the surfactant foaming agent formulates small voids that can increase the compressive strength of the mix and provide better resistance to loading. More importantly, mixes C40, C55, C65, and C 75 exhibit at least 200 psi of compressive strength for cellular grout at 28 days, which is the minimum criterion specified in ASTM C869/C869M-11 (ASTM, 2016).

The failure mode of cellular grouts may be influenced by their density, as shown in Figure E.43. Failures in the form of splitting were seen for the mix at the highest density (Mix C75), while local crushing was observed for the mix with the low density (Mix C20). As an example, the cellular grout cylinder labeled C20 showed signs of breakdown on its base surface. The specimens were able to withstand an increased load after they had passed the point of early local failure. When the cylinder was loaded, the voids began to collapse and the grout particles came into contact with one another, causing the specimens to become more compact; as a result, the specimens were able to withstand high loading even after the initial breaks which comes at a cost of additional deformations.

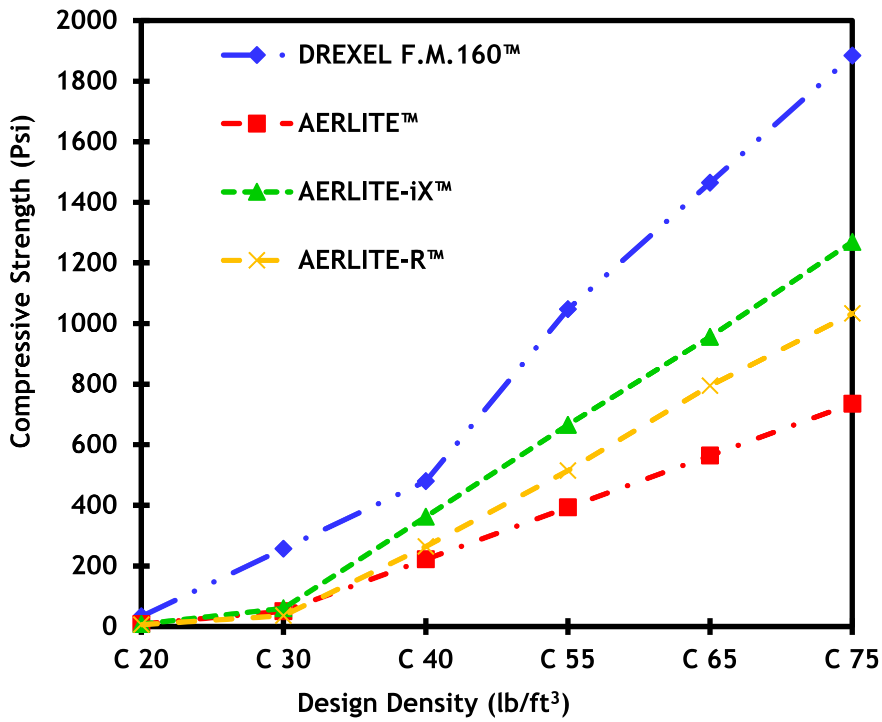
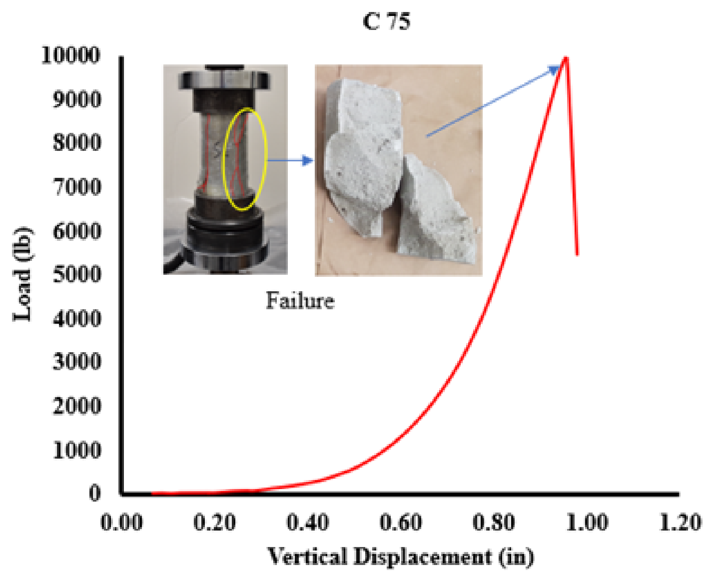
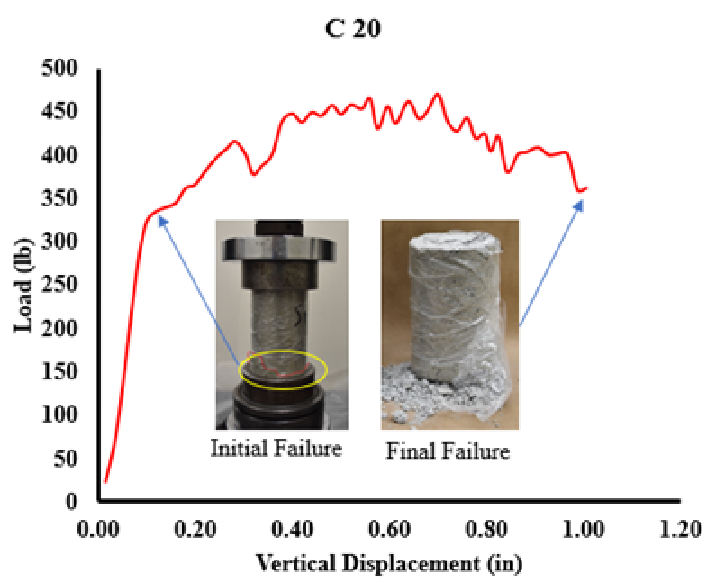


Figure E.42: Compressive Strength of Cellular Grout Mixtures.



(a) High-Density Failure Mode (Mix C75)



(b) Low-Density Failure Mode (Mix C20)

Figure E.43: Failure Types of Cellular Grouts with Different Densities.

E.9.2.2.2 Splitting tensile test results

Cellular grouts with different densities ranging from a low density of 20 lb/ft^3 to a high density of 75 lb/ft^3 that were prepared with different foaming agents were used to make split tensile specimens. After completely curing for 28 days, the test specimens were subjected to splitting tensile tests using an Instron 5569 universal testing machine.

Figure E.44 shows the relationship between the split tensile strength on the y-axis and the density of the mixture on the x-axis. It was revealed that an increase in the design density of the mix was related to an increase in the split tensile strength of the material. This increase may be attributed to the relatively large quantity of cement in the mixture and the relatively low foam content. However, as compared to the results for synthetic and protein foaming agents of the same density, there is a discernible improvement in the surfactant's ability to withstand foaming. For example, when measured at 75 lb/ft^3, the splitting strength of cellular grout mixed using AERLITE-iX^{TM} was found to be significantly lower than that of cellular grout mixed with AERLITE-R^{TM} and AERLITE^{TM}, with a difference of 16%, 23%, and 32% relative to the mix with Drexel, respectively.

As a result of the tiny size of the voids that the surfactant created in most of the cellular grout mixes, it is possible to deduce that the mix can withstand larger loads and increase its overall strength. Following ASTM C869/C869M-11(ASTM 2016), the minimum split tensile strength of 25 psi must be met. Therefore, mixing cellular grout with either surfactant, or synthetic, or protein foaming agents will result in a split tensile strength of at least 25 psi, which is the minimum required by ASTM.

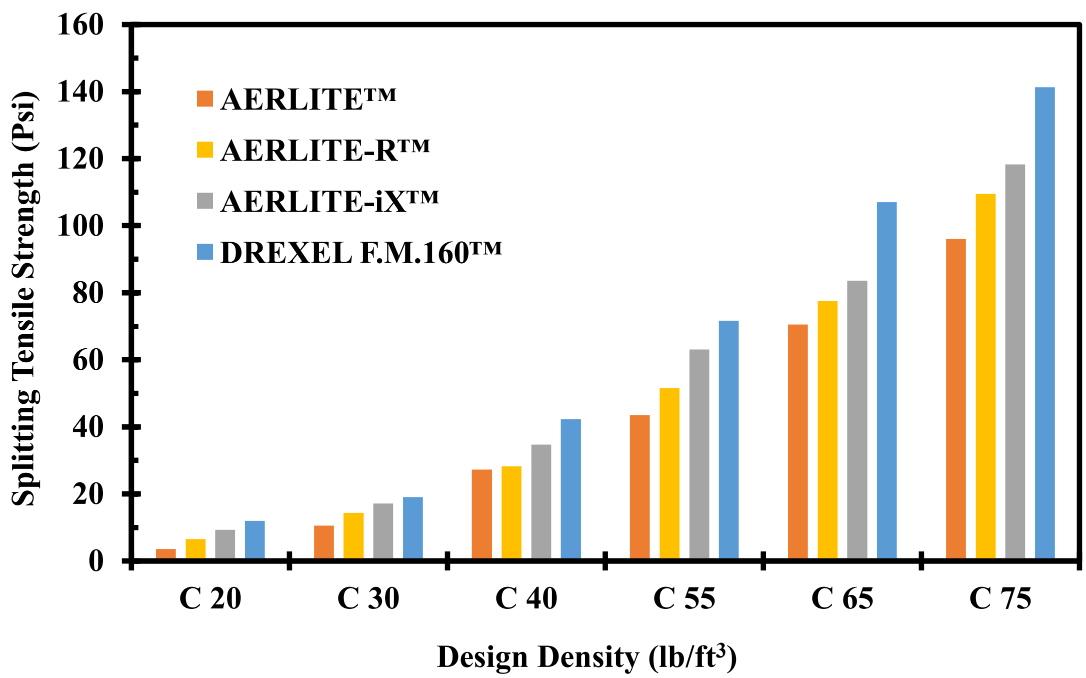


Figure E.44: Split Tensile Strength for Mixes with Different Densities.

E.9.2.2.3 Oven-dry density

After 28 days of curing, the oven-dry density of each cellular grout mix was measured. Because cellular grout mixes are made with various densities, each density of cellular grout were analyzed separately, and the impact of the foaming agent was also investigated. Comparisons of density results for the various cellular grout mixes are shown in Figure E.45.

A comparison was made between the cast-wet density of each foaming agent and Equation (6.1.2.3b) from ACI 523.3R-14. Mix C20 with various foaming agents showed a significant decrease in density. In particular, when mixing cellular grout with synthetic foaming agents AERLITE-iX™ and AERLITE-R™, the impact of the different foaming agents seems quite evident, with a loss in the density of 63% and 58%, respectively. However, when mixing the cellular grout with surfactants or protein foaming agents such as DREXEL F.M.160™ and AERLITE™, only a 43% loss of density was recorded.

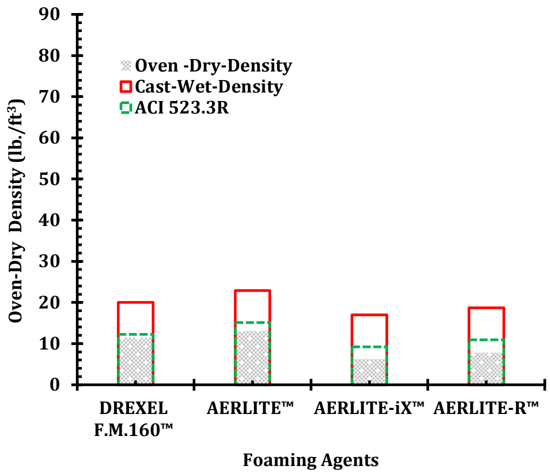
Grout mixes with greater densities such as Mix C30 followed the same pattern as that for Mix C20, demonstrated density losses when using AERLITE-iX™ and AERLITE-R™ of 39% and 38%, respectively. In contrast, mixes prepared with DREXEL F.M.160™ and AERLITE™ showed density losses of less than 31%. When foam comprises just 69% of the mix design volume, as in Mix C40, the cellular grout causes less of a decrease in density. Mixes with DREXEL F.M.160™ had much lower decreases (only 14%), while all other kinds of AERLITE foaming agents showed significantly higher loss rates (ranging from 20% to 28%). These mixes still fulfill the standards of ASTM C796 for a density of 30 ± 2.5 lb/ft^3 for an oven-dry density of cellular grout, since the density results ranged from 27.97 to 33.04 lb/ft^3 after the grouts were dried in the oven.

The addition of foaming agents can potentially cause greater decreases in density (particularly in low-density cellular grouts such as Mix C20 and Mix C30) with higher amounts of foaming agents but will cause much lesser decreases for C65 and C75 mixes. In addition, independent of the foam type, Mix C40 satisfies ASTM requirements for the oven-dry density of cellular grout. Therefore, it is possible to construct a non-linear equation by ignoring the impact of the foaming agents, as derived from in Figure E.46. In the future, the following equation may be used to predict the oven-dry densities of cellular grout mixes with various wet densities:

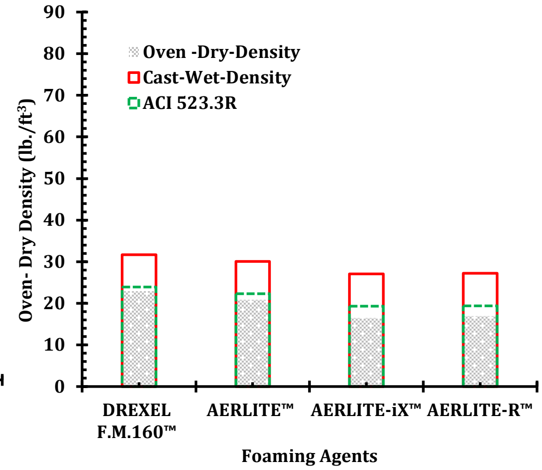
$$\gamma_{ODR} = 16.7\ (\gamma_{CWD})^{-1.164}$$

E.9.2.2.4 Water absorption tests

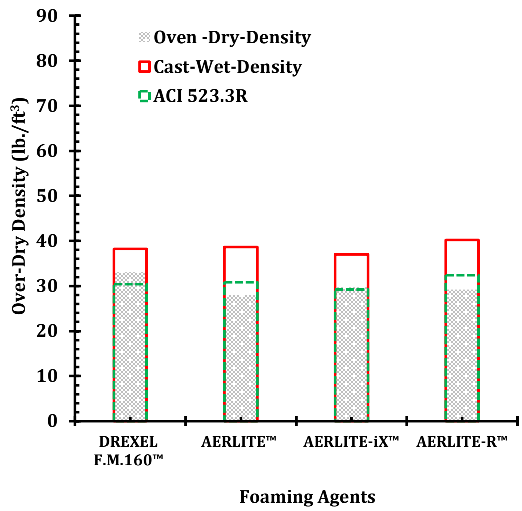
After determining the oven-dry densities of the cellular grouts, the grout specimens were immersed in water, and their densities were recorded until the difference between the most recent two measurements were less than 1%. The variance in water absorption for cellular grout results with different densities and foaming agents are presented in Figure E.48. Importantly, independent of the foaming agent utilized in the grout mix, the water absorption of the cellular grout was shown to rise with the increase in density. This was one of the most interesting observations made about this material. When the volume of the foam increases, the volume of the entrained air pores also increases; this causes the paste content to decrease, which in turn causes a reduction in the volume of the capillary pores. The decrease in the volume of the capillary pores, in turn, causes a tendency toward decreased water absorption. According to the findings of previous research that was carried out by Nambiar and



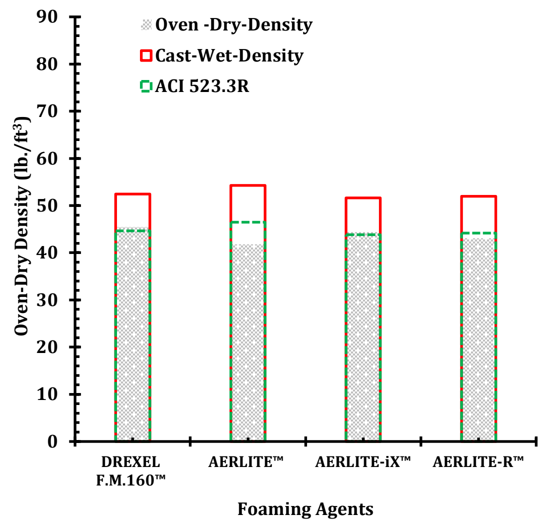
(a) C20 Oven-Dry Density



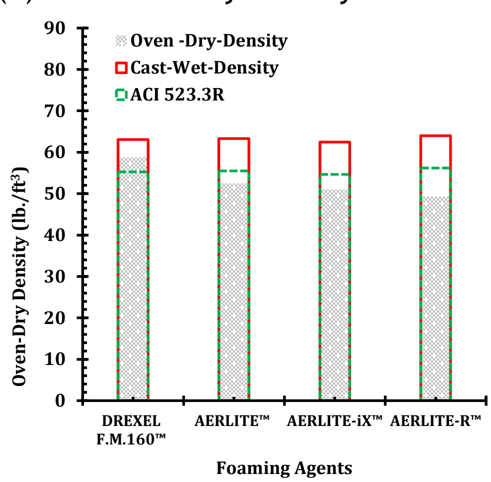
(b) C30 Oven-Dry Density



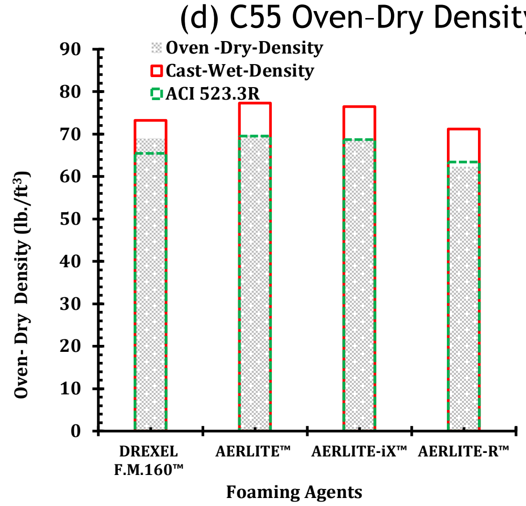
(c) C40 Oven-Dry Density



(d) C55 Oven-Dry Density



(e) C65 Oven-Dry Density



(f) C75 Oven-Dry Density

Figure E.45: Oven-Dry Densities for Cellular Grout Mixes.

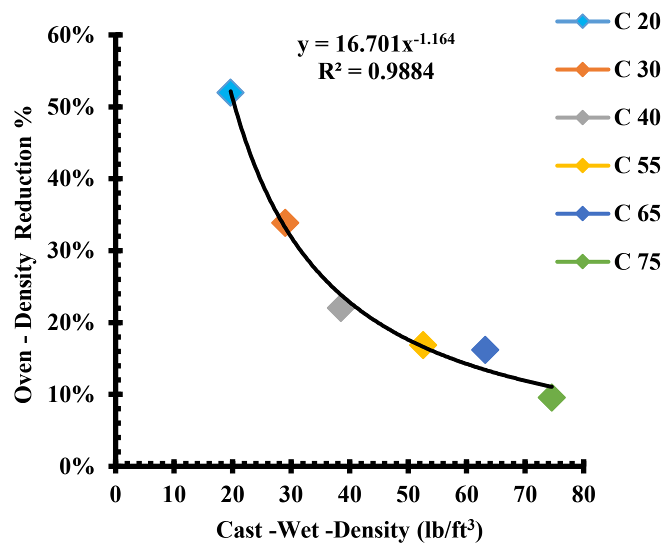


Figure E.46: Oven-Dry Density Reduction vs. Cast-Wet Density.

Ramamurthy (2007), cement mixtures that did not include foam had more significant water absorption rates than foamed concrete mixes, as illustrated in Figure E.47. On the other hand, the graph in Figure E.48 indicates that the impact of the type of foaming agents seems lower than the impact of the quantity of foam added to the mixture. For example, a protein-based foaming agent such as AERLITE™ can absorb more water than a surfactant-based foaming agent such as DREXEL F.M.160™, and the difference may be as much as 28% in certain cases (such as for Mix C20). These significant disparities seem to be smaller than the differences resulting from the use of synthetic foaming agents AERLITE-iX™ and AERLITE-R™, which are less than 18% at the same density. ASTM C869 limits the maximum amount of water that may be absorbed as a volume percentage to 25%. As a result, it is evident from the chart that the ASTM constraints can be satisfied by mixing cellular grouts with any one of the four foaming agents. Moreover, the data provided for each mix with various foaming agents can be used to generate an exponential trend line, *y* = 0.1438e(0.1804 x (γ_{CWD})). Therefore, this equation can assist in predicting the water absorption for cellular grouts mixed with foaming agents that are protein-based, synthetic-based, or are surfactants.

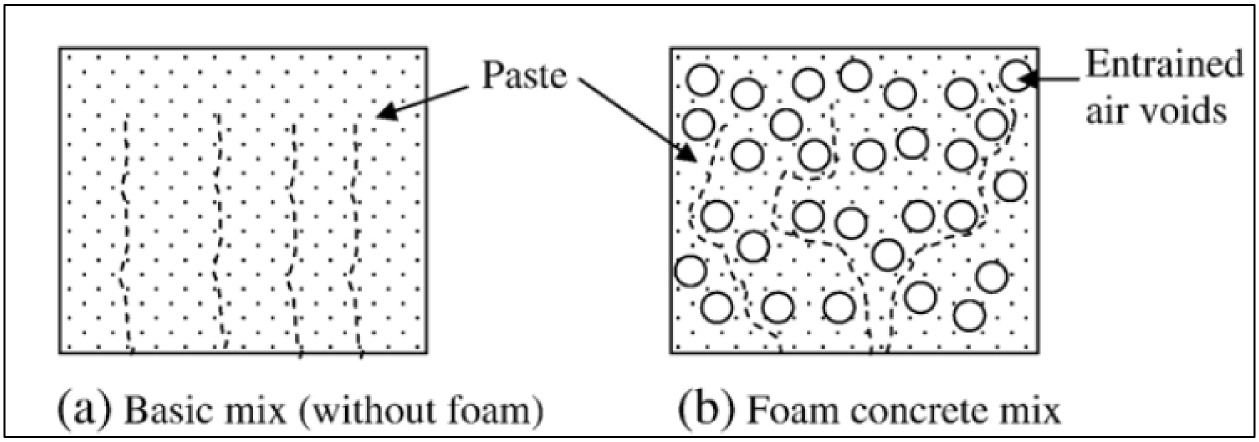


Figure E.47: Movement of Water into Non-foamed Concrete and the Corresponding Foamed Concrete (Nambiar and Ramamurthy, 2007).

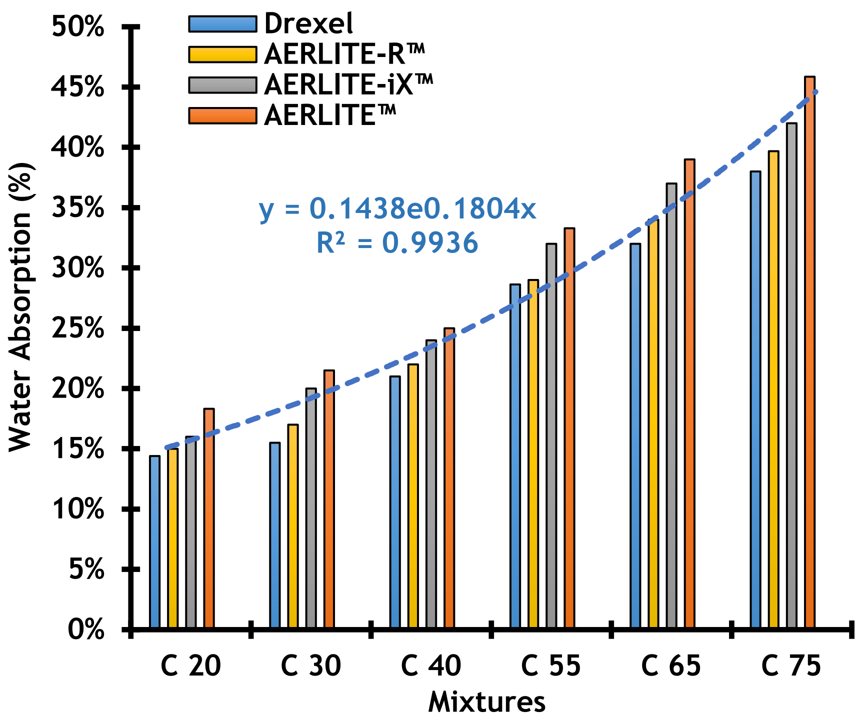


Figure E.48: Water Absorption vs. Cellular Grout Mixtures.

E.9.2.2.5 Dry shrinkage

The percentage variance of drying shrinkage over time for cellular grout prepared using different foaming agents is shown in Figure E.49. The primary drying shrinkage of cellular grout occurred in the first 14 days. After that, the drying shrinkage seems steady with no significant changes. Surfactant foaming agent DREXEL F.M.160™ exhibited the most significant shrinkage at high and low cellular grout densities, while the protein-based foaming agent AERLITE™ showed the lowest shrinkage. The explanation for the higher drying shrinkage of the surfactant is linked to the small pore sizes in the grout. Therefore, it is clear that the synthetic and protein-based foaming agents had a higher number of large-sized pores. The large pores create a slight pressure on the small pores inside the mix. The additional pressure on a small bubble is greater than the pressure on a large bubble, causing the small bubble to break, which makes the large bubble even larger. Figure E.50 shows the void distribution of C20 mixes prepared with DREXEL F.M.160™ foaming agent and AERLITE-R™. A sample of the mix with DREXEL F.M.160™ foaming agent shows finer voids, whereas the mix with AERLITE-R™ shows larger voids. Overall, it can be inferred that as the density of the cellular grout increases, the drying shrinkage values also increase. The high shrinkage is due to the large quantity of hydration product (i.e., cement) and the absence of aggregate, resulting in higher drying shrinkage in the cellular grout. At lower densities, the foam quantity (i.e., the number of air bubbles in the specimen) is high, causing a reduction in cement quantity and, hence, less of a hydration reaction, which induces low shrinkage. According to the report by ACI Committee 523.3R (ACI, 2014), the normal shrinkage range for cellular grout is between 0.1% and 0.4%; all the mixes tested in this study fall within this range.

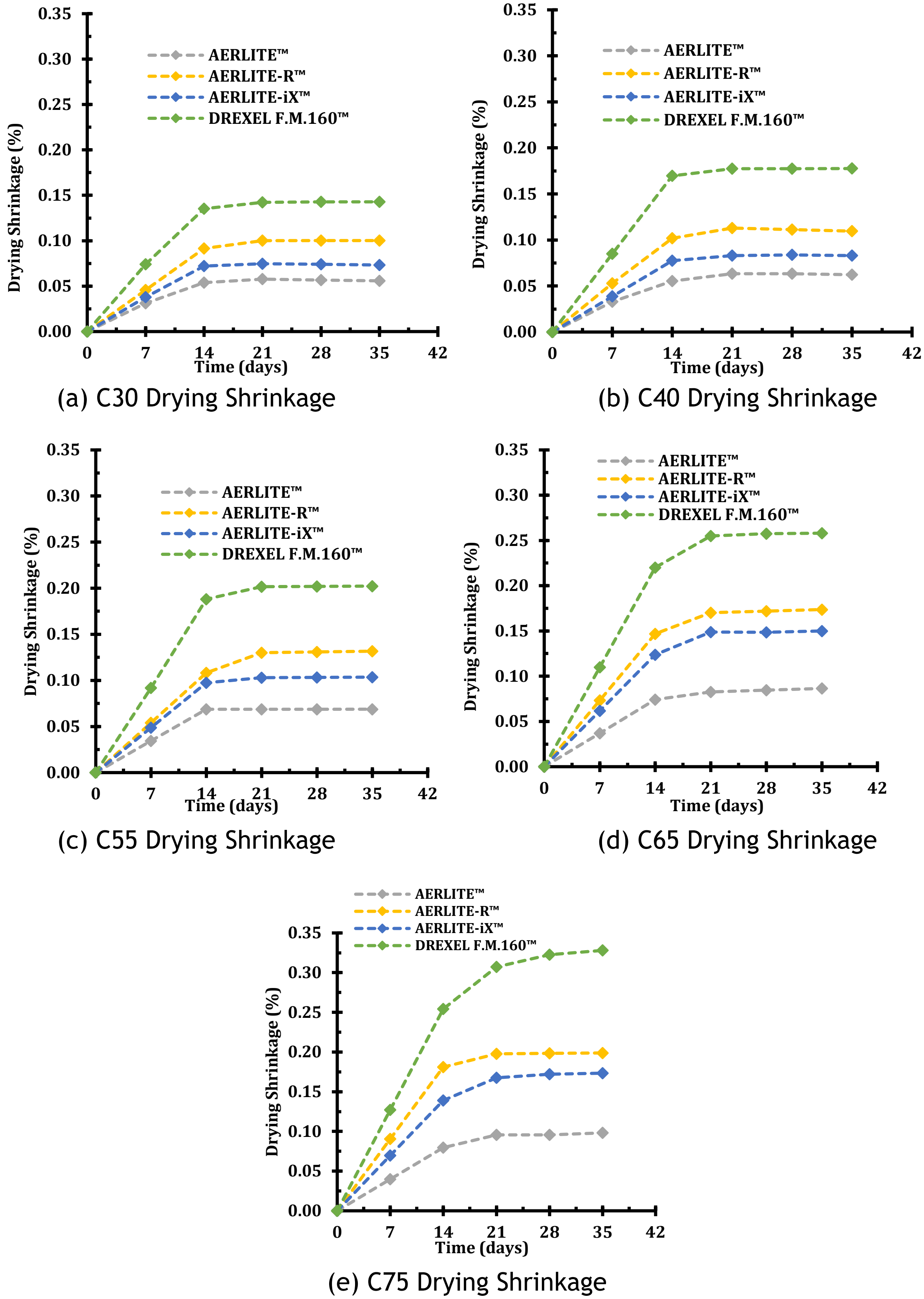


Figure E.49: Drying Shrinkage for Cellular Grout Mixes with Different Foaming Agents.

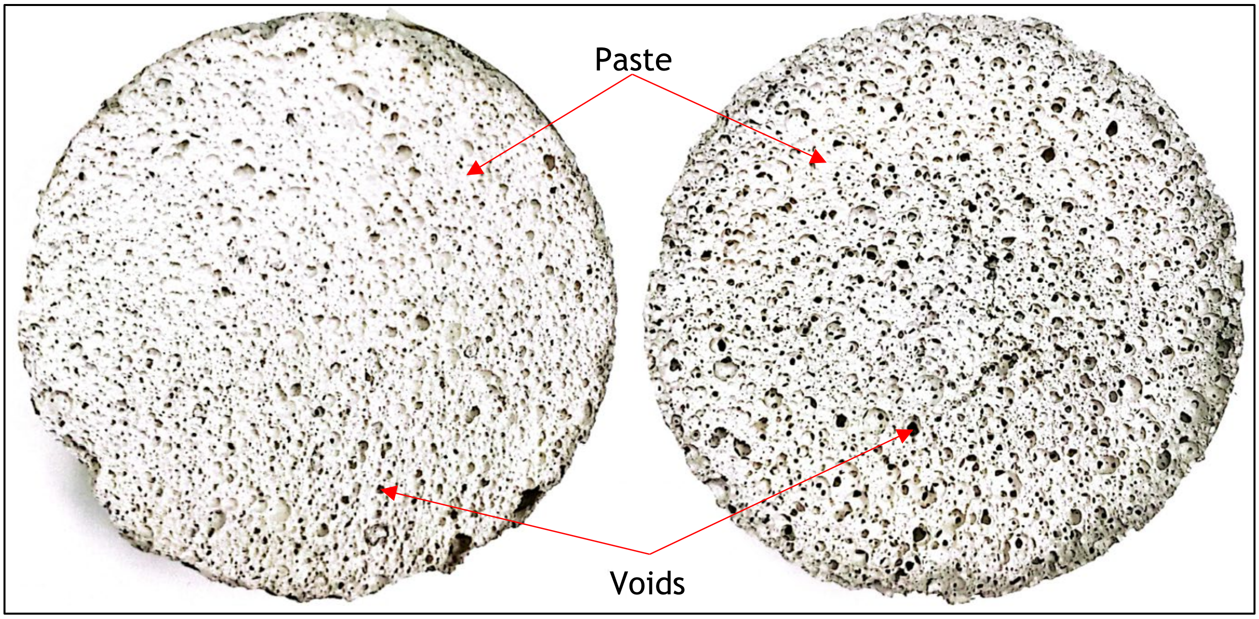


Figure E.50: Void Distribution for Cellular Grout Mix C20 Prepared using DREXEL F.M.160™ Foaming Agent (*left*) and AERLITE-R™ Foaming Agent (*right*).

E.10 Selection of the Optimum Cellular Grout Mixture for Annulus Void Fill

The cellular grouts considered for this project were made with densities that varied from 10 to 75 lb/ft^3. Because of its lower unit weight, cellular grout applies less hydrostatic pressure on the liner than denser grouts like CLSM. The normal unit weight of CLSM is about than 100 lb/ft^3, but the unit weight of cellular grout is much less than 100 lb/ft^3. This low unit weight could assist the cellular grout to travel a long distance inside the sliplined culvert during pumping, which is an additional advantage (ISCO Industries, 2013).

Given that there are no requirements for cellular grouts used for filling the annulus of a sliplined culvert, it is essential to determine the grade of the cellular grout to be used. According to the study compiled as part of NCHRP Project 24-12 (Folliard, 2008), flow and unconfined compressive strength might be beneficial for void fill applications. However, it was observed from our experiments carried out on most cellular grout grades that other factors, such as mixing and placing cellular grouts at a high temperature, could lead to progressive collapse.

Ultra-low density of some cellular grout mixes (such as Mix C10) was another factor that was considered in this project. Table E.10 summarizes the findings of the experiments that were performed, and it contains both the fresh and the hardened characteristics of the cellular grouts. It also includes the results of the tests performed only on the foam. At the beginning of this study, the different varieties of foam were able to meet the minimum density standards for foam as specified by ASTMC 796 and ACI 523.3R-14.

In addition to the experiments with the foam density, it is proposed that mixing the foam at room temperature would prevent instability of the foam volume before the foam is mixed with the cement slurry. Furthermore, the produced foam should not be exposed to high temperatures before being added to the slurry, as this would result in a decrease in the volume of the foam. Another concern with the instability of cellular grout is preparing a cellular grout with an extremely low density (such as Mix C10), which results in instability throughout the hardening process (over the initial 24-hour period). The grout selection needs to be limited to cellular grouts with densities ranging from 20 to 75 lb/ft^3. The guidelines in ASTM C869/C869M provide that the density of the cellular grout should either fulfill density after pumping of 40 ± 3 lb/ft^3 with an oven dry density for Type I cement of 30.4 ± 2.5 lb/ft^3, or an oven dry density for Type III cement of 30 ± 2.5 lb/ft^3. Within the scope of this project, Type III cement was the preferred type of cement.

Due to the restricted space available in our lab, it was not possible to pump the grout in the lab; as a result, the fresh density (also known as the cast-wet *density*) was regarded as the density of the grout after pumping. Because of this, it was discovered that measuring the fresh density of C40 would satisfy the ASTM C869/C869M standard for the production of cellular grout. Most of the mixes also met the minimum spread suggested by ACI Committee 229 (ACI, 2013), except for two mixes (C20 and C30 when mixed with a surfactant foaming agent) that did not fulfill the minimum spread requirement of 8 inches. Similarly, the efflux time required to pass a stem diameter of ½ inch when subjected to the force of gravity was significantly longer for all grades of cellular grout mixed with surfactant foaming agents but significantly shorter for synthetic and protein foaming agents. According to ASTM C869/C869M, the mechanical parameters of compressive strength and split tensile strength were required to have values of 200 and 25 psi, respectively. Therefore, C40 mixes with any foaming agent will satisfy the ASTM minimum requirements for the qualities of its mechanical components. In addition, the amount of water that could be absorbed was limited to a maximum of 25%; Mix C40 was found to be compliant with these water absorption standards. Overall, Mix C40 seems to fulfill ASTM and ACI standards (ASTM C869/C869 M for manufacturing cellular grout and the recommendations of ACI Committee 229). As a result, Mix C40 is suitable for use as a grout for splined culverts. ODOT Specification also recommends C40 cellular grout for sliplined culvert annulus void filling application.

E.11 Results of Parallel Plate Loading Test on Sliplined Culvert Specimens

E.11.1 Host and liner pipe tests

Before conducting tests on a sliplined culvert specimens, separate parallel plate tests on the host pipe and the liner pipe were carried out to determine the load-carrying capacity of each pipe. Figure E.51 shows the plot for the load applied to the pipe alone versus the diameter change in inches for both pipes. The plot for the applied load versus the percentage of change in diameter, shown in Figure E.52, would be a better representation of the load-carrying capacities of these two pipes, as the diameter of the host pipe is 18 inches, while the diameter of the liner pipe is 12 inches. During loading, the crown and invert of the pipes moved closer to one another, resulting in a reduction in the vertical diameter of the pipes; nonetheless, the distance between the culvert springlines increased (i.e., the horizontal diameter increased). Figure E.53 shows the host and liner pipe before and after parallel-plate loading tests were performed.

Both pipes exhibited a linear relationship between the applied load and the change in diameter up to the yield point, as shown in Figures E.51 and F.52. However, the difference in diameter between the host and liner pipes increased more in the vertical direction than in the horizontal direction when the same amount of force was applied. For example, when a force of 400 lbf was applied vertically to a set of liner pipes, the vertical diameter changed by a factor of 2; at the same applied load, the ratio of the liner pipe was 2.2 for horizontal diameter. The vertical diameter change of a flexible pipe for liner pipes in sliplined culverts must be between 5% and 8% to meet serviceability standards (Smith et al., 2015; Rahmaninezhad et al., 2019). Therefore, a 5% vertical diameter variation was considered for the host and liner pipe in this investigation to determine the load carrying capacity. As a direct consequence, the host pipe supported a greater load than the liner pipe. At a vertical diameter change of 5%, the host pipe could support a load of around 584 lbf. In contrast, the liner pipe's load-carrying capacity of 423 lbf was found to be around 28% lower than that of the host pipe, when both pipes were subjected to the same vertical diameter change.

Table E.10: Summary of Cellular Grout Test Results

Foaming Agent	**Name**	**Drexel**	**Aerlite™**	**Aerlite-iX™**	**Aerlite-R™**
	Type	Anionic/ non-ionic surfactant blend	Protein	Synthetic	Synthetic
Tests	Density (lb/ft^3) (ASTM C796)	5.4	4.6	5.5	5.5
	Stability (°F)	65 to 70: Stable			
		100: Unstable			

Table E.10: Summary of Cellular Grout Test Results [Continued]

Foaming Agent	Fresh Properties					
	Mix	Fresh Density, lb/ft^3 (ASTM C138)	Flow Cone, sec. (ASTM C939) (35 sec)	Flowability, in. (ASTM D6103) (8 in.)	Air Content, % (ASTM C138)	Stability Test (ASTM C940)
DREXEL F.M.160™	C10	10±3	N/N	N/N	N/N	Unstable
	C20	20±3	175	7	85	Stable
	C30	30±3	162	7.5	80	Stable
	C40	40±3	144	8	70	Stable
	C55	55±3	121	8.5	50	Stable
	C65	65±3	110	9	40	Stable
	C75	75±3	100	9.5	30	Stable
Aerlite™	C10	10±3	N/N	N/N	N/N	Unstable
	C20	20±3	36	9	83	Stable
	C30	30±3	40	10	83	Stable
	C40	40±3	53	11.25	68	Stable
	C55	55±3	61	11.75	55	Stable
	C65	65±3	73	12	37	Stable
	C75	75±3	86	12.5	33	Stable
Aerlite-iX™	C10	10±3	N/N	N/N	N/N	Unstable
	C20	20±3	54	8	80	Stable
	C30	30±3	58	9	85	Stable
	C40	40±3	71	10.25	63	Stable
	C55	55±3	86	11	57	Stable
	C65	65±3	91	11.25	34	Stable
	C75	75±3	97	11.5	36	Stable
Aerlite-R™	C10	10±3	N/N	N/N	N/N	Unstable
	C20	20±3	43	8.25	90	Stable
	C30	30±3	51	9.25	70	Stable
	C40	40±3	62	10.5	73	Stable
	C55	55±3	74	11.25	63	Stable
	C65	65±3	83	11.5	32	Stable
	C75	75±3	89	11.75	37	Stable

N/N: not applicable due to ultra-low density or specimens breaking.

Table E.10: Summary of Cellular Grout Test Results [Continued]

Foaming Agent	Hardened Properties					
	Mix	Compressive Strength, psi (ASTM D4832), (200 psi)	Split Tensile Strength, psi (ASTM C496), (25 psi)	Oven-Dry Density (ASTM C495), (30±2.5 lb/ft^3)	Water Absorption (ASTM C796), (25%)	Drying Shrinkage, % (ASTM C592)
DREXEL F.M.160™	C10	N/N	N/N	N/N	N/N	N/N
	C20	33.06	12	11.45	14	N/N
	C30	256.08	19	22.92	16	0.14278
	C40	479.29	42.3	33.04	21	0.17754
	C55	1047.61	71.7	45.45	29	0.20196
	C65	1465.01	107	58.85	32	0.25751
	C75	1884.35	141.3	68.97	38	0.32246
Aerlite™	C10	N/N	N/N	N/N	N/N	N/N
	C20	7.96	3.56	13.1	18	N/N
	C30	50.747	10.5	20.83	22	0.05682
	C40	221.89	27.25	27.97	25	0.06333
	C55	393.03	43.5	41.8	33	0.06875
	C65	564.18	70.5	52.49	39	0.08457
	C75	735.33	96	69.69	46	0.09576
Aerlite-iX™	C10	N/N	N/N	N/N	N/N	N/N
	C20	7.85	9.28	6.27	16	N/N
	C30	59.94	17.1	16.48	20	0.074
	C40	362.2	34.7	29.72	24	0.08375
	C55	665.49	63.1	44.37	32	0.10323
	C65	955.82	83.6	51.06	37	0.14841
	C75	1269.47	118.3	68.73	42	0.17198
Aerlite-R™	C10	N/N	N/N	N/N	N/N	N/N
	C20	5.95	6.5	7.81	15	N/N
	C30	36.18	14.38	16.93	17	0.10007
	C40	264.22	28.25	29.23	22	0.11122
	C55	514.15	51.5	43.11	29	0.13085
	C65	794.27	77.5	49.35	34	0.17198
	C75	1032.88	109.5	62.29	40	0.19835

N/N: not applicable due to ultra-low density or specimens breaking.

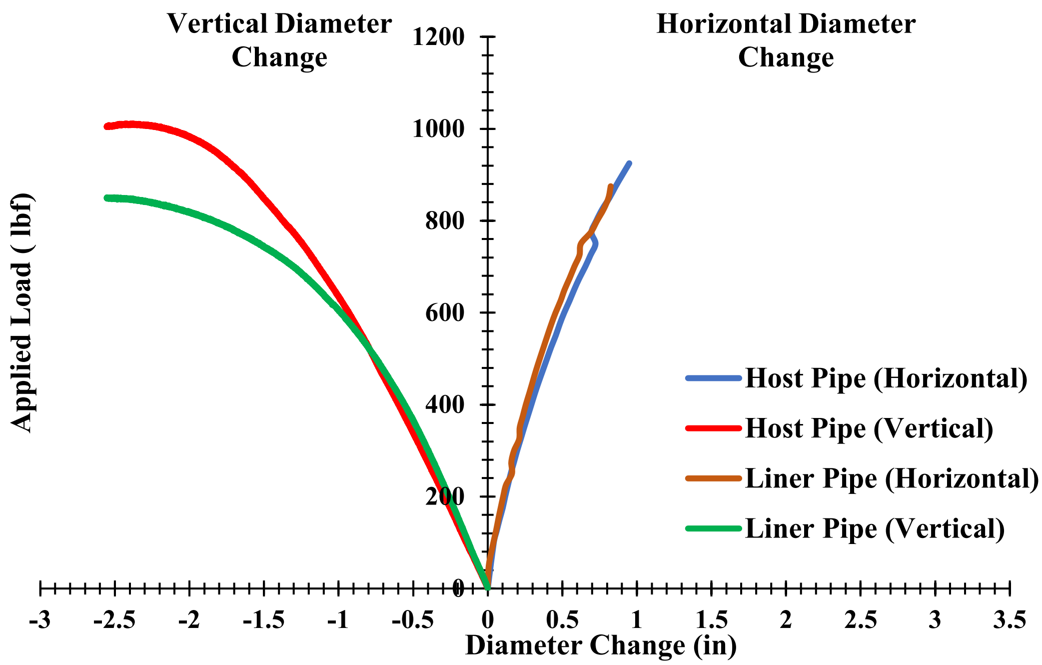


Figure E.51: Applied Load vs. Diameter Change of Host and Liner Pipe.

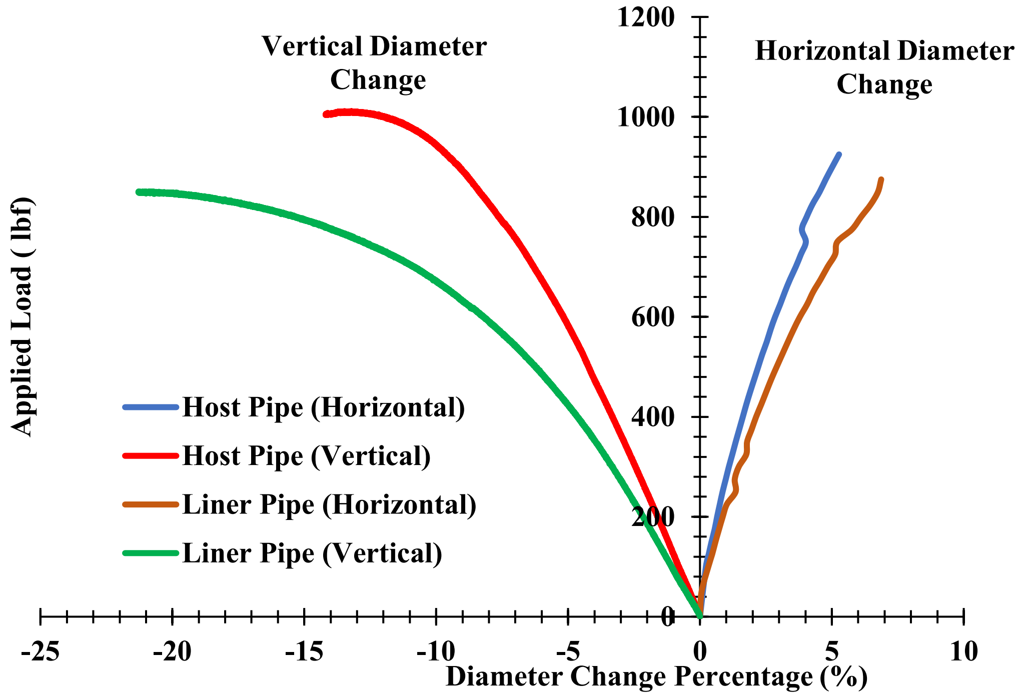
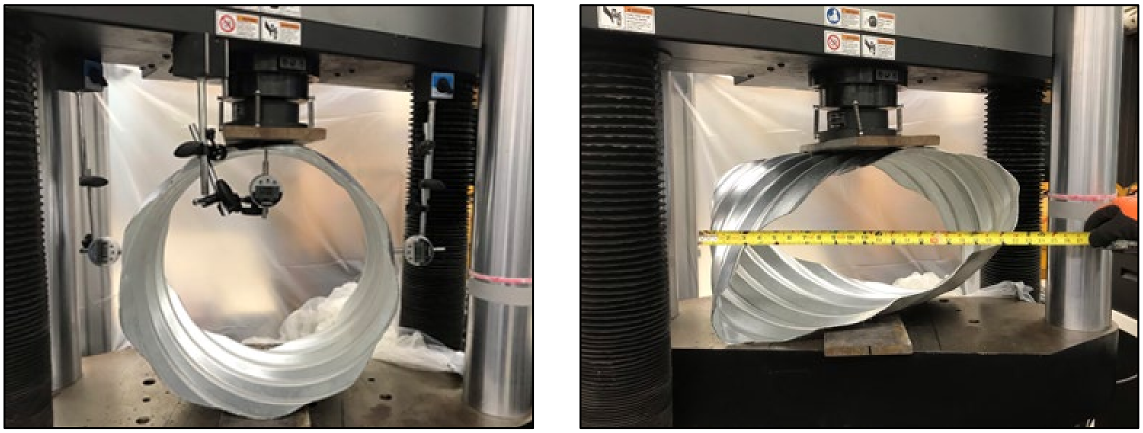


Figure E.52: Applied Load vs. Percentage Diameter Change of Host and Liner Pipe.



(a) Setup for Liner Pipe Loading. (b) Liner Pipe after Loading.

Figure E.53: Parallel Plate Loading Test of Corrugated Steel Liner Pipe.

E.11.2 Parallel-plate loading tests of sliplined culverts with no voids or defects

Parallel-plate loading experiments were performed on sliplined culvert specimens with two different grouts, Mix A (a typical CLSM mix) and C40 cellular grout. The grout condition before and after the parallel-plate loading tests of culverts that were sliplined with Mix A and C40 are shown in Figure E.54 and Figure E.55, respectively. As a result of the many cracks that were found in the crown and springline locations, a large amount of Mix A grout spalled out of the culvert test specimen. In contrast, the sliplined culvert specimen that was made with C40 cellular grout exhibited only a few cracks at the crown and springline positions.

Figure E.54: Sliplined Culvert Using CLSM Grout Mix A,
Before (*left*) and After (*right*) Parallel-plate Load Test.

Figure E.55: Sliplined Culvert using C40 Cellular Grout Mix,
Before (*left*) and After (*right*) Parallel-plate Load Test.

Figure E.56 presents a graph of the applied load versus the change in diameter for culvert test specimens that were sliplined with CLSM Mix A grout and C40 cellular grout. As illustrated in Figure E.57, the first crack appeared at the crown location of the culvert test specimen with CLSM Mix A grout when a load of 1,300 lbf was applied, and this was associated with a vertical diameter change of 0.11 in.

In contrast, the first crack appeared at the crown position of the culvert test specimen with C40 cellular grout at 192% higher applied load (3,800 lbf) or by an approximate factor of 2.9, as shown in Figure E.58. This occurred when the culvert specimen experienced a vertical diameter change of 0.13 in. Since the first crack appeared in the same location for both culvert specimens, the crown position is considered the most critical in the load carrying behavior of sliplined culverts. This figure shows that the applied force and the diameter change maintain a linear relationship until the first crack occurs; after that, the trends for both diameter changes of the culvert gradually start to become non-linear. Because of this, the culvert with C40 cellular grout had a better load-carrying capacity than the culvert with CLSM Mix A grout. Specifically, at a vertical diameter change of 5% (0.9 in), the culvert with CLSM Mix A grout had a load-carrying capacity of 4,163 lbf. In contrast, the load-carrying capacity of a culvert with C40 cellular grout was 58% greater than that of a culvert with CLSM Mix A grout (7,096 lbf), and this was achieved while maintaining the same percentage change in vertical diameter. Likewise, the culvert with CLSM Mix A grout exhibited a 57% lower load-carrying capacity (4,350 lbf) than the culvert with C40 cellular grout, which experienced a horizontal diameter variation of 0.5 inches (7600 lbf). Although the pipe stiffness would typically decrease after yielding, the culvert with C40 cellular grout had a dramatic rise in stiffness after a 1.24-in. change in vertical diameter and a 0.4-in. change in horizontal diameter. Based on the evidence presented here, the ultimate load-carrying capacity of the culvert with C40 cellular grout is significantly greater than that of the culvert with CLSM Mix A grout.

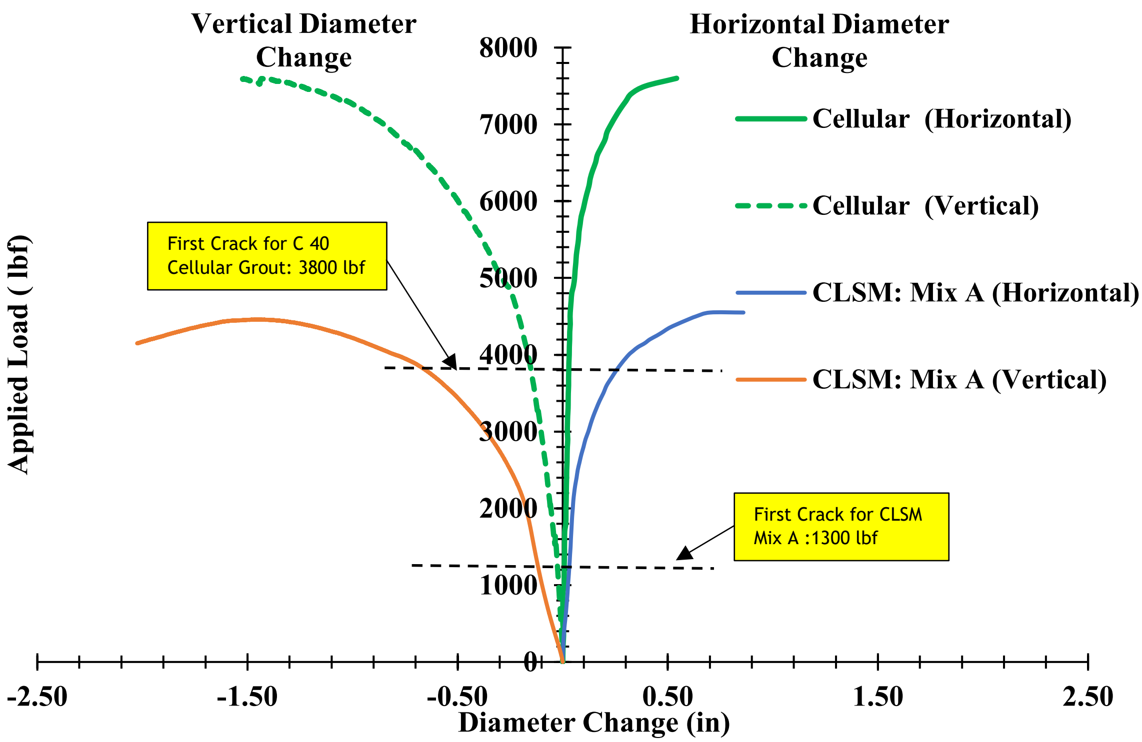


Figure E.56: Applied Load vs. Diameter Change of Sliplined Culverts Using CLSM Grout Mix A and C40 Cellular Grout.

Figure E.57: First Crack Occurred in CLSM Mix A Grout at 1,300 lbf.

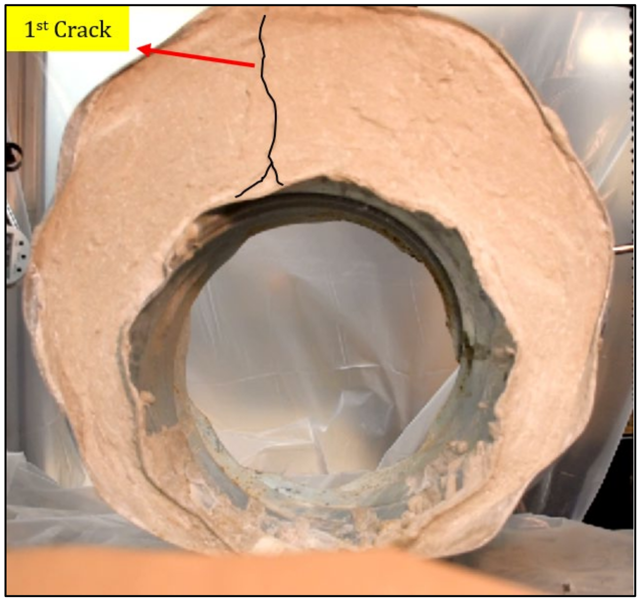


Figure E.58: First Crack Occurred in C40 Cellular Grout at 3,800 lbf.

The contribution of the grout to the load carrying capacity of the sliplined culvert may be calculated by utilizing the load-carrying capacities of the host pipe and the liner pipe. Table E.11 presents the contribution of the grout to the load-carrying capability of the culvert with CLSM Mix A and the culvert with C40 cellular grout. From the results shown in this table, the grout makes the considerable amount of contribution to the load-carrying capacity of a sliplined culvert.

Table E.11: Contribution of Grout to the Load-Carrying Capacity of Sliplined Culverts

Grout Type	**Load-Carrying Capacity of Culvert*, *A* (lbf)**	**Contribution of Host Pipe, *H* (lbf)**	**Contribution of Liner Pipe, *L* (lbf)**	**Contribution of Grout, *G* (lbf); $G = A - H - L$**
CLSM Mix A Grout	4,163	584	423	3,156
C40 Cellular Grout	7,096	584	423	6,089

*considering a 5% change in vertical diameter.

E.11.3 Parallel-plate loading test of sliplined culverts with voids

As indicated previously, most of the voids in the annulus of a sliplined culvert are likely to be located at the crown and the springline locations. The influence of void location on the load-carrying capacity of the culvert grouted with C40 cellular grout was investigated by performing parallel-plate loading tests on sliplined culverts with voids at the springline or crown positions. Figure E.59 and Figure E.60 show the condition of the sliplined culvert specimen and grout before and after the application of loads in the parallel-plate testing method with voids at the springline and the crown, respectively. Of the two, the sliplined culvert that contains voids at the springline position exhibited many more cracks. In addition, a small amount of the grout was split off from the springline location. In contrast, the sliplined culvert host pipe with voids at the crown deflected greatly under loading, and delamination was noted on both sides of the culvert. A crack at the springline position and radial cracks between 10 o'clock and 2 o'clock were observed; an additional crack was also present between these two positions.

The applied load versus the change in diameter is shown in Figure E.61 for sliplined culverts with different types of defects. These culverts are Type I, which has no voids in the grout; Type II, which has voids at the crown position; and Type III, which has voids at the springline position. At a force of 3,000 lbf, the culvert with voids at the springline exhibited its initial hairline crack, as shown in Figure E.62. In contrast, the first hairline crack appeared in the culvert with voids at the crown at an applied load of 500 lbf, as shown in Figure E.63. Therefore, the load-carrying capacities of sliplined culvert with voids at the springline or at the crown are much lower than that of a sliplined culvert that is completely filled.

For example, the load-carrying capacity of the sliplined culvert with voids at the springline was 6,082 lbf when the vertical diameter changed by 5%, which was 0.9 inches for C40 cellular grout. In contrast, the load-carrying capacity of the sliplined culvert with a void at the crown was 1,977 lbf for C40 cellular grout, which is lower than that for a culvert with voids at the springline by a factor of 3 at the same percentage of vertical diameter change (5%).When looking at the load-carrying capacity for a culvert with a change in horizontal diameter of 0.5 inches, it is evident that the sliplined culvert with voids at the springline had a load capacity that is 220% greater than that for the culvert with a void at the crown. From these findings, it can be concluded that the load-carrying capacity of the grout in a sliplined culvert is affected by the location of the voids in the annulus. In addition, a void that occurs at the crown position of a sliplined culvert has a greater detrimental effect on the load-carrying capacity of the culvert than voids at the springline.

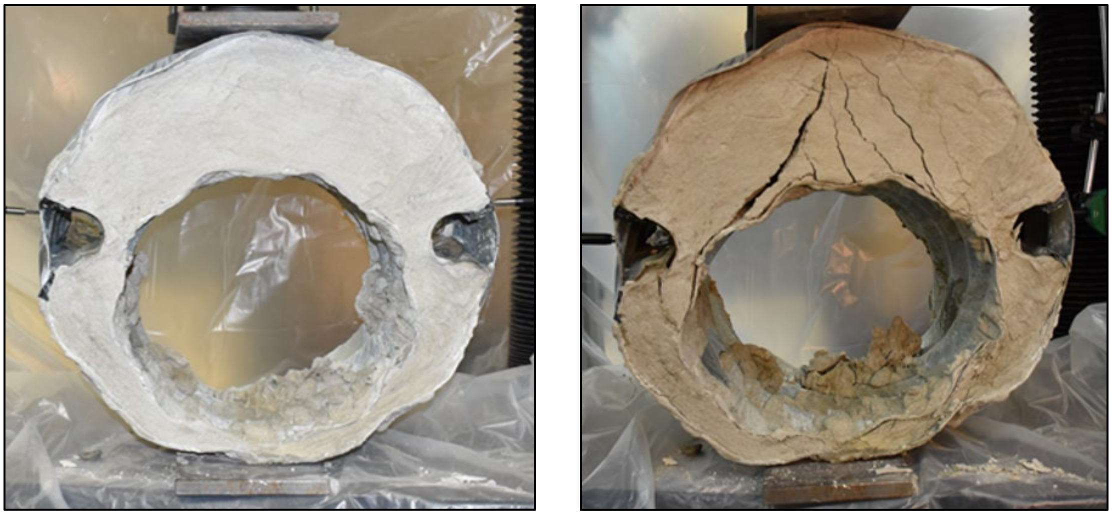


Figure E.59: Sliplined Culvert using C40 Cellular Grout with Voids at the Springline: Before (*left*) and After (*right*) Parallel-plate Load Test.

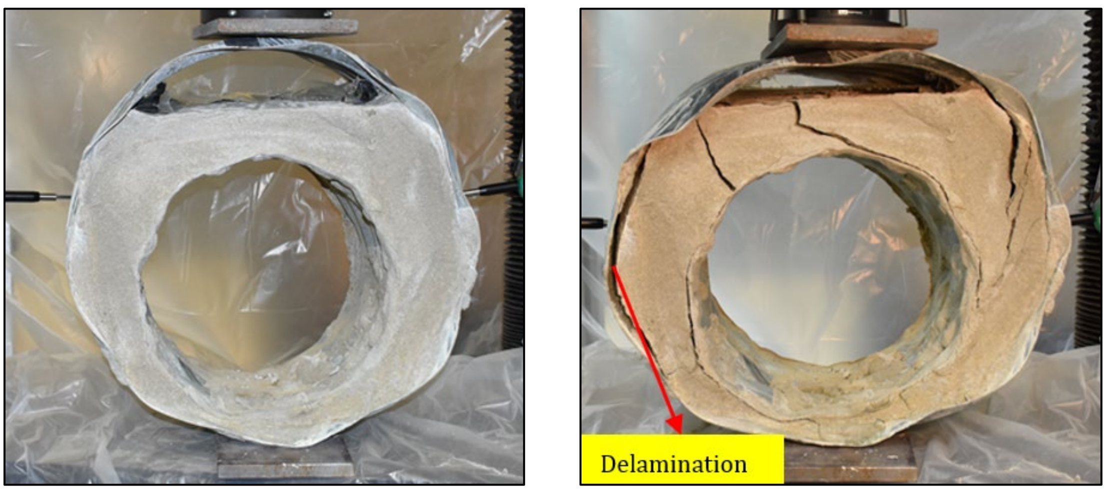


Figure E.60: Sliplined Culvert using C40 Cellular Grout with Voids at the Crown: Before (*left*) and After (*right*) Parallel-plate Load Test.

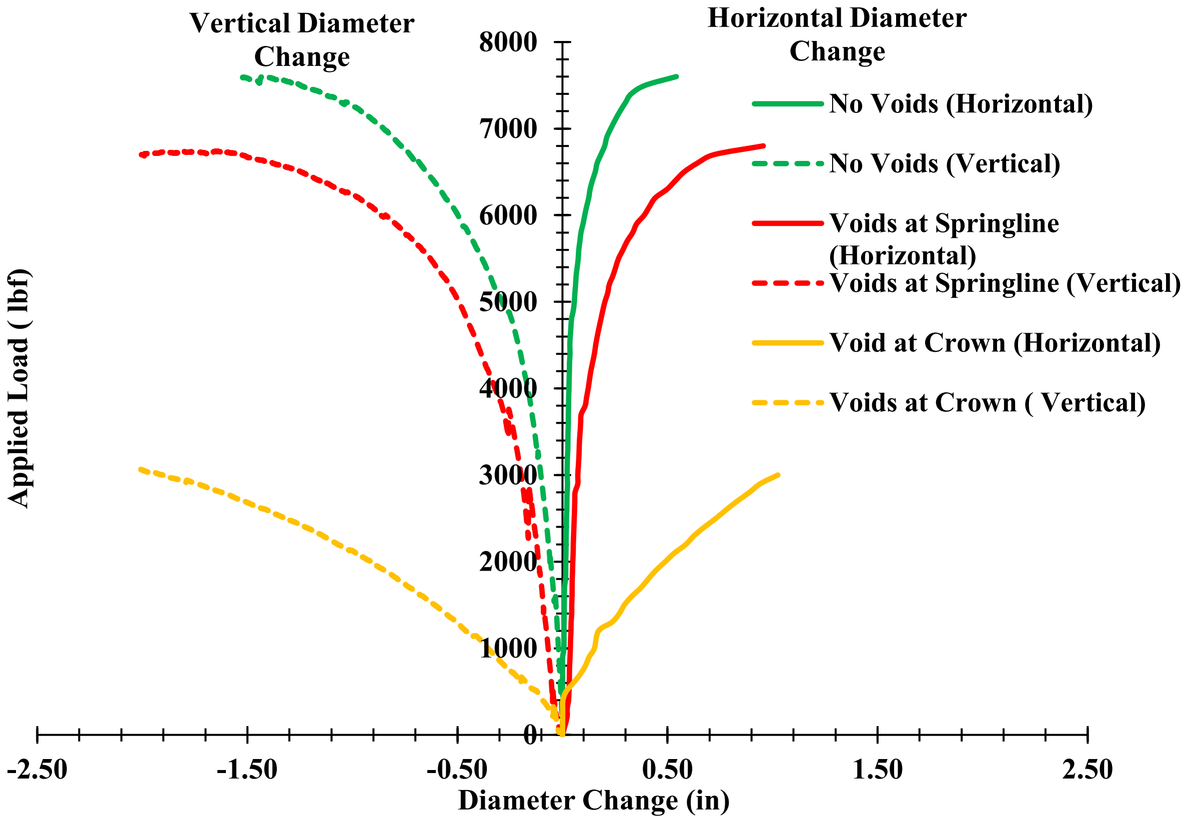


Figure E.61: Load-carrying Capacities of Sliplined Culverts with C40 Cellular Grout with No Voids and with Voids at the Springline or the Crown.

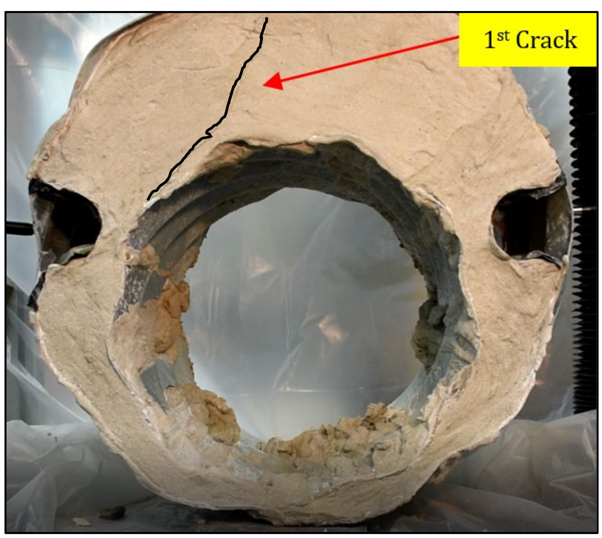


Figure E.62: First Crack in a Culvert with C40 Cellular Grout with Voids at the Springline.

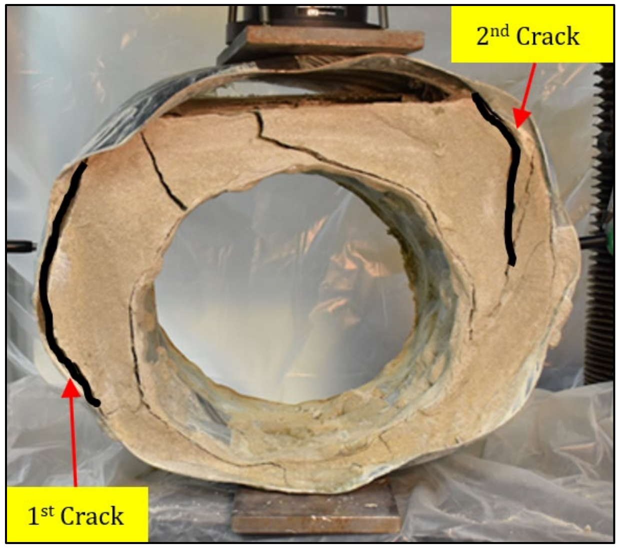


Figure E.63: Initial Cracks of Sliplined Culvert with C40 Cellular Grout with Voids at the Crown.

The effect of grout on the load-carrying capacities of sliplined culverts with no voids and voids at the crown or springline position are summarized in Table E.12. It can be noticed that voids significantly impact the grout's contribution to the load-bearing capacity of the culvert. For example, the grout's contribution was 21% lower when voids are at the springline location as compared to that for a fully filled annulus. In contrast, when a void is present at the crown, the grout's contribution is reduced by 87%. These findings suggest that voids at the crown may be the main cause of vertical and horizontal distortion of the culvert as well as delamination at the sides of the culvert. Voids at the crown position are more detrimental to the performance of sliplined culverts than the voids at springlines.

Table E.12: Load-Carrying Capacities of the Sliplined Culverts using C40 Grout Mix and at a 5% Vertical Diameter Change

Culvert	Applied load at 1st crack (lbf)	Load-Carrying Capacity of Culvert*, *A* (lbf)	Contribution of Host Pipe, *H* (lbf)	Contribution of Liner Pipe, *L* (lbf)	Contribution of Grout, *G* (lbf); *G = A − H − L*
C 40 Mix Culvert (No Void)	3,800	7,096	548	423	6,125
C 40 Mix Culvert (Void at Springline)	3,000	6,082	548	423	5,111
C 40 Mix Culvert (Void at Crown)	500	1,977	584	423	1,006

* considering a 5% change in vertical diameter

E.12 Concluding Comments

The following conclusions can be made based on the main findings of tests on the fresh and hardened properties of the cellular grout:

- Foaming agents play a role in determining the density of the resulting foam. Protein-based foaming agents produced a less dense foam than synthetic and surfactant foaming agents. There may be some variations in density, but overall, they are well within the range allowed by ASTM C796 and ACI 5283.3R-14.
- Conditions that may affect foam stability are to be taken into account in studies on foaming stability. For example, it was discovered that mixing foaming agents with high-temperature water (100 ^{o}F) before adding the foam to the slurry mix, will affect the foam's stability and cause the foam to have lower performance. Because of this, it is concluded that normal room temperature (68 ^{o}F to 72 ^{o}F) is ideal for preparing the foam before mixing it with cement slurry.
- This study considered cellular grout with various densities, which may range from 10 to 75 lb/ft^3. As the cellular grout stability tests indicated, casting cellular grout with an exceptionally low density (such as 10 lb/ft^3 for C10 cellular grout) will lead to progressive collapse within the first few hours after casting, since C10 cellular grout contains a significant amount of foam (contributing about 96% of the total volume of the mix). C10 cellular grout was eliminated from further consideration because of its unstable performance. Not only does the ultra-low density affect the performance of a cellular grout but mixing and placing a cellular grout at a high temperature (100 ^{o}F) is the primary factor that contributed to the instability of the grout.
- The w/c ratio considerably impacts the cast-wet density. Using the method outlined in ACI 523.R.14 for designing the mix proportions of a cellular grout, the resulting

w/c ratio may vary from 0.2 to 0.4 for grouts with various densities (ranging from 10 to 75 lb/ft^3), but results in a cast-wet density that exceeds the standard acceptance limit (which is the design density ±3 lb/ft^3). After mixing multiple batches of grouts, it was discovered that adjusting the w/c to 0.5 would result in a cast-wet density that falls within the acceptable range.

- One of the most important endeavors of this project is to guarantee that the cellular grout can flow or spread freely. This was accomplished by using both a spread test and a flow cone test as the basis. According to the experimental findings, slurry grout mixed with protein-based or synthetic-based foaming agents perform better in the spread test and flow cone test than slurry grout mixed with a surfactant foaming agent. For example, the results of the experimental testing demonstrated that the spread of most cellular grout mixes fulfills the minimum ACI spread standards of 8 inches, except for C20 and C30 mixes that were prepared with a surfactant foaming agent. In addition, all cellular grout mixes were found to flow through a discharge tube with a diameter of ½- inch despite having different densities and different foaming agents.
- The volume of plastic air content in cellular grout was determined in this project. A linear relationship was found between the plastic density (cast-wet density), the air content or the percentage of foam. In addition, mixing different foaming agents with cellular grouts, such as synthetic-based or protein-based foaming agents or surfactants was found to have only a slight impact on the plastic air content of the cellular grout, despite the fact that the plastic density remains the same for the different grouts.
- Specimens mixed with surfactants or protein foaming agents exhibited lower losses of oven-dry density than those mixed with synthetic foaming agents. However, C40 cellular grout prepared using any of the four foaming agents meets the requirements of ASTM C796 for the oven-dry density of cellular grout (30.4±2.5 lb/ft^3)
- Water absorption of the cellular grout has a uniform impact, with the experimental results suggesting that water absorption increases gradually with the density of the cellular grout. When cellular grout was mixed with surfactant foaming agents, the percentage of water absorption was found to be the lowest. On the other hand, the water absorption percentage was highest when the slurry mix was mixed with protein-based foaming agents, and grouts prepared with synthetic-based foaming agents showed an average value. According to ASTM C796, the maximum water absorption must be less than 25%, and C40 cellular grout was found to comply with this standard. Conversely, mixtures C55, C65, and C75 exhibited substantial absorption of water because of the lower quantity of foam added to the slurry mix.
- There is a positive relationship between drying shrinkage and the density of the cellular grout. The drying shrinkage values also increase when there is a greater rise in the density of the cellular grout. High-density cellular grouts such as C65 and C75 mixes have a significant amount of dry shrinkage because of their high cement contents and lack of aggregates. In contrast, grouts with lower densities (such as C20 and C30 mixes) exhibit less dry shrinkage due to the high quantity of foam. The type of foaming agent used was also found to influence the dry shrinkage. For

example, cellular grouts mixed with surfactant foaming agents showed more drying shrinkage than those mixed with protein-based or synthetic-based foaming agents. Despite the fact that different foaming agents have different drying shrinkage rates, most mixtures that were investigated in this study still conform to the ACI Committee 523.3R limits for cellular grout shrinkage, with drying shrinkage rate limits of 0.1% and 0.4%.

- The type of foaming agent was found to affect the mechanical properties of the grout material, including compressive strength and split tensile strength. The results of both tests demonstrated that the performance of the mixtures was significantly improved by adding surfactant foaming agents as opposed to synthetic-based or protein-based foaming agents. The minimum requirements of ASTM C869/C869M-11 for cellular grout are met by mixes C40, C55, C65, and C75 at 28 days, as measured by compressive strength (minimum of 200 psi) and split tensile strength (minimum of 25 psi).
- Parallel plate loading tests were carried out on the representative sliplined culvert specimens using two grouts (CLSM Mix A and C40 cellular grout) that had voids in various positions. The findings demonstrated that voids have a substantial influence on the contribution of the grout to the structural strength. When compared to the strength of a culvert with a completely filled annulus, for example, the grout's contribution to the strength of a culvert with voids at the springline was 21% lower. In contrast, when voids are located near the crown, the grout's contribution to the strength of the culvert is reduced by 84% as compared to the grout's contribution in a culvert with a completely filled annulus. From these results, voids at the crown position of a sliplined culvert are a primary source of vertical and horizontal deformation as well as delamination at the sides of the culvert and are more detrimental to the structural load-carrying performance than the voids at springline positions.

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Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX F

Controlled Low Strength Mortar (CLSM) Grout

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Prepared for:
The Ohio Department of Transportation,
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February 2023
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U.S. Department of Transportation
Federal Highway Administration

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APPENDIX F
CONTROLLED LOW STRENGTH MORTAR (CLSM) GROUT

F.1 Introduction

The key objective of the laboratory testing of controlled low strength mortar (CLSM) grout is to identify the most important characteristics affecting the performance of annulus void fill materials in the annulus void filling of sliplined culverts. Assessment of fresh and hardened properties of CLSM will aid in understanding the impact of materials, mix proportions, and other characteristics on the filling of annulus voids. This appendix discusses the materials used in CLSM mix design, basic mix proportions from several transportation agencies, and tests that were conducted on improved trial mixes to investigate the important engineering properties of CLSM.

F.2 Materials

In general, CLSM is a mixture of binder materials (such as Portland cement, fly ash, fine aggregate, etc.) and water. Air entraining admixtures (AEA) and several other admixtures are used to improve the flowability of the mixture. For the CLSM grout mixture in this project, Cement Type I/II and Class F are used as cementitious materials, along with Class C Fly Ash fine aggregate, water, AEA, and a flowable fill admixture. The properties of all the materials used in this study are described in the following subsections.

F.2.1 Cement

Type I/II Portland Cement was obtained from Fairborn Cement Company (Xenia, Ohio) and supplied by W. L. Tucker Supply Co. (Cuyahoga Falls, Ohio), one of the largest suppliers from Northeast Ohio. The Portland cement was tested by Fairborn Cement in accordance with ASTM C150 (ASTM, 2020) and AASHTO M 85 (AASHTO, 1994). The supplier stated that the cement supplied met all the requirements from the specifications. The chemical compositions and physical properties of Portland cement are presented in Table F.1 and Table F.2, respectively.

F.2.2 Fly ash

Some types of Fly ash act as a cementitious material when added to concrete mixtures. Fly Ash aids in forming a stable mix and improves the workability, and it can improve the long-term strength of CLSM. The CLSM mixtures in this project were prepared using both Class C and Class F fly ash, which were obtained from Fly Ash Direct (a service of Waste Management, Inc., in Cincinnati, Ohio). Both the Class C and Class F fly ash are reported to meet the requirements of AASHTO M 295 (AASHTO, 2011) and ASTM C618 (ASTM, 2019). The results of the physical and chemical analysis of Class C and Class F fly ash, which were performed by Fly Ash Direct, are shown in Table F.3 and Table F.4, respectively.

Table F.1: Standard Composition Requirements of Portland Cement

Chemical Composition (ASTM C 114)	Specification	ASTM C150 Type I	ASTM C150 Type II	Result
Silicon dioxide (SiO_2), %	--	--	--	19.1
Aluminum oxide (Al_2O_3), %	Maximum	--	6.0	4.5
Ferric oxide (Fe_2O_3), %	Maximum	--	6.0	3.1
Calcium oxide (CaO), %	--	--	--	62.1
Magnesium oxide (MgO), %	Maximum	6.0	6.0	4.7
Sulfur trioxide (SO_3), %	Maximum	3.0	3.0	3.3
Loss on ignition (LOI), %	Maximum	3.5	3.5	2.5
Insoluble residue, %	Maximum	1.5	1.5	0.54
Alkalies (Na_2O equivalent), %	--	--	--	0.82
Tricalcium silicate (C_3S), Potential %	--	--	--	61
Dicalcium silicate (C_2S), Potential %	--	--	--	6
Tricalcium aluminate (C_3A), Potential %	Maximum	--	8	6
Tetracalcium aluminoferrite (C_4AF), Potential %	--	--	--	9
$C_3S + 4.75C_3A$	Maximum	--	100	92
CO_2, %	--	--	--	1.5
Limestone, %	Maximum	5.0	5.0	3.6
$CaCO_3$ in Limestone, %	Minimum	70	70	97

Table F.2: Standard Physical Requirements of Portland Cement

Physical Requirements	Specification	ASTM C150 Type I	ASTM C150 Type II	Result
Blaine fineness (ASTM C204), m^2/kg	Range	260 min.	260–430	411
Time of setting (Vicat; ASTM C191), Initial Set, minutes	Minimum	45	45	90
Time of setting (Vicat; ASTM C191) Final Set, minutes	Maximum	375	375	196
Air content (ASTM C185), %	Maximum	12	12	7
Autoclave expansion (ASTM C151), %	Maximum	0.80	0.80	0.16
Expansion in water (ASTM C1038), %	Maximum	0.02	0.02	0.013
Normal consistency (ASTM C187), %		--	--	26.2
Heat of hydration (ASTM C1702) 3 day, cal/g		--	--	82
1 Day compressive strength (ASTM C109), psi	--	--	--	2781

Table F.2: Standard Physical Requirements of Portland Cement [Continued]

3 Day compressive strength (ASTM C109), psi	Minimum	1740	1450	4385
7 Day compressive strength (ASTM C109), psi	Minimum	2760	2470	5251
28 Day compressive strength (ASTM C109), psi	Minimum	4060	4060	6193

Table F.3: Chemical and Physical Analysis of Class C Fly Ash

Physical or Chemical Property	**AASHTO M 295**	**ASTM C618**	**Actual Value**
Fineness (+325 Mesh)	34% max.	34% max.	13.30%
Fineness variation	5.0% max.	5.0% max.	2.60%
Moisture content	3.0% max.	3.0% max.	0.05%
Density (ASTM C188), g/cm^3	--	--	2.70
Density variation	5.0% max.	5.0% max.	1.20%
Loss on ignition	5.0% max.	6% max.	0.15%
Soundness	0.8% max.	0.8% max.	0.04%
Strength activity index (SAI), 7 days	75% min.	75% min.	96.80%
Strength activity index (SAI), 28 Days	75% min.	75% min.	100.80%
Water req. % control	105% max.	105% max.	94.20%
Silica (SiO_2)	--	--	36.85%
Aluminum oxide (Al_2O_3) w/minor oxides	--	--	20.17%
Ferric oxide (Fe_2O_3)	--	--	5.58%
Total	50% min.	50% min.	62.60%
Sulfur trioxide (SO_3)	5% max.	5% max.	1.53%
Calcium oxide (CaO)	--	--	26.27%
Magnesium oxide (MgO)	--	--	5.63%
Available alkalies (Na_2O)	1.50% max.	--	1.44%

Table F.4: Chemical and Physical Analysis of Class F Fly Ash

Physical or Chemical Property	**AASHTO M 295**	**ASTM C618**	**Actual Value**
Fineness (+325 Mesh)	34% max.	34% max.	26.40%
Fineness variation	5.0% max.	5.0% max.	1.90%
Moisture content	3.0% max.	3.0% max.	0.10%
Density (ASTM C188), g/cm^3	--	--	2.39
Density variation	5.0% max.	5.0% max.	0.95%
Loss on ignition	5.0% max.	6% max.	1.53%
Soundness	0.8% max.	0.8% max.	−0.02%
Strength activity index (SAI), 7 days	75% min.	75% min.	75.70%
Strength activity index (SAI), 28 Days	75% min.	75% min.	76.00%
Water req. % control	105% max.	105% max.	98.30%
Silica (SiO_2)	--	--	47.22%
Aluminum oxide (Al_2O_3) w/minor oxides	--	--	27.53%
Ferric oxide (Fe_2O_3)	--	--	13.37%
Total	50% min.	50% min.	88.12%
Sulfur trioxide (SO_3)	5% max.	5% max.	1.46%
Calcium oxide (CaO)	--	--	2.55%
Magnesium oxide (MgO)	--	--	0.65%

Table F.4: Chemical and Physical Analysis of Class F Fly Ash [Continued]

Physical or Chemical Property	AASHTO M 295	ASTM C618	Actual Value
Available alkalies (Na_2O)	1.50% max.	--	2.70%
Sodium oxide (Na_2O)			1.76%
Potassium oxide (K_2O)			1.88%
Total alkalies (as Na_2O equivalent)			3.00%

F.2.3 Fine aggregate

The fine aggregate (sand) was supplied by W. L. Tucker Supply Co. The fine aggregate was found to meet the requirements of ASTM C33 (ASTM, 2018) as shown in Figure F.1 and listed in the ODOT Construction and Material Specifications (ODOT, 2019). The fine aggregate was in a saturated, surface dry condition and was sieved using a No. 4 sieve. The gradation analysis, which was performed in the lab according to the ASTM C136 (ASTM, 2019), is presented in Table F.5.

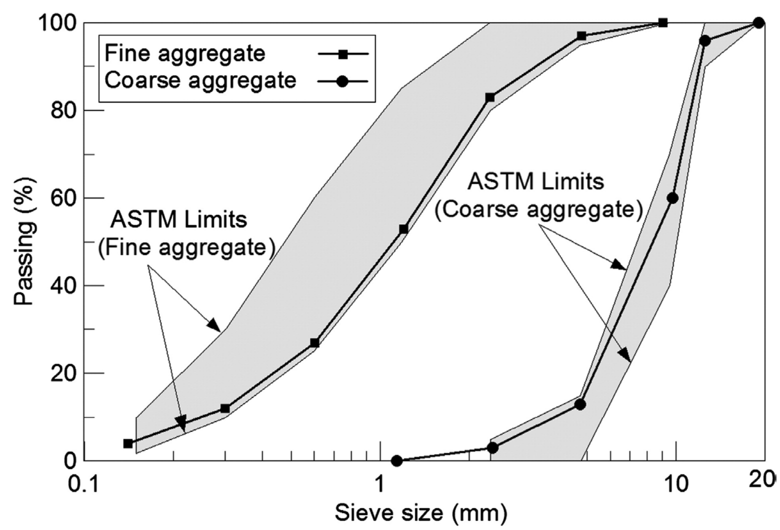

Figure F.1: ASTM C33 Upper and Lower Limits for Fine Aggregate (Bolouri Bazaz and Khayati, 2012).

Table F.5: Sieve Analysis of Fine Aggregate

Sieve Size	Natural Sand Total Percent Passing	Manufactured Sand Total Percent Passing
No. 4	100	100
No. 8	95 to 100	95 to 100
No. 50	10 to 40	20 to 40
No. 100	0 to 15	10 to 25
No. 200	0 to 5	0 to 10

F.2.4 *Water*

Tap water was used to prepare all CLSM mixtures. No special requirements were stipulated for potable water used in the mixtures.

F.2.5 Admixtures

F.2.5.1 *Air-Entraining Agents*

Air-entraining agents (AEAs) are chemical admixtures that are commonly used for CLSM mixtures. Sika® AIR admixture (Sika Corporation, Lyndhurst, N.J.) was used in the CLSM mix in this project. This air entraining admixture meets the physical requirements for AEA outlined in ASTM C260, which are summarized in Table F.6.

Table F.6: Physical Requirements of Air-Entraining Admixtures

Physical Factor	Requirement
Initial time of setting, allowable deviation from control (h:min), not more than	1:15 earlier or 1:15 later
Final time of setting, allowable deviation from control (h:min), not more than	1:15 earlier or 1:15 later
Compressive strength (3 days), min., % of control	90
Compressive strength (7 days) compressive strength, min., % of control	90
Compressive strength (28 days), min., % of control	90
Flexural strength (3 days), min., % of control	90
Flexural strength (7 days), min., % of control	90
Flexural strength (28 days), min., % of control	90
Length change, max. shrinkage (alternative requirements): Percent of control	120
Length change, max. shrinkage (alternative requirements): Increase over control, %	0.006
Length change, max. shrinkage (alternative requirements): Relative durability factor, min.	80
Length change, max. shrinkage (alternative requirements): Bleeding of the net amount of mixing water, max. % over control	2

F.2.5.2 *Fill Flow*

Another chemical admixture that has been used in the concrete industry to increase the flowability and reduce the water-cement ratio is Fill Flow (shown in Figure F.2). It is a dry-powdered surfactant that is compatible with conventional CLSM mixtures and does not contain calcium chloride or any other corrosive agents. According to Fritz-Pak Corporation, the recommended dosage rate for Fill Flow is to use one 1-lb bag and 25 to 30 gallons of water for 1 cubic yard of CLSM mix, using a mixing time of 5 to 7 minutes after all ingredients are added. Fritz-Pak Corporation provides a sample mix design for 1 cubic yard of CLSM mixture that includes 2200 lbs of sand or fine aggregate, 200 lbs of water, 50 to 100 lbs of cement, and 1 lb of Fill Flow. The unit weight of a mix that incorporates Fill Flow is typically 90 to 120 lbs/ft^3. The manufacturer recommends that Fill Flow be added at the job site to prevent the possibility of spilling during transporting. In addition, if the admixture seems hard, it is not recommended to use it in the mix, as it will not break up during mixing.

Fill Flow creates numerous air bubbles in solutions with high mineral concentration (such as cement pastes), and these bubbles act as "ball bearings" in the mix, increasing the volume of a conventional CLSM mix by 20% to 35% and reducing the water demand by 50%. Moreover, the strength of mix would not be decreased due to the increased air content resulting from the lower water-cement ratio. The use of a superplasticizer or a water-reducer may reduce the effectiveness of Fill Flow.

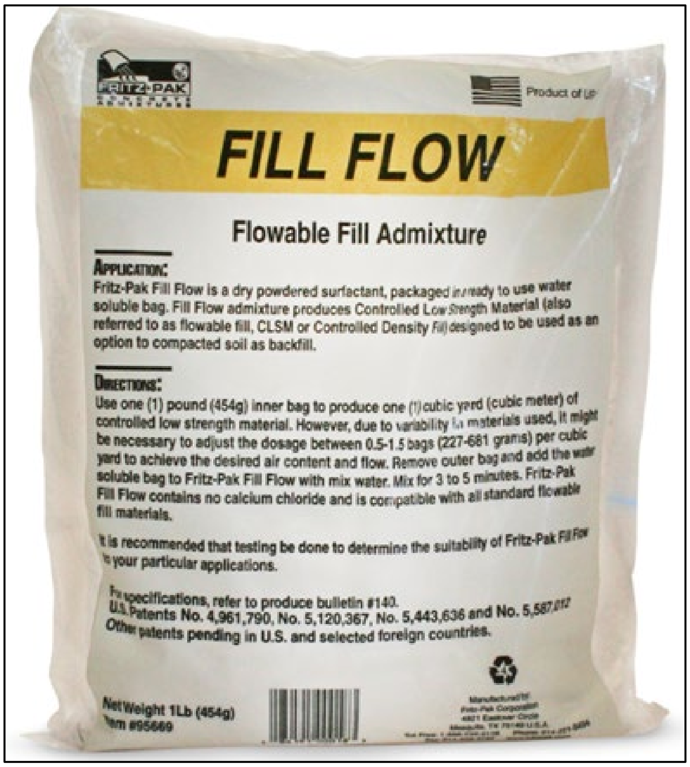

Figure F.2: Fill Flow Admixture.

Traditional CLSM mixtures have some common problems, such as excess bleed water, a disproportionate ratio of water and cement, and issues encountered during pumping. In order to make the mix flowable, many contractors will simply add water to the mix, which can create additional bleed. On the other hand, extra wet CLSM mixtures can also segregate during the pumping process. Fill Flow admixtures can make the mix flowable without the addition of excess water.

The advantages of using Fill Flow admixtures are provided below.

- Fill-Flow can reduce the material cost by increasing the yield volume due to the increase in the air content in the mix by about 20-25% air, thus resulting in significant reduction of material quantities.
- Patented water-soluble Fritz-Pak bag readily breaks down even in very fluid mixes.
- Easy handling and storage because Fill Flow is a dry powder, not a liquid.
- No problems with leakage, heat damage, or freezing.
- Produces an extremely fluid material with minimal shrinkage or segregation.
- CLSM can be placed directly from the ready-mix truck.
- Produces very stable air content.
- Cost-effective admixture for CLSM, as the cost for Fill Flow is $1.96/lb (large scale supply), which is the amount recommended for 1 yd^3 of CLSM grout.
- CLSM mixtures produced with Fill Flow are more pumpable and are faster to discharge from the truck.

F.2.5.3 *Mixing Procedure of Fill Flow*

In this project, the binder materials (such as cement, fly ash, and fine aggregate) were initially mixed with a small amount of water (about ¼ of the total amount needed). Fill Flow was added to the CLSM mixture with no access water (as shown in Figure F.3a) and was mixed for at least 5 to 7 minutes. It was found that adding too much water will cause the bubbles to become unstable; the foam will collapse, and bleed water will be produced. Alternately, water was added to the Fill Flow powder prior to pouring it into the dry binder materials (as shown in Figure F.3b). In both cases, the CLSM mix showed a similar air content.

Figure F.3: Mixing Fill Flow: Adding Powder Directly to the Mix (left), Mixing Fill Flow with Water Prior to Adding it to the Mix (right).

F.3 Mix Proportions

As there is no standard mix proportion specified for CLSM, several compositions and proportions that are typically used by different state transportation agencies were considered for this study. The primary purpose of the experimental tests was to identify the mix proportions for a flowable mix with the maximum spread (greatest flowability), minimal segregation, the least amount of bleeding and shrinkage, adequate compressive strength, and an acceptable setting time. All mixes contained cement and water, and the mixtures were divided into three groups based on the content of sand and/or fly ash (Class C and/or Class F): Group A mixtures contained both fine aggregate (sand) and fly ash, Group B mixtures contained fine aggregate only (no fly ash), and Group C contained fly ash only (no sand). The water-to-binder ratio, which was within the range of 0.32 to 3.51, was chosen by trial and error to obtain a self-flowable CLSM grout mix. Typical control mixtures were considered from each group and were given designations of Mix A, Mix B, and Mix C.

The goal of the study on mix proportions was to improve upon the three basic control mixes, with at least two variations in each group (the modified mixes are designated with names that incorporate the group letter as well as a number). Mixtures in Group A had around 1.3% to 4.4% cement by weight, 6.7% to 10% fly ash, and 71% to 78% sand. Mixtures in Group B had 3.5% to 5.7% cement by weight and a sand content of 81% to 84%. Mixtures in Group C contained 0% to 5.3% cement and had a high fly ash content (from 66% to 73%). Fill Flow admixture was used in half of the modified mixes in each group (Mixes A-4, A-5, B-2, C-3, and C-4). The mix proportions for all mixtures in this study are summarized in Table F.7.

Table F.7: CLSM Mixture Proportions

Mix ID	Mix Type	Cement Content (lb/yd^3)	Fly Ash Type	Fly Ash (lb/yd^3)	Sand Gradation	Sand Content (lb/yd^3)	Air Entraining Admixture (mL)	Fill Flow (g)	Water content (lb/yd^3)	Water/ Binder
A	Typical Mix	50	Class F	250	100% Passing Sieve No. 4	2910	0	--	500	1.67
A-2	Modified Mix	100	Class F	350	100% Passing Sieve No. 8	2578	0	--	540	1.20
A-3	Modified Mix	150	Class F	350	100% Passing Sieve No. 4	2590	0	--	521	1.04
A-4	Modified Mix	150	Class C	350	100% Passing Sieve No. 4	2590	0	1620	324	0.65
A-5	Modified Mix	100	Class F	350	100% Passing Sieve No. 4	2590	0	1620	324	0.72
B	Typical Mix	100	N/A	0	100% Passing Sieve No. 4	2420	729	--	351	3.51
B-1	Modified Mix	150	N/A	0	100% Passing Sieve No. 4	2227	702	--	375.3	2.50
B-2	Modified Mix	150	N/A	0	100% Passing Sieve No. 4	2160	0	1620	297	1.98
C	Typical Mix	0	Class F, Class C	1500 (Class F); 297 (Class C)	N/A	0	0	--	850	0.47
C-1	Modified Mix	150	Class F	2000	N/A	0	0	--	702	0.33
C-2	Modified Mix	150	Class F	2000	N/A	0	0	--	864	0.40
C-3	Modified Mix	150	Class F	2000	N/A	0	0	1107	702	0.33
C-4	Modified Mix	50	Class F, Class C	1500 (Class F); 300 (Class C)	N/A	0	0	1620	585.9	0.32

F.4 Mixing Procedure and Sample Preparation

CLSM is typically batched and mixed in the same way as a normal mortar/ concrete mixture. In this study, the dry mixture components (i.e., cement, fly ash, fine aggregate, fill flow admixture, etc.) and water were pre-measured to produce 1-ft^3 CLSM mixtures (Figure F.4). An electric mortar mixer (Figure F.5) was used to prepare the CLSM mixes. The drum of the mixer has a total capacity of 4.25 ft^3 and a paddle speed of 38 rpm, which is sufficient for producing a homogenous mix. In the mix procedure, the dry components were mixed thoroughly using the mortar mixer for at least 1 to 2 minutes. After ensuring a homogenous distribution of the dry materials, water was added and mixed until a smooth grout was obtained (Figure F.6).

Figure F.4: Measured Mixture Components Needed to Produce One Cubic Foot of CLSM Mix.

Figure F.5: Mortar Mixer used to Mix CLSM Grout: Side View (*left*), Top View (*right*).

Figure F.6: Mixing CLSM Grout using a Mortar Mixer: Mixing Dry Components (*left*), CLSM Mix after Addition of Water (*right*).

F.4.1 Casting of CLSM and sample preparation

A total of 12 cylindrical specimens with a diameter of 3 in. and a length of 6 in. were prepared from each mixture. The specimen molds were placed on a flat, level, and hard surface so that the CLSM mixtures could be poured into the molds without any compaction. Later, after curing, the cylindrical specimens were used for compressive strength tests, dry density tests, and water absorption tests.

F.4.2 Design of the experiments

Several laboratory tests were performed on specimens prepared from each of the 13 CLSM mixtures. Both fresh properties (such as density, efflux time, flowability, air content, and bleeding) and hardened properties (i.e., compressive strength, shrinkage, and settlement) were investigated using the relevant ASTM test methods, as summarized in Table F.8.

Table F.8: Tests Conducted on CLSM Mixtures

Type of Property	Property	ASTM Test Method
Fresh properties	Density	ASTM C138 (ASTM, 2001)
Fresh properties	Fluidity	ASTM C939 (ASTM, 2010)
Fresh properties	Flowability/ Slump	ASTM D6103 (ASTM, 2017)
Fresh properties	Air content	ASTM C138 (ASTM, 2001)
Fresh properties	Bleeding test	ASTM C940 (ASTM, 2016)
Hardened properties	Compressive properties	ASTM D4832 (ASTM, 2016)
Hardened properties	Shrinkage	ASTM C596 (ASTM, 2018)
Hardened properties	Water Absorption	ASTM C796 (ASTM, 2019)
Hardened properties	Oven dry density	ASTM C495 (ASTM,1999)

F.5 Fresh CLSM Properties

F.5.1 Flowability

Flowability of CLSM mixtures was measured in accordance with ASTM D6103-17 (ASTM, 2017). The test is performed using a 3-inch-diameter by 6-inch-high cylinder and a smooth, non-porous base plate with dimensions of 36” × 36” × 0.5”, as shown in Figure F.7. The cylinder is filled to the top edge with CLSM mixture and is leveled with a stiff metal straightedge. The spillage from the cylinder is removed after striking off. The cylinder is then lifted quickly (within 5 seconds) to allow the fresh mix to freely flow over the smooth plate. It is recommended to complete the entire test (from the start of filling through to the removal of the flow cylinder) without interruption within an elapsed time of 60 seconds. The diameter of the largest resulting spread diameter of the CLSM grout is measured using measuring tape (as shown in Figure F.8) and recorded. Two measurements of the spread diameter (the second measurement is made perpendicular to the first) are taken, and the final spread is calculated by taking the average of the two measurements.

Figure F.7: Base Plate for Flow Consistency Test of CLSM.

Figure F.8: Measurement of Spread Diameter to Calculate the Flowability of a Fresh CLSM Mixture: First Measurement (*left*) and Second Measurement (*right*).

F.5.2 Flow of grout (flow cone method)

It is very important to measure the grout flow to obtain a flowable mix in both the field and the laboratory. Test method ASTM C939-16a, “Flow of Grout for Preplaced-Aggregate Concrete” (ASTM, 2016), is used to determine the time of efflux of a specified volume of CLSM grout as it passes through a standardized flow cone (as shown in Figure F.9a). In this test, a flow cone is mounted firmly on a frame to prevent vibration. The accuracy of the flow cone should be checked before using it for grout flow; the time of efflux of water indicated by the stopwatch should be 8.0 ± 0.2 sec, according to the ASTM standard. After verifying the accuracy, the flow cone is moistened by filling the cone with water 1 min. prior to pouring the CLSM grout sample. The grout sample is then introduced into the cone (as shown in Figure F.9.b), making sure that the discharge tube is kept closed using one finger until the grout surface rises and comes into contact the point gauge. Once the grout reaches the point gauge, the finger can be removed and, simultaneously, a stopwatch is activated. The time indicated by the stopwatch after a sufficient amount of grout has passed through the flow cone (such that light is visible through the discharge tube), is considered to be the efflux time for the grout. An efflux time of fewer than 35 seconds is considered to be suitable for the purposes of the ASTM test. However, there is no recommendation on the range of efflux time that is required to demonstrate good flow.

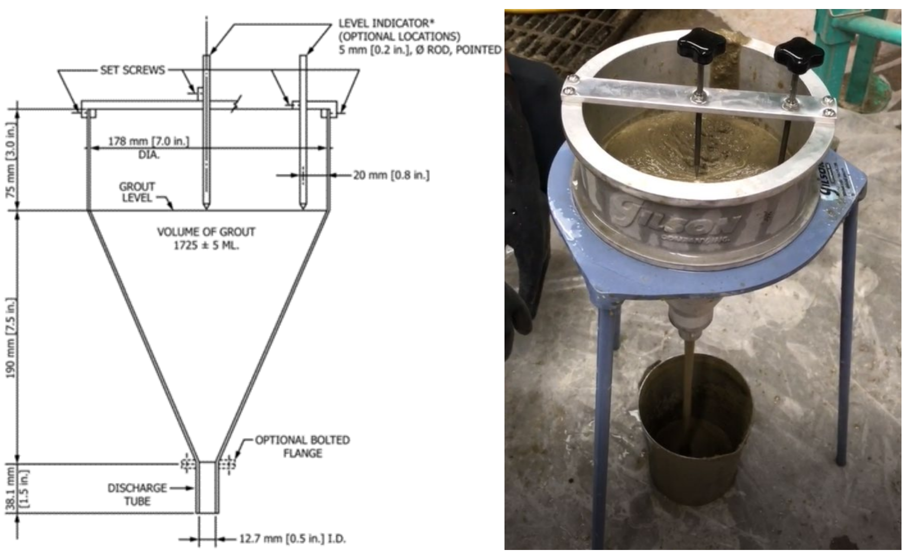

Figure F.9: Grout Flow Test for CLSM mixtures: Diagram of Test Setup (*left*), Flow Cone Mounted in a Support Frame (*right*).

F.5.3 Density

The density of the freshly mixed CLSM was measured in accordance with ASTM D6023-16. In this test, a cylindrical steel mold that is 8 in. in diameter and 8.75 in. in depth is filled with fresh grout mix as shown in Figure F.10. The top surface of the CLSM is leveled using a smooth plate. The mass of the CLSM grout is determined by subtracting the mass of the empty mold from the gross mass of the mold when filled with grout. Lastly, the density of the CLSM mix is obtained by dividing the mass of the CLSM mix by the volume of the mold. A sample calculation for a mold with a weight of 9.7 lb, a diameter of 8 in., and a depth of 8.75 in. is shown below:

$$Mold + Grout\ Weight = 40\ lb$$

$$Grout\ Weight = (40\ lb - 9.7\ lb) = 30.3\ lb$$

$$Mold\ Volume = \pi * (d^2 h)/4 = \pi * 8^2 * 8.75/4 = 439.82\ in^3 = 0.25\ cu.ft.$$

$$Grout\ Density = Grout\ Weight\ /\ Mold\ Volume = \frac{30.3\ lb}{0.25\ ft^3} = 119\ lb/ft^3$$

Figure F.10: Density Test for Freshly Mixed CLSM.

F.5.4 Air content

The air content of the freshly mixed CLSM grout was determined according to ASTM C231-22a (ASTM, 2022). Figure F.11 shows an air meter that conforms to ASTM requirements. The vertical air chamber has a measuring bowl and cover assembly. The operational principle of this meter consists of equalizing a known volume of air at a known pressure in a sealed air chamber as shown in Figure F.11 with the unknown volume of air in the CLSM sample; the dial on the pressure gauge is calibrated in terms of percent air for the observed pressure at which equalization takes place. For the air content test in this project, the measuring bowl was filled with CLSM grout and rodding was not necessary for these flowable mixtures. After that, the cover was secured to the measuring bowl. The main air valve between the air chamber and the measuring bowl was closed, and both the petcocks in the cover were opened. Water was added through one petcock until water emerges from the opposite petcock. The air bleeder valve on the air chamber was closed, and air was pumped into the air chamber until the gauge needle was on the initial pressure line. The gauge hand was stabilized at the initial pressure line by pumping or bleeding off air as necessary and by tapping the gauge lightly by hand. Finally, the main air valve between the air chamber and the measuring bowl was opened. The percentage of air on the dial of the pressure gauge indicated the air content of the CLSM. After the test was completed, the pressure was released by opening both petcocks, and the cover was removed.

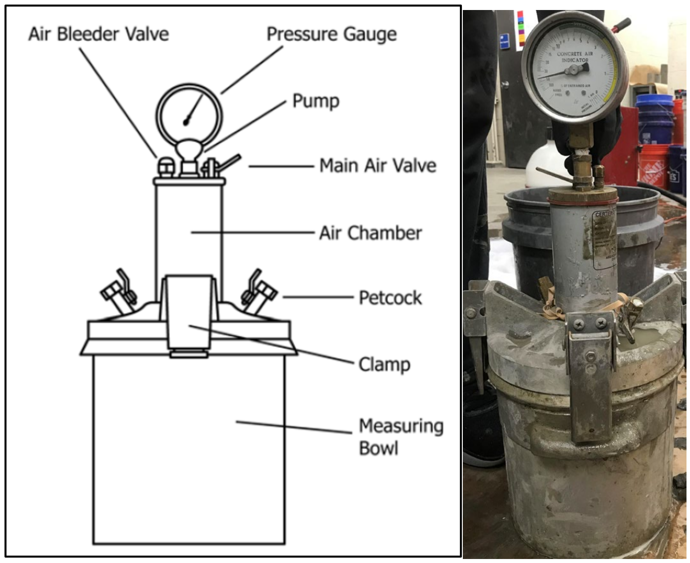

Figure F.11: Air Content Test: Diagram of a Vertical Air Chamber (*left*), Vertical Air Chamber used for Air Content Test of a CLSM Mixture (*right*).

F.5.5 Bleeding test

In this test, the amount of accumulated bleed water at the surface of the freshly mixed CLSM grout is determined. The standard test method for determining the amount of bleeding of a freshly mixed grout is ASTM C940-16, which is conducted using the setup shown in Figure F.12. Immediately after the mixing of the CLSM grout, the freshly mixed grout was introduced to a 1000-mL graduated cylinder until it reached 800 ± 10 mL volume, as shown in Figure F.12. The volume of the grout specimen was recorded at that time, and the graduated cylinder was covered to prevent water from evaporating. The reading at the upper surface of the grout and the volume of bleed water were recorded at 15-min intervals for the first hour and at 60 min intervals thereafter until two consecutive readings at the same value were recorded. According to the ASTM standard, the test should be discontinued 180 min after the initial reading. The ratio of the bleed water volume to the grout specimen volume is known as the *bleeding percentage* of the CLSM mixture.

$$Bleeding\ (\%) = \frac{V_w}{V_1} \times 100 \quad \text{(F.1)}$$

where V_1 is the volume of the specimen at beginning of test (in mL) and V_w is the volume of decanted bleed water (in mL).

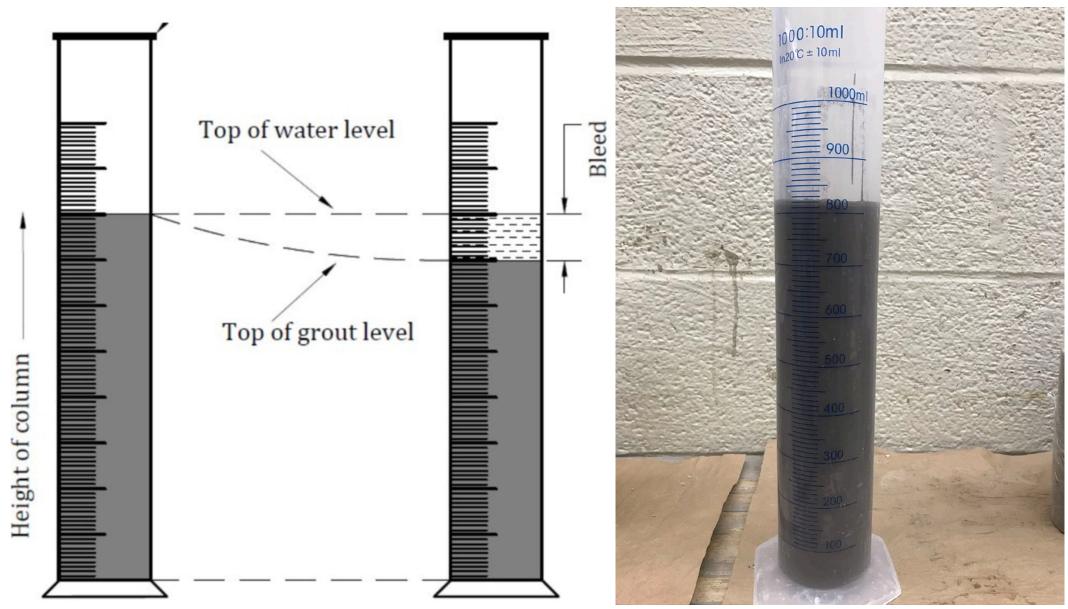

Figure F.12: Bleeding Test of Freshly Mixed CLSM Grout: ASTM C940 Setup (*left*), Graduated Cylinder used for the Bleeding Test (*right*).

F.6 Hardened Properties of CLSM

F.6.1 Unconfined compressive strength test

The unconfined compressive strength of CLSM specimens was determined using standard test method ASTM D4832-16 (ASTM, 2016). To prepare CLSM samples for compressive strength testing, 3-in. × 6-in. molds were used. Due to the weak early-age strength, the specimens were demolded 3 days after casting. Throughout this process, proper care was taken to ensure that the cylindrical samples would not be damaged. The samples were maintained in a curing room at 100% relative humidity for 28 days. The unconfined compressive strength test of the CLSM (see Figure F.13) was conducted after 28 days of curing using an Instron 5569 universal testing machine. The compressive loading was applied to the cylinder sample at a loading rate of 10 lb/sec to ensure that the failure of the cylinder would not occur in less than 2 min., as required by the test method. The equation for calculating the compressive strength is as follows:

$$C = \frac{L}{\pi D^2/4} \quad \text{(F.2)}$$

where C is the compressive strength (in psi), D is the nominal diameter of cylinder (in inches) and L is the maximum load (in lbf).

Figure F.13: Unconfined Compressive Strength Test: Setup with Specimen Loaded into Test Frame (*left*), Test Specimen that Failed when Loaded (*right*).

F.6.2 Drying shrinkage test

To determine any changes in length of specimens of CLSM mixtures, a standard test was conducted following ASTM C596-18 and ASTM C157-17. In this test, four 1” × 1” × 10” specimens were prepared for each mixture type as shown in Figure F.14. The shrinkage prisms were demolded 2-3 days after casting and were carefully handled. Because of the low strength and fragile nature of CLSM, some specimens broke during handling, and the gauge studs did not properly bond with the hardened mortar. The shrinkage samples were cured for 7 days before taking the initial comparator readings. Following this, the samples were stored in a drying room maintained at a temperature of 73 ± 3 °F and a relative humidity of 50 ± 4%. Readings were taken on a weekly basis for the next four weeks, using a length-comparator with a digital indicator (shown in Figure F. 15). No changes in recorded readings were observed after 28 days for any of the mixtures. The calculation for the length change or shrinkage of any specimen at any age after the initial comparator reading is as follows:

$$\Delta L_x = \frac{CRD - initial\ CRD}{G} \times 100 \qquad \text{(F.3)}$$

where *ΔLx* is the length change (shrinkage) of the specimen at any age (%), *CRD* is the difference between the comparator reading of the specimen and the reference bar at any age, and *G* is the gauge length (10 in.).

Figure F.14: Prism Samples used for Drying Shrinkage Measurements.

Figure F.15: Determination of the Change in Length of a CLSM Sample: Measuring an Invar Reference Bar in the Length Comparator (*left*), Length Comparator with a Shrinkage Sample of CLSM (*right*).

F.6.3 Water absorption and oven-dry density

The water absorption percentage and oven-dry density of the CLSM mixtures were measured in accordance with ASTM C642-13 (ASTM, 2013) and ASTM C495-19 (ASTM, 2019), respectively. Water absorption tests were conducted at 28 days of age for all CLSM mixtures. Initially, three cylindrical samples (3 in. in diameter by 6 in. in length) from each mixture were kept in an oven at 110 ± 5 °C (as shown in Figure F.16) and were weighed at 24-hr intervals until the loss in dry weight did not exceed 1% between each interval; the final weight is considered to be the dry mass of the specimen. After measuring the dry mass, the specimens were submerged in water maintained at approximately 21 °C for at least 48 hr (also shown in Figure F.16). The test specimens were then taken out every 24 hr, surface-dried by removing excess moisture with a towel, and weighed to obtain the wet mass of the specimen. The water absorption and oven-dry density were calculated based on the following equations:

$$Water\ Absorption\ (\%) = \frac{Volume\ of\ water\ absorbed\ by\ test\ specimen\ in\ 24\ h}{Volume\ of\ test\ specimen} \times 100 \quad \text{(F.4)}$$

$$Oven\ dry\ density\ (lb/ft^3) = \frac{Dry\ mass\ of\ the\ test\ specimen\ (lb)}{Volume\ of\ test\ specimen\ (ft^3)} \quad \text{(F.5)}$$

Figure F.16: Water Absorption Test of CLSM Specimens:
CLSM Specimens in the Oven (*left*), CLSM samples Submerged in Water (*right*).

F.7 Parallel Plate Loading Tests

Parallel plate loading tests were conducted on sliplined corrugated steel culvert specimens to determine their load-carrying capacities and facilitate a comparison between traditional CLSM grouts and the improved CLSM grout mixtures. In addition, to investigate the effect of voids on sliplined culverts, parallel plate loading tests were also conducted on a few sliplined culvert test specimens with voids at the crown and springline. The following subsections describe the preparation of sliplined culvert specimens, the parallel plate loading test setup, the test apparatus, the materials used for the tests, and other details.

F.7.1 Pipes and grout materials

F.7.1.1 *Host Pipe and Liner Pipe*

Zinc-coated (galvanized) corrugated steel pipes (shown in Figure F.17) were utilized for both the host and liner pipes of the sliplined culvert specimens prepared in this project. This corrugated steel pipe meets the requirements of ASTM A929–18 (ASTM, 2018) and AASHTO M 218 (AASHTO, 2011). The nominal diameter of the host pipe was 18 in., and the nominal diameter of the liner pipe was 12 in. The wall thickness of both pipes was 14 gauge (2 mm), and the nominal corrugation size was 2 ⅔ in. × ½ in. ASTM A929-18 requires that the flat steel sheet used to fabricate the pipe should have a tensile strength of 45 ksi, a yield strength of 33 ksi, and an elongation over 2 in. of 20%. In this project, 20-ft lengths of pipe of each diameter, which were procured from WinWater of Akron, were cut into 12-in. sections to meet the requirements of the parallel plate loading test, per ASTM D2412-21 (ASTM, 2021).

Figure F.17: Galvanized Corrugated Metal Pipe

F.7.1.2 *Grouts*

Two types of CLSM grouts were selected for use in the culvert specimens in this experimental program. The first, Mix A, is a typical grout mix; the second, Mix A-5, is a modified grout based on Mix A. The mix proportions of the grouts and the design compressive strength are presented in Table F.9.

Table F.9: Grout Mix Design for Parallel Plate Test

Proportion/Property	Mix A (Typical Mix)	Mix A-5 (Modified Mix)
Cement content	50 lb/yd^3	100 lb/yd^3
Fly ash type	Class F	Class F
Fly ash content	250 lb/yd^3	350 lb/yd^3
Fine aggregate	100% Passing Sieve No. 4	100% Passing Sieve No. 4
Fine aggregate content	2910 lb/yd^3	2590 lb/yd^3
Air entraining admixture	0 mL	0 mL
Fill Flow admixture	0 g	1620 g
Water content	500 lb/yd^3	324 lb/yd^3
Water/binder	1.67	0.72
Density	123 lb/ft^3	93 lb/ft^3
Compressive strength	92 psi	278 psi

F.7.2 Test setup for parallel plate loading test

In this project, parallel plate loading tests were performed on six sliplined culvert test specimens. In addition, samples of the host pipe and liner pipe were also tested to examine their load-carrying capacities using ASTM D2412-21 (ASTM, 2021). Several characteristics, such as the load at specific deflections, pipe stiffness, and the stiffness factor can be determined using this test. A universal testing machine with a load capacity of 300 kips with a crosshead movement of 0.25 in./min. was used in this research to apply vertical load on the sliplined culvert using the setup shown in Figure F.18. The host pipe and liner pipe were also tested using this device.

In the parallel plate test, two parallel steel bearing plates are used to apply load on the specimen. Flat and smooth plates with a thickness of ½ inch, a width of 6 in., and a length of 15 in. (which was longer than the specimen length) were used to transfer the load without any bending or deformation. In order to measure the change in diameter or deformation, digital dial gauges were placed in locations that were parallel and perpendicular to the direction of loading. The gauges, which had a range of 0 to 2 in. and a resolution of 0.0005, met the requirements of the ASTM standard for an instrument that is accurate to the nearest 0.010 in.

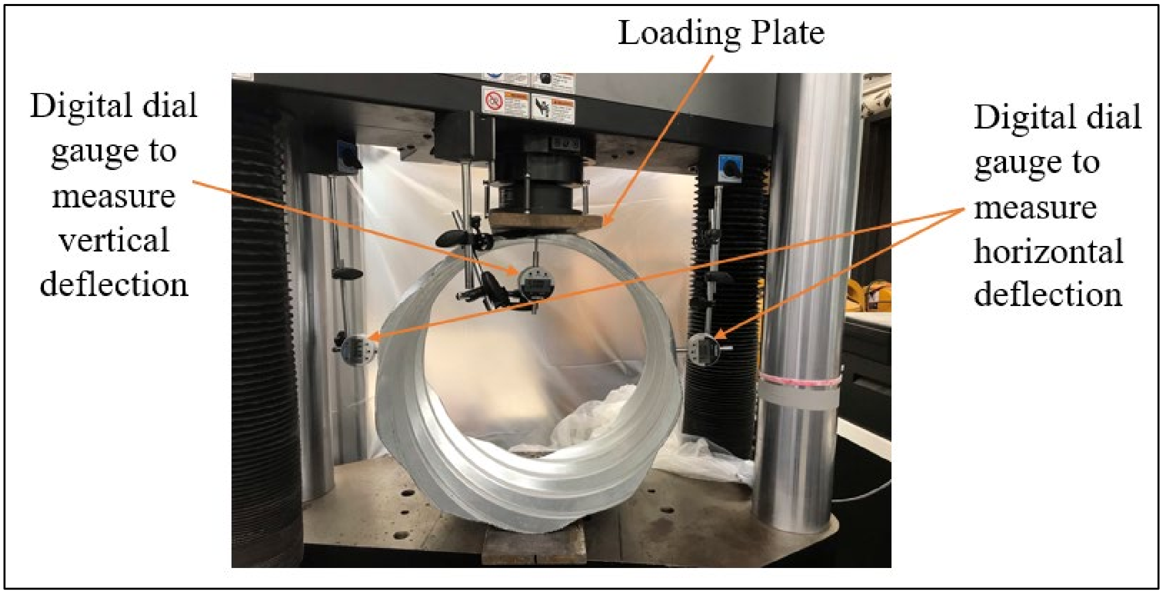

Figure F.18: Setup for Parallel Plate Loading Tests of a Corrugated Steel Pipes.

F.7.3 Parallel plate test configuration

In this research study, parallel plate tests were conducted on three types of sliplined culverts: Type I had no voids in the grout, Type II had a void at the crown position, and Type III had voids at the springline (as shown in Figure F. 19). To facilitate a comparison between the typical and modified CLSM mixes, tests were conducted with two CSLM grouts (Mix A and Mix A-5) on a culvert with no voids (Type I). Two specimens of each mix were prepared for this test. Sliplined culverts grouted with Mix A-5 with 2-in. voids at different positions were tested to evaluate the reduction in load-carrying capacity of the rehabilitated pipe due to the voids and void positions. A summary of the tests is shown in Table F.10.

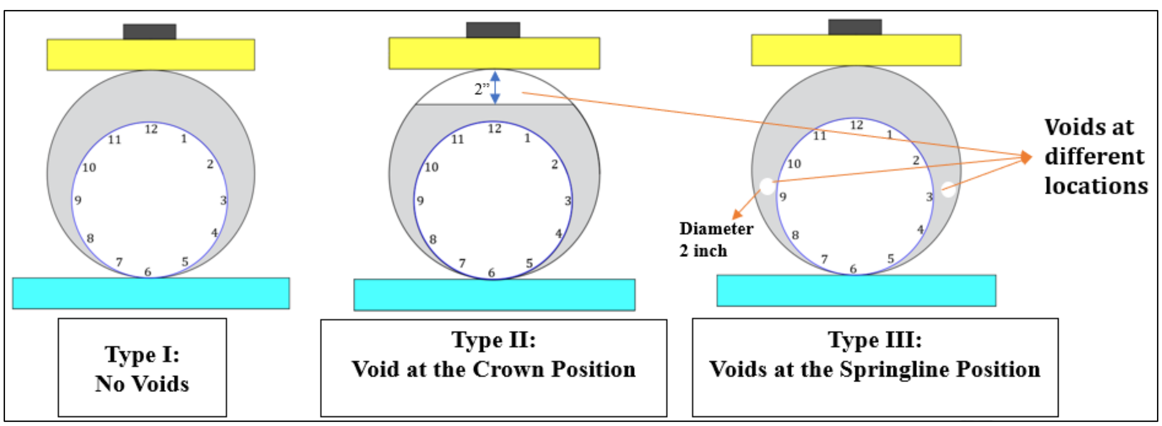

Figure F.19: Parallel Plate Test Configurations.

Table F.10: Configuration for Parallel Plate Tests of Culverts

Culvert Type	Mix	No. of Specimens
No voids (Type I)	Mix A	2
No voids (Type I)	Mix A-5	2
Void at the crown (Type II)	Mix A-5	1
Voids at springline (Type III)	Mix A-5	1

F.7.4 Sliplined culvert specimen preparation for parallel plate tests

Figure F.20 shows the process of preparing the culvert specimens. First, 20-ft-long corrugated metal pipes were cut into 1-ft sections. The bottom of the host pipe section was then wrapped with plastic to prevent the leakage of grout. The liner pipe was placed inside the host pipe, and the liner pipe was packed with sand to keep it stable while the annular space between the host pipe and liner was filled with grout. Finally, the annulus space was filled with a CLSM grout mixture (see Figure F.21).

Figure F.20: Preparation of Host Pipe and Liner: Cutting the Liner Pipe (*left*), Wrapping the Bottom of Host Pipe with Plastic (*center*). Liner Pipe Packed with Sand (*right*).

Figure F.21: Filling Annulus Voids of a Type I Culvert with CLSM Grout (Mix A-5): Pouring the Grout (*left*), Culvert Specimen with Fully Grouted Annulus (*right*).

Figure F.22 and Figure F.23 show the process for creating voids at the crown and springline of the Type II and Type III culvert test specimens, respectively. The 2-inch void at the crown of the sliplined pipe of the Type II culvert specimen was created by attaching Styrofoam at the crown position of the host pipe. Similarly, two cardboard tubes with diameters of 2 in. and a length of 12 in. were placed at the 3 o'clock and 9 o'clock positions of the Type III culvert specimen to create voids at the springline. The Styrofoam and tubes were removed from the culvert specimens 3 days after casting. The resulting specimens are shown in Figure F.24.

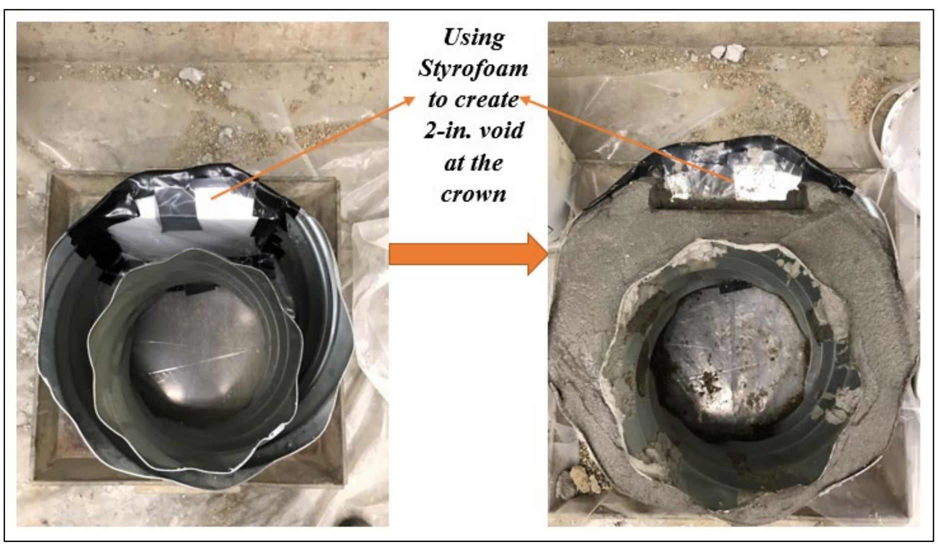

Figure F.22: Creating a Crown Void in the Sliplined Culvert.

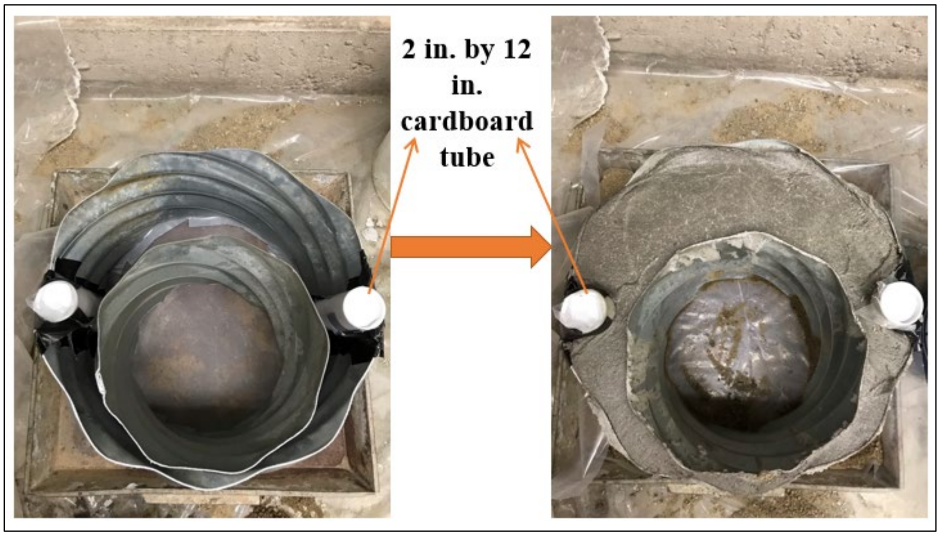

Figure F.23: Creating Springline Voids in the Sliplined Culvert.

Figure F.24: Sliplined Culvert Specimens: One with a Void at Crown (*left*) and One with Two Voids at the Springline (*right*).

Eventually, all of the sliplined culverts specimens were moved to the curing room (which was maintained at a relative humidity of 100%) and cured for 28 days (as shown in Figure F.25) before being subjected to parallel plate load tests.

Figure F.25: Sliplined Culvert Specimens in the Curing Room.

F.8 Results of Tests on Fresh CLSM Properties

This section provides a summary and discussion of the results of tests conducted in the laboratory to determine the fresh properties of CLSM mixtures, which aided in determining the best mixture proportions for an optimized CLSM mixture. These tests included flowability, air content, density, bleeding, and efflux time for typical and modified CLSM mixes in three test groups. The results of parallel plate tests on the sliplined culvert specimens are also presented. The analysis of these results provided an understanding of the effect of grout strength and the position of voids in the annulus on the load-carrying capacity of a sliplined culvert. Table F.11 presents the results of the tests conducted to determine the fresh properties.

Table F.11: Fresh Properties of Typical and Improved CLSM Mixtures

Mix ID	Flowability (inches)	Air Content (%)	Density (lb/ft^3)	Bleeding (%)	Efflux Time (sec)
Mix A	7	1.5	123	2.5	N/A
Mix A-1	16.5	0.4	119	1.4	15
Mix A-2	16	0.8	119	4.9	20
Mix A-3	16.5	1	121	4.9	15
Mix A-4	12.5	30	91	0.0	45
Mix A-5	11.5	30	93	0.0	37
Mix B	7	25	99	1.3	N/A
Mix B-1	13	20	103	2.5	34
Mix B-2	10.5	25	97	0.1	40
Mix C	17	0.7	99	3.8	10
Mix C-1	10.3	0.8	103	0.6	100
Mix C-2	17	0.7	100	3.7	16
Mix C-3	12	1.7	107	1.9	45
Mix C-4	12	1.8	105	0.9	70

F.8.1 Flowability

ACI Committee 229 (ACI, 2013) suggests meeting a spread diameter of at least 8 inches to allow good flowability for a CLSM mix. Figure F.26 shows that the flowability values of nearly all CLSM mixes tested in this project were greater than 8 in., except for two of the typical mixes (Mix A and Mix B). The flowability results for Group A CLSM mixes showed that all of the modified mixes were highly flowable and had better spread than the typical mix (Mix A). Similarly, in Group B, the modified mixes also had higher flowability than the typical mix (Mix B). In contrast, the typical Mix C in Group C, along with one modified mix (Mix C-2), showed better flowability than the remaining modified mixes (Mixes C-1, C-3, and C-4).

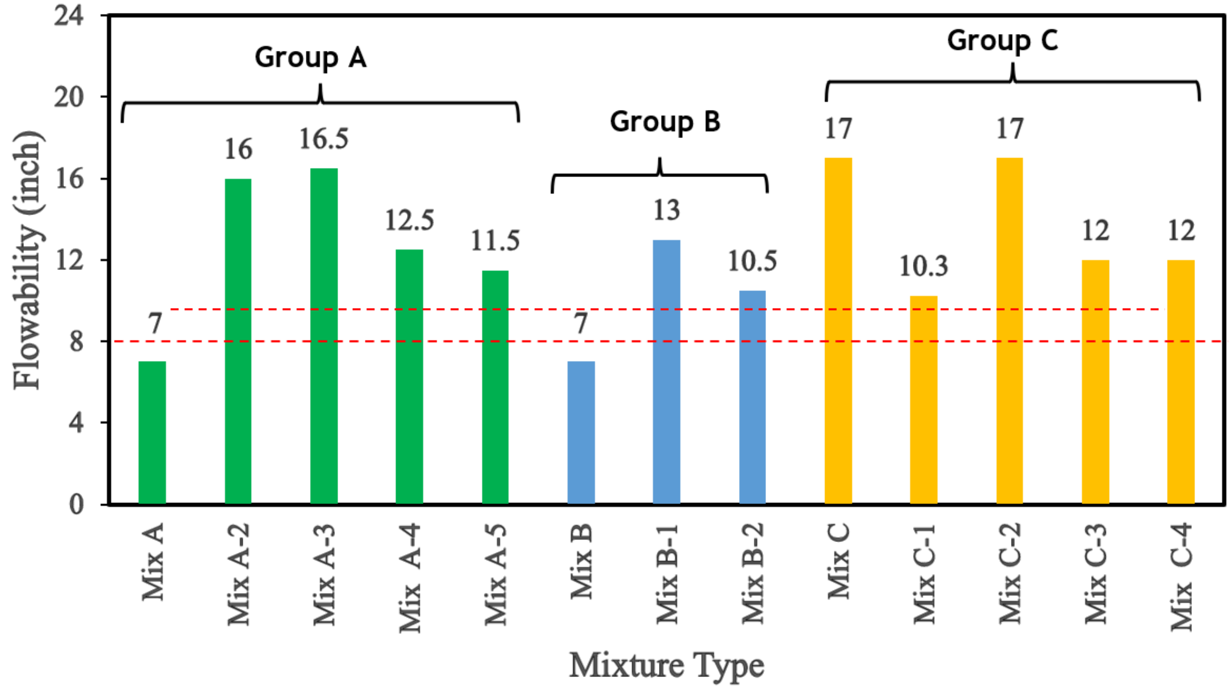

Figure F.26: Flowability of CLSM Mixtures.

ACI Committee 229 (2013) also reported that, in addition to the spread diameter, it is very important to have low segregation of the CLSM mixes during casting. It was found that all typical mixes (Mixes A, B, and C) had noticeable segregation during casting. Some of the modified CLSM mixtures (Mixes A-4, A-5, B-2, and C-4) were smoothly mixed and showed no segregation. This finding was attributed to the use of Fill Flow admixture, which created air bubbles in the CLSM mix and produced flowable mixes with no noticeable segregation.

In general, the amount of water in a CLSM mix controls the flowability (Nataraja and Nalanda, 2008). Figure F.27 presents the water-binder ratios of all CLSM mixes. These results show that there is no direct relation between the water-binder ratio and flowability. Thus, the water-binder ratio did not significantly affect the flow of CLSM mixtures.

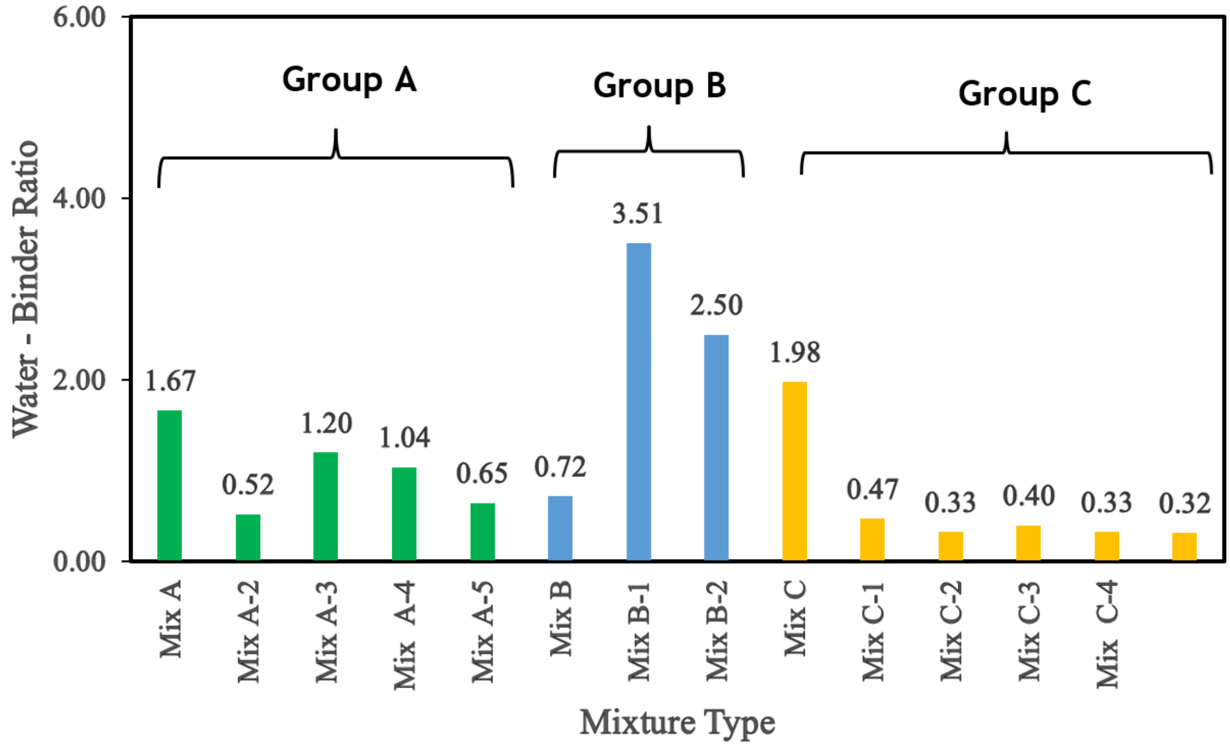

Figure F.27: Water–Binder Ratios of CLSM Mixtures.

F.8.2 Flow of grout (flow cone method)

The flow of CLSM grout, which was measured following ASTM C939-16a (ASTM, 2016), and the efflux times required for the CLSM grout mixtures to pass the flow cone are presented in Figure F.28. The flow cone test could not be performed for two typical mixes, Mix A and Mix B. Due to the high fine aggregate or sand contents (78% to 84%) of these two mixes and their low percentages of cementitious materials (1.3% to 3.5% cement content) and fly ash (6.7%), these grouts were unable to flow through a flow cone with a ½-inch discharge tube.

Although there is no recommendation on the range of efflux time needed to demonstrate good flow of CLSM mixes, the Florida Department of Transportation (FDOT) and the Indiana Department of Transportation (INDOT) have recommended a maximum efflux time of 30 sec ± 5 sec in their specifications. The results shown in Figure F.28 reveal that the efflux times of all CLSM mixes tested as part of this project were in the range of 10 sec to 100 sec. For Group A, all four of the modified mixes showed better flowability than the typical mix, with efflux times ranging between 15 sec and 45 sec. The two modified mixes in Group B, Mix B-1 and Mix B-2, showed better flowability than the typical mix, with efflux times of 34 sec and 40 sec, respectively. In contrast, the typical mix in Group C showed better flowability than all four of the modified mixes. It can be noticed from the results in Figure F.28 that the flowabilities of Mix C-1 and Mix C-4 were considerably lower due to their high efflux time (i.e, 100 sec and 70 sec, respectively). This finding is attributed to a reduction in the water-binder ratios of Mix

C-1 and Mix C-4, which were 0.33 and 0.32, respectively, as compared to the typical mixture (Mix C, which had a water-binder ratio of 0.47).

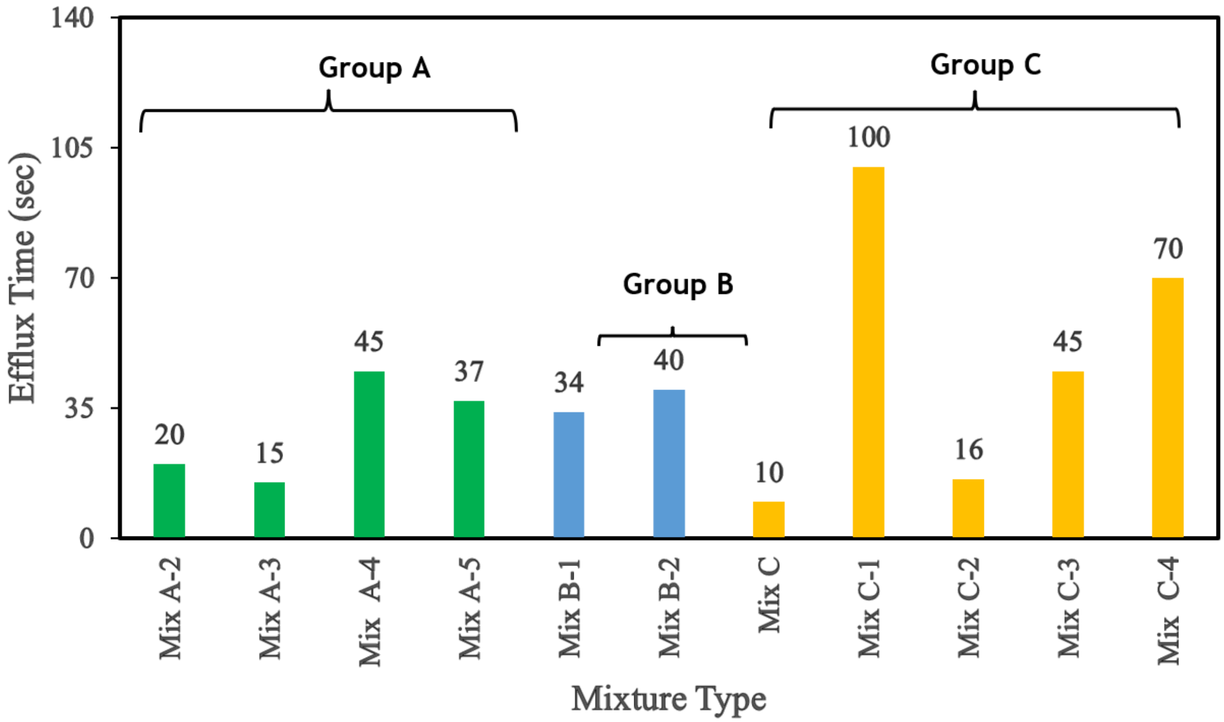

Figure F.28: Efflux Time from Flow Cone Test of CLSM Mixtures.

F.8.3 Bleeding

Generally, if excess water is used in the CLSM grout mixes (more than the amount needed for hydration), the excess amount rises to the surface of the mix and is considered as *bleed water*. Figure F.29 shows the bleeding values (the excess water, expressed as a percentage of all water added to the mix) at 3 hr for all CLSM mixtures tested. The bleeding values of all groups of mixtures were in the range of 0% to 4.9%. Mix A-4, Mix A-5, and Mix B-2 showed no bleeding. The lack of bleeding can be attributed to the Fill Flow admixture that was incorporated into these mixtures, which lowered the amount of water needed to obtain a flowable mix. In particular, the water contents of Mixes A-4 and A-5 were decreased by 31% as compared to the typical mix (Mix A), which resulted in no bleeding in these two mixtures. Likewise, Mix B-2 showed almost zero bleeding due to the 15% reduction in water content as compared to the typical mixture (Mix B). These observations suggest that the water content in the mix proportion plays a vital role in the amount of bleeding exhibited by a CLSM mixture. For Group C, Mix C and Mix C-2 showed higher bleeding (3.8%, and 3.7%, respectively). In contrast, Mix C-1 and Mix C-4 had lower bleeding values (0.6%, and 0.9%, respectively) than other mixes in the group; these results were expected, due to the smaller water-binder ratio in these two mixes.

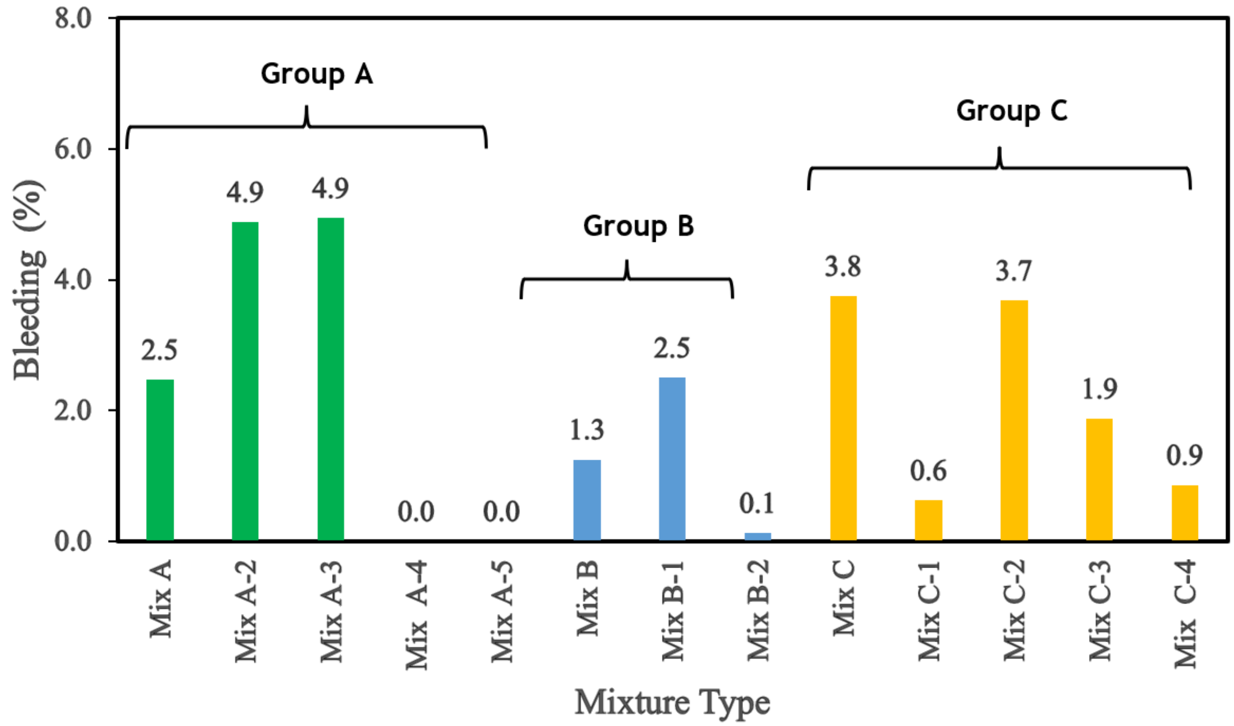

Figure F.29: Bleeding of the CLSM mixtures.

F.8.4 Wet density

The wet density of the fresh CLSM specimens was measured immediately after casting, and the results for the CLSM mixtures are shown in Figure F.30. The densities of the CLSM mixtures fell in the range of 91 to 123 pcf. For Group A, Mix A, Mix A-2, and Mix A-3 exhibited a similar range of wet densities as the range for normal fresh density (115 to 145 pcf) suggested by ACI Committee 229 (2013). The densities of the remaining two mixes in this group, Mix A-4 and Mix A-5, were up to 26% lower than the densities of the other Group A mixtures. Similarly, the density of Mix B-2 was 5.8% lower when compared to other mixtures in Group B. For Group C, all mixtures had density values of approximately 100 pcf. The reduction in the fresh densities of some of the CLSM mixes can be attributed to the Fill Flow admixture, as this admixture can increase the air content by up to 30% as a result of the numerous air bubbles that are formed during mixing. A lower wet density for the mix may improve the pumpability of the grout materials and make them easier to place.

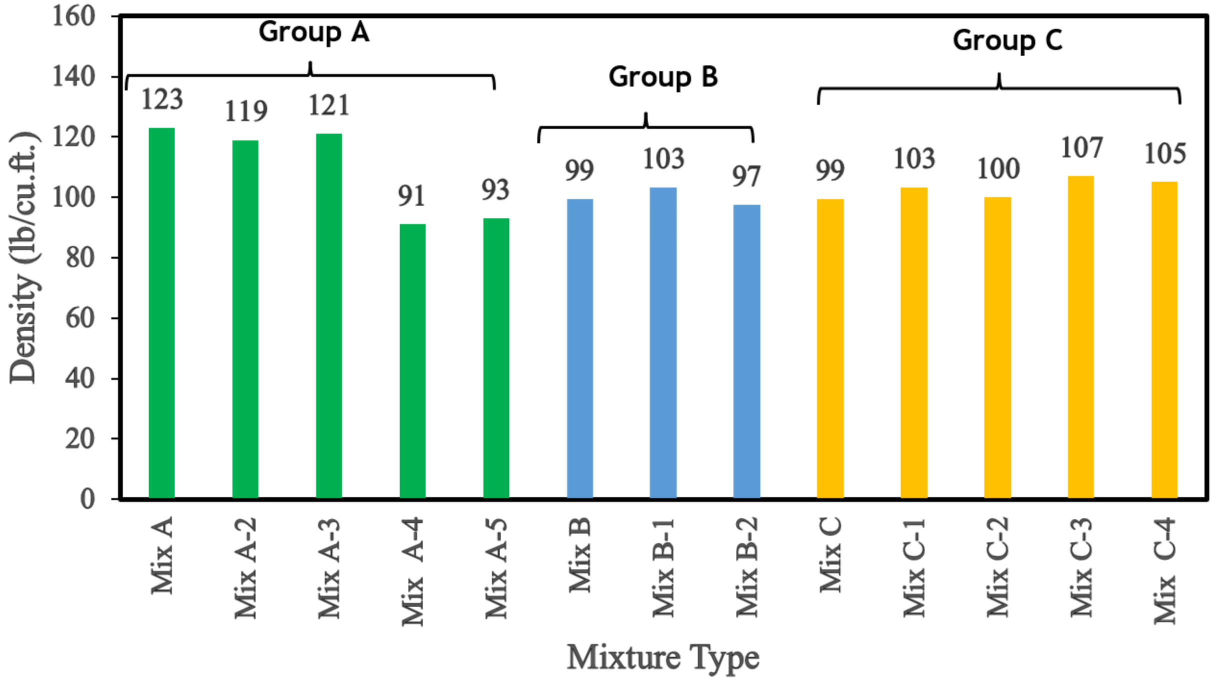

Figure F.30: Fresh Density of the CLSM mixtures.

F.8.5 Air Content

Figure F.31 exhibits the measured air content of the tested CLSM mixtures immediately after mixing. The Group B mixtures had an air content of around 20% to 25%, which is attributed to the use of air-entraining agents and Fill Flow admixtures in all the mixtures in this group. For Group A mixtures, the air contents were generally around 1%. However, it is interesting to note that Mix A-4 and Mix A-5 both had air contents of 30%. The use of Fill Flow increased the volume of these mixes and made them more cost-effective to produce due to the increased volume. For the Group C mixtures, the air contents were in the range of 0.7% to 1.8%; even the use of Fill Flow in Mix C-4 did not generate any increase volume in the mixture.

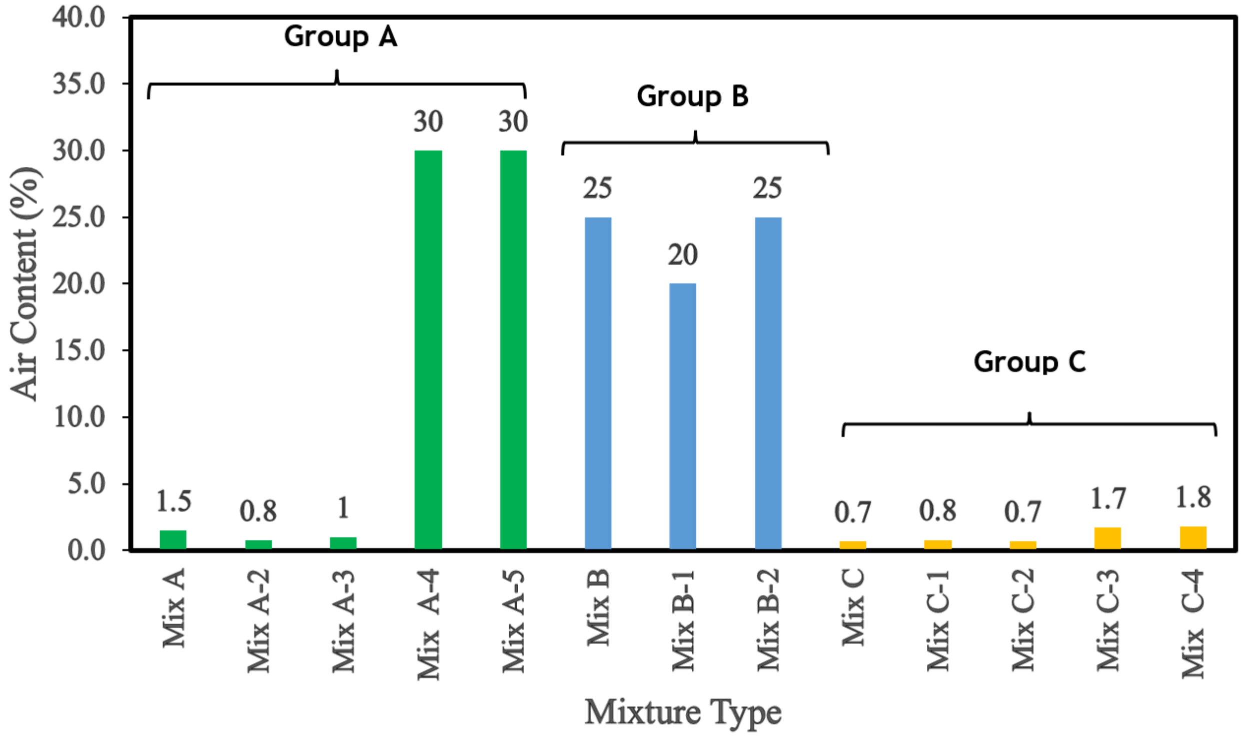

Figure F.31: Air Content of CLSM mixtures.

F.9 Results of Hardened CLSM Properties

F.9.1 Unconfined compressive strength of CLSM mixes

The compressive strength was investigated for 3 groups of CLSM mixtures after 28 days of curing. Figure F.32 and Table F.12 present the compressive strength of tested CLSM mixes. Most state transportation agencies have recommended the minimum compressive strength of 100 psi in their specifications. However, ODOT specification mentions a range of 50 to 100 psi compressive strength for CLSM. Figure F.32 shows that the compressive strengths of all CLSM mixtures meet the ODOT specification of 50-100 psi. However, the unconfined compressive strengths of Mix A and Mix B were, respectively, 8% and 44% below the 100 psi limit specified by most transportation agencies.

For Group A CLSM mixtures, the compressive strength of Mix A-5 was increased by 202% as compared to the typical mix (Mix A). This increase in strength may be attributed to the cement content in Mix A-5, which was 100% higher (100 lb as compared to 50 lb) than the content for Mix A (see Table F.12). Likewise, the compressive strengths of Mix A-3 and Mix A-4 were increased up to 376% by using a higher cement content (200% more cement than in the typical mix). For Group B mixtures, Mix B-1 had 184% higher compressive strength, as it had a 50% higher cement content than the typical mixture, Mix B. The compressive strength of Mix B-2 (almost 100 psi) was higher than Mix B; however, its compressive strength was 37% lower than that for Mix B-1. This finding suggests that the utilization of fill flow admixture might create some bubbles in the mix, and this higher porosity may have lowered the compressive strength compared to the corresponding mixes without Fill Flow. All Group C mixtures had compressive strength values that were significantly greater than 100 psi. The typical mixture in this group, Mix C, included Class F Fly Ash in the binder materials. It is clear from Figure F.32 that increasing the cement content by 50 lb per cubic yd in Mix C-4 resulted in a 58% increase in compressive strength. Similarly, a 150-lb increase in the cement content per cubic yard improved the compressive strength of the grout mixture by up to 296%.

Table F.12: 28 Day Compressive Strength of CLSM Mixes

	Mix ID	**Compressive Strength (psi)**
Group A	Mix A	92
	Mix A-2	225
	Mix A-3	438
	Mix A-4	417
	Mix A-5	278
Group B	Mix B	56
	Mix B-1	159
	Mix B-2	98
Group C	Mix C	301
	Mix C-1	914
	Mix C-2	611
	Mix C-3	1192
	Mix C-4	476

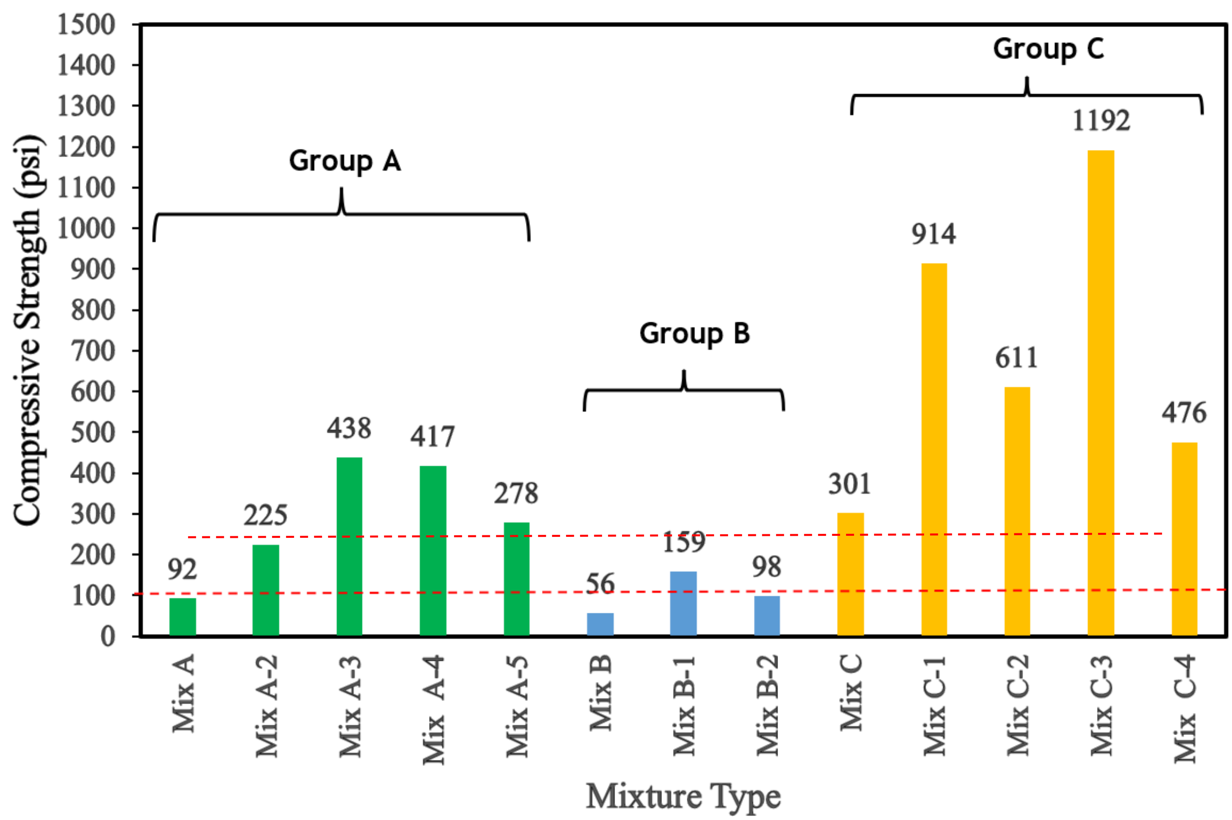

Figure F.32: 28 Day Compressive Strength of CLSM Mixes.

F.9.2 Drying Shrinkage of CLSM Mixtures

The drying shrinkage of all CLSM mixtures was measured using a digital length comparator until 35 days after casting following the ASTM C596 standard. The shrinkage values for all mixes in microstrain at 7, 14, 21, 28, and 35 days are presented in Table F.13 and are plotted in Figure F.33. It is clear from the results that the shrinkage values for nearly all CLSM mixes did not change significantly after 28 days. The results show a wide range of shrinkage values (a range from 65 to 1478 µ-strains) for both the typical and modified CLSM mixes. According to the ACI Committee 229 (2013), the normal range of shrinkage in CLSM is between 200 and 500 µ-strain.

The 28-day shrinkage values of all the CLSM mixes are plotted in Figure F.34. From this figure, it can be noticed that the shrinkage values for the Group A mixtures were within the limit specified by ACI Committee 229. By comparing the 28-day shrinkage values of all mixtures in Group A, it can be noticed that the shrinkage values in the modified mixes are up to 83% higher than that of the typical mixture (Mix A). When considering the mix proportions (see Table F.13), it is clear that the fine aggregate contents in the modified Group A mixes were up to 12% lower as compared to the typical mix, and this may have contributed to the increase in shrinkage.

For the Group B mixtures, the shrinkage values of 89 and 65 µ-strain, for Mix B and Mix B-1, respectively, were considerably below the normal limit. As the amount of sand in Mix B-2 was reduced by 11% as compared to the typical mixture (Mix B), this modified mix showed higher shrinkage than other mixes in Group B. However, the shrinkage of this mix was closer to the upper limit of the normal range reported by ACI Committee 229.

The shrinkage of the typical mixture of Group C (Mix C) could not be measured because the shrinkage test specimens crumbled upon demolding, as shown in Figure F.35. The average shrinkage of modified Group C mixtures, 1018 μ-strain, was significantly higher than for CLSM mixtures in the other groups and is also above the normal shrinkage limit. By incorporating a higher content of Class F fly ash (up to 70% of total mix) and a high amount of water (up to 25% of the mix) without fine aggregates and only a very small quantity of cement increased the shrinkage in the modified Group C mixtures. Nonetheless, for all modified mixtures in the group, only the shrinkage of Mix C-4 was within the normal limit. This may be attributed to the lower water content in this mix, which was 31% lower than that for the typical mixture in this group (Mix C).

Table F.13: Shrinkage Values (μ-strain) for CLSM Mixes

Mix ID	7 days	14 days	21 days	28 days	35 days
Mix A	0	196	204	213	213
Mix A-2	0	284	320	364	364
Mix A-3	0	307	338	391	391
Mix A-4	0	336	391	387	402
Mix A-5	0	322	378	378	391
Mix B	0	36	71	89	124
Mix B-1	0	36	50	65	67
Mix B-2	0	493	542	550	553
Mix C-1	0	716	1067	1069	1180
Mix C-2	0	802	1456	1478	1598
Mix C-3	0	948	1043	1096	1188
Mix C-4	0	378	389	430	440

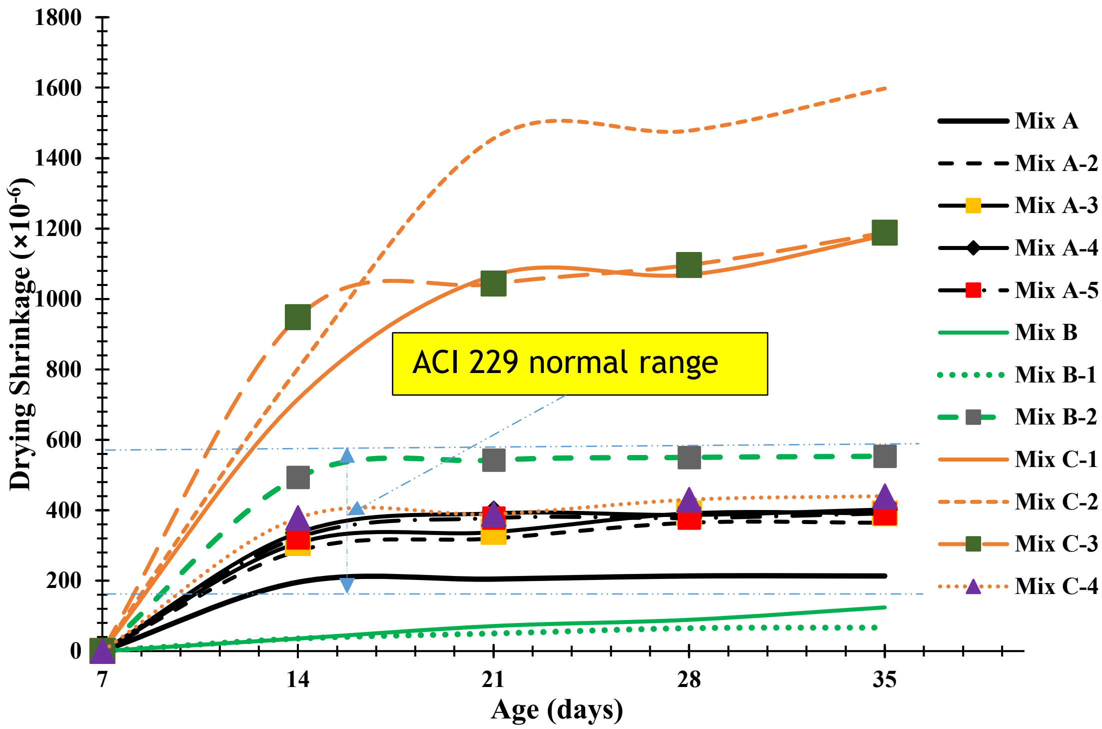

Figure F.33: Drying Shrinkage of CLSM mixtures.

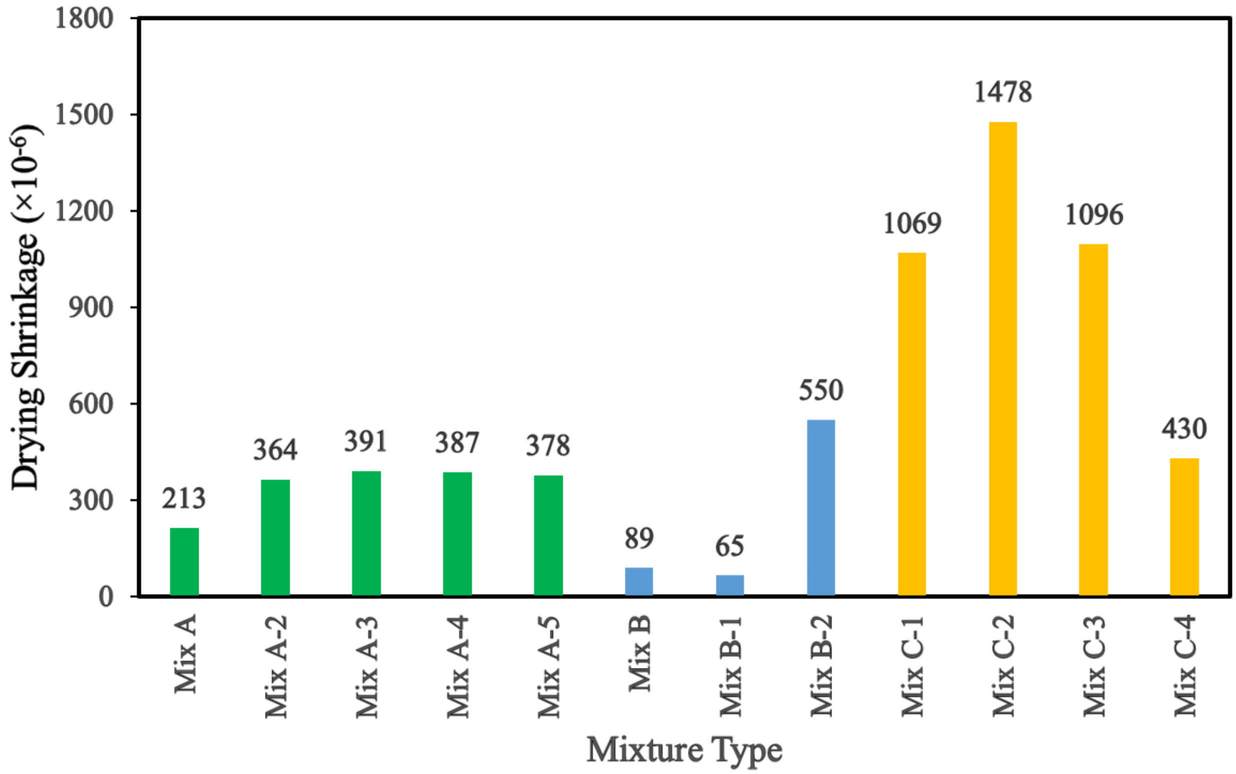

Figure F.34: Drying Shrinkage of CLSM Mixtures at 28 Days After Casting.

Figure F.35: Broken Shrinkage Samples Prepared from CLSM Mix C.

F.9.3 Water Absorption and Oven-dry Density of CLSM Mixtures

Figure F.36 shows the water absorption of both the typical and improved CLSM mixes and indicates that the range of water absorption was between 10.9% and 29.5%. For Group A, Mix A-5 absorbed the highest percentage of water. As Fill Flow admixture created air bubbles in Mix A-5, this high water absorption value could be due to the higher porosity of this mix. Mix A-4 had 19% lower water absorption compared to Mix A-5. This implies that increasing the cement content would decrease the water absorption percentage. Furthermore, the increase of 18% in water absorption in Mix B-2 compared to Mix B indicates that Fill Flow admixture can create higher porosity in a CLSM mix than air-entraining agents. Figure F.36 shows that the Group C mixtures absorbed an average of 27% water, which was significantly higher than for the other groups of mixtures. Figure F.37 shows that the specimens prepared from Mix C were broken during handling; because of this, the water absorption of these specimens could not be determined.

The oven-dry density of all the CLSM mixtures was measured after 28 days of curing. Figure F.38 presents a comparison of different groups of CLSM mixtures. From the comparison of the wet and dry density values for CLSM presented in Table F.14, it can be seen that the dry density of all mixtures was lower than the wet density; this may be due to the loss of water from the mixtures. The dry density values of the Group C CLSM mixtures were up to 16% lower than the wet density values. For CLSM mixtures in Groups A and B, this reduction was quite low (only in the range of 2% to 8%).

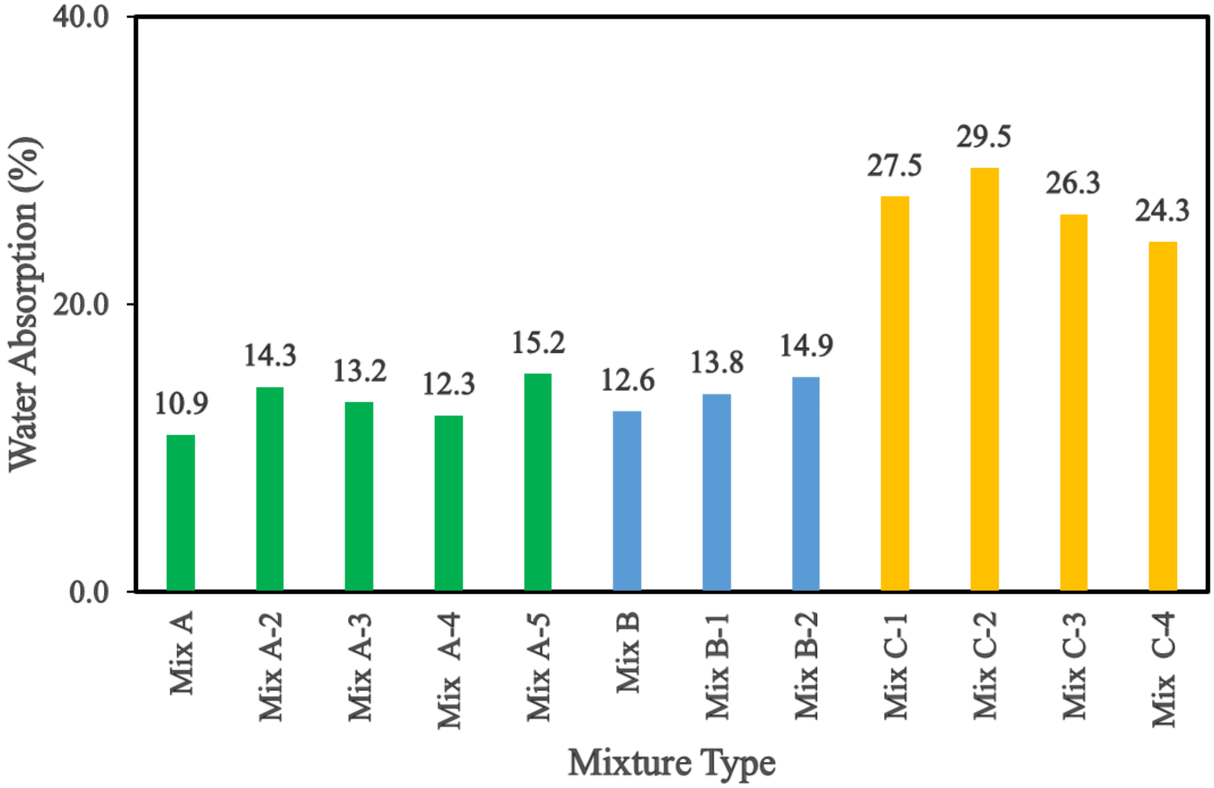

Figure F.36: Water Absorption Values for CLSM mixtures.

Figure F.37: Broken Water Absorption Sample (Mix C).

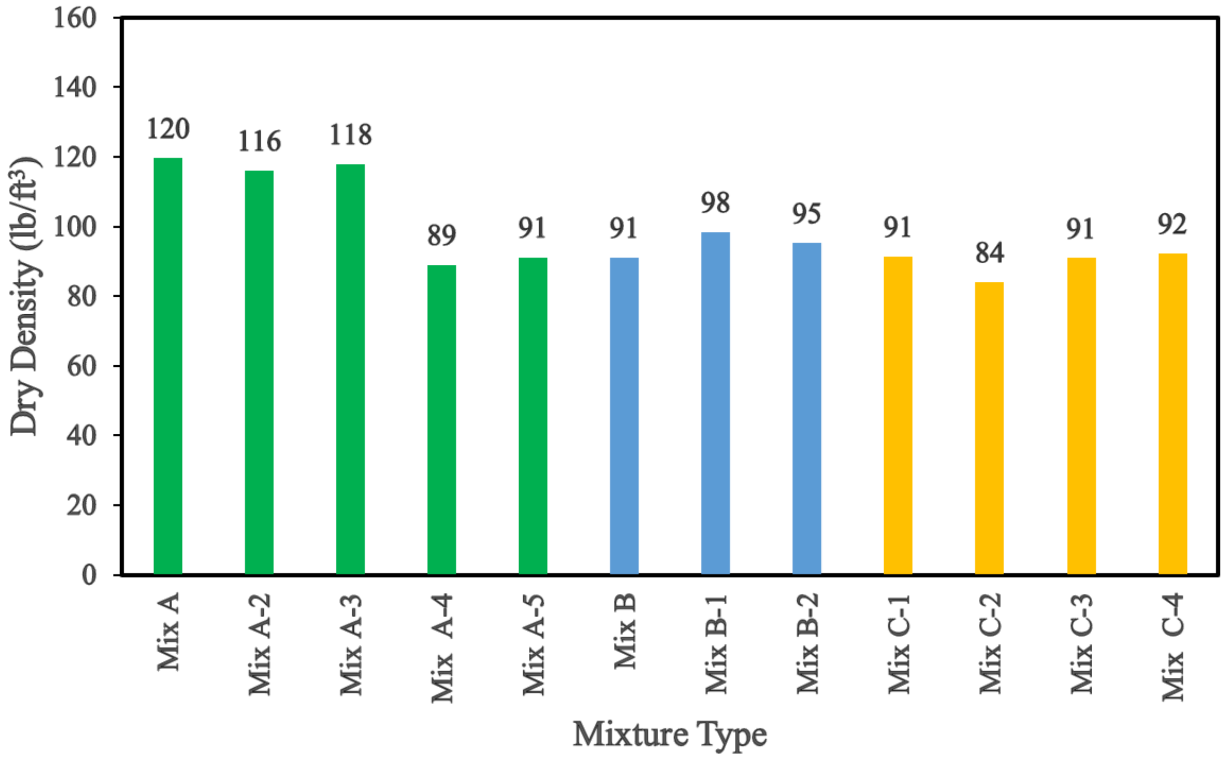

Figure F.38: Dry Density Values for All CLSM Mixtures.

Table F.14: Comparison of the Wet and Dry Density Values of Tested CLSM mixtures

Mix ID	Wet Density (lb/ft^3)	Dry Density (lb/ft^3)
Mix A	123	120
Mix A-2	119	116
Mix A-3	121	118
Mix A-4	91	89
Mix A-5	93	91
Mix B	99	91
Mix B-1	103	98
Mix B-2	97	95
Mix C-1	103	91
Mix C-2	100	84
Mix C-3	107	91
Mix C-4	105	92

F.10 Selecting the Optimum CLSM Mixture for Annulus Void Fill

According to the report for NCHRP Project 24-12 (Folliard, 2008), two potentially important properties for void fill application are unconfined compressive strength and flowability. In addition, high bleeding can lead to higher drying shrinkage and can cause delamination in a sliplined culvert. The evaluation of the laboratory tests to determine several important characteristics of CLSM mixtures aids in the selection of the best mix proportions for annulus void fill materials used in sliplined culverts. Below is a summary of the optimal mixtures from each test group.

- **Group A Mixtures**: Among the mixtures in Group A, Mix A-4 and Mix A-5 showed zero bleeding, and the volume of these mixes was increased by 30% over the typical mix (Mix A). Moreover, the lower fresh density of these mixes would make them easier to pump into annulus voids than other CLSM mixes. The compressive strengths of Mix A-4 and Mix A-5 are higher than that of the typical mix (Mix A). Although the 28-day drying shrinkage for Mix A-4 (with a microstrain of 387) and Mix A-5 (with a microstrain of 378) are a little higher than that for Mix A (a microstrain of 213), the good flowability, zero bleeding, and high compressive strength as well as the lower wet density make Mix A-4 and Mix A-5 the optimal mixtures from Group A.

- **Group B Mixtures**: Mix B-2 is the optimum mix from Group B, as this mixture was the only mix in this group that showed almost zero bleeding. In addition, the volume of this mixture was 25% higher than the typical mix (Mix B). Mix B-2 also has better flowability (with an efflux time of 40 sec.) than Mix B, which had no flow through the flow cone. In addition, Mix B-2 had a compressive strength of nearly 100 psi as well as the lowest density (97 lb/ft^3) of all mixtures in this group.

- **Group C Mixtures**: Mix C-4 was found to be the most favorable option of the mixes in Group C. This mixture had the lowest 28-day drying shrinkage value (with a microstrain of 430) of all mixes in this group, it showed almost zero bleeding (0.86%), and it had high compressive strength.

The advantages and drawbacks of the four optimal mixtures (Mixes A-4, A-5, B-2, and C-4) are summarized in Table F.15.

Table F.15: Advantages and Disadvantages of the Optimal Mixtures

Mix Types	Advantages	Disadvantages
Mix A-4	• The use of Fill Flow increased the volume by 30% over the typical mix (Mix A) • The mix showed zero bleeding • The flowability/spread diameter was 12½" (as compared to 7" for Mix A) • Use of Class C fly ash increased the compressive strength • Lower cast density may provide better pumpability of the mix	• Class C fly ash may not be readily available • Not cost-effective to produce • Contains higher cement content (200% more) compared to the typical mix • Higher shrinkage as compared to Mix A
Mix A-5	• Cost-effective to produce • The use of Fill Flow increased the volume by 30% over the typical mix (Mix A) • The mix showed zero bleeding • The spread diameter in the flowability test was 11½" (as compared to 7" for Mix A) • Efflux time (37 sec) is lower than that of Mix A-4 (45 sec) • Lower cast density may provide better pumpability of the mix	• Shrinkage for this mix is a little bit higher than the typical Mix A
Mix B-2	• The volume is increased by 25% over the typical mix (Mix B) • This mix showed almost zero bleeding (0.13%) • Flow is better than that for the typical mix (Mix B)	• This mix has higher shrinkage (microstrain of 550) than typical Mix B (microstrain of 89)
Mix C-4	• This mix shows almost zero bleeding (0.86%) • Compressive strength is high • Lower shrinkage than for Mix C	• Fill Flow did not increase the volume of this mix • The efflux time (70 sec) is higher than that for Mix C (10 sec)

Considering the advantages and drawbacks for the four optimum mixtures listed in Table F.15, it can be concluded that Mix A-5 is the best mixture among all the CLSM mixes considered in this study. For this reason, Mix A-5 was selected for grouting of the a sliplined culvert specimens to facilitate a comparison to the typical mixture of the same group (Mix A) in order to evaluate the effect of the grout strength on the load-carrying capacity of the sliplined corrugated steel pipes, as will be discussed in the following section.

F.11 Results of Parallel-Plate Loading Tests of Sliplined Culvert Specimens

F.11.1 Loading tests for the host and liner pipe

In order to understand the contribution of the load-carrying capacities of the corrugated steel host pipe and liner pipe prior to conducting the parallel-plate loading tests of the sliplined culvert samples, parallel-plate tests were conducted on both pipes individually. For both pipes, the distance between the crown and the invert was reduced during loading (i.e., the vertical diameter decreased), and the distance between the two springline voids increased (i.e., the horizontal diameter increased). Figure F.39 presents a plot of the applied load (lbf) vs. diameter change (in.) for both pipes. Because of the difference in the diameter of the host pipe (18 in.) and the liner pipe (12 in.), it was considered more informative to plot the applied load versus percentage change in diameter (see Figure F.40), as this comparison could more accurately show the difference in the load-carrying capacities of the two pipes. Figure F.41 shows photos of the liner pipe before and after the parallel-plate loading tests.

The plots in Figure F.39 and Figure F.40 indicate that before reaching the yield point, the relationship between the applied load and the diameter change was linear for both pipes. The vertical diameter change was larger than the horizontal diameter change at the same applied load for both the host pipe and liner pipe. For example, the ratio of vertical diameter change to horizontal diameter change for the liner pipe was 2 at an applied load of 400 lbf, and the ratio was 2.2 at the same applied load (400 lbf) for the liner pipe. Typically, a vertical diameter change of 5% to 8% for a flexible pipe is considered as a serviceability criterion in practice (Smith et al., 2015; Rahmaninezhad et al. 2019). In this project, the load-carrying capacities of the host pipe and liner pipe were considered at a vertical diameter change of 5%. The host pipe was found to have a higher load-carrying capacity (584 lbf) than the liner pipe (423 lbf), which indicates that the load-carrying capacity of the liner pipe is approximately 28% lower than that of the host pipe.

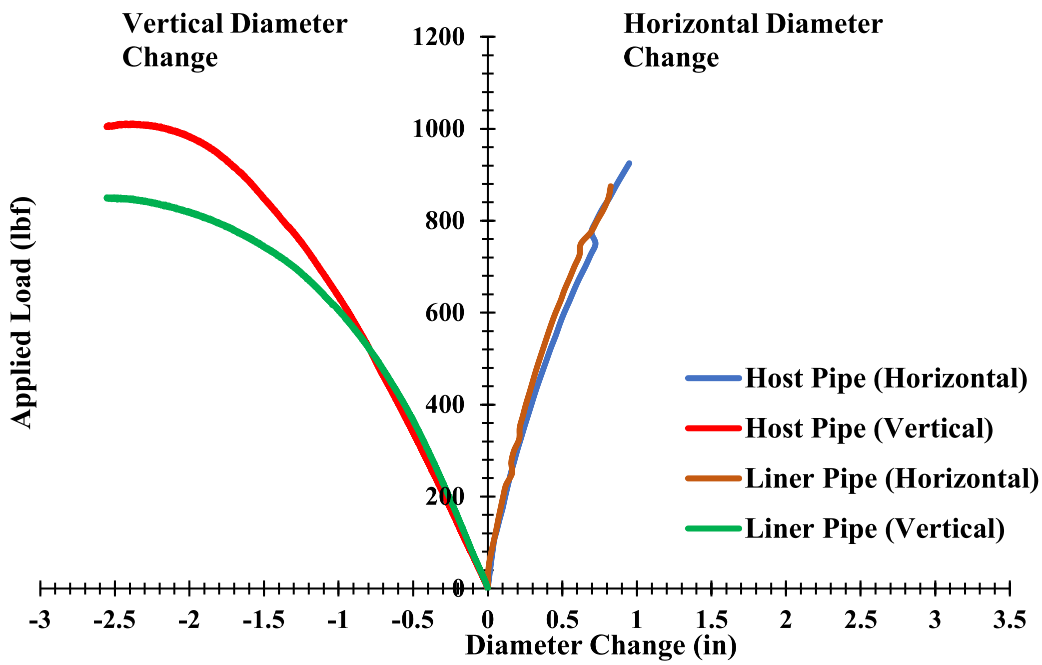

Figure F.39: Applied Load vs. Diameter Change of Host and Liner Pipe.

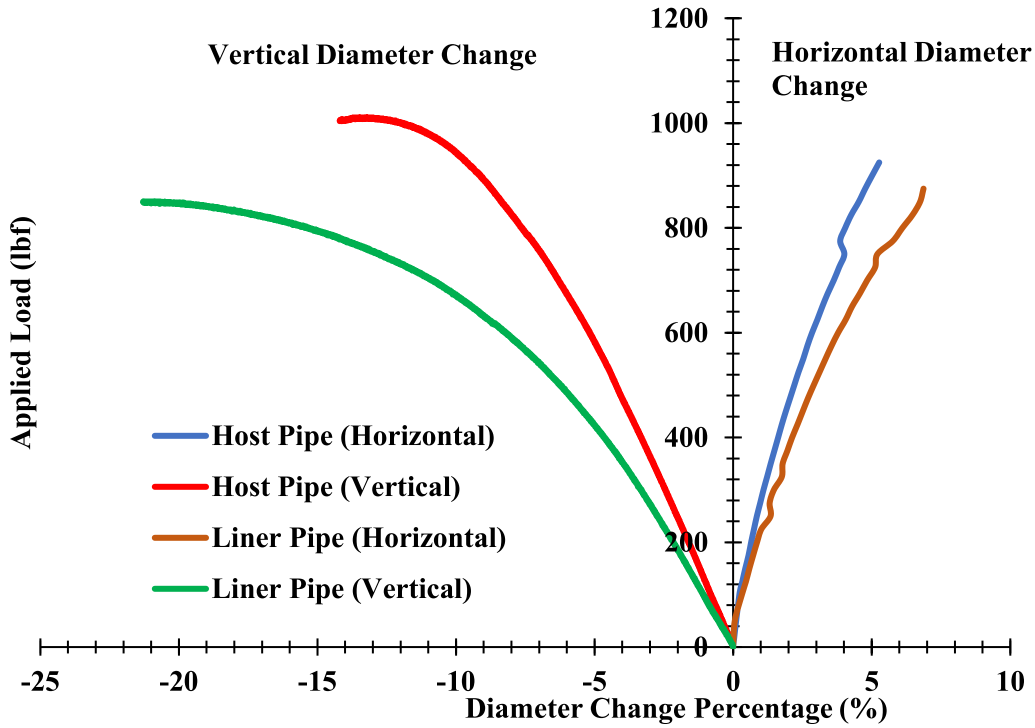

Figure F.40: Applied Load vs. Percentage Change in Diameter of Host and Liner Pipe.

Figure F.41: Parallel-Plate Loading Tests:
Liner Pipe Before (*left)* and After Loading (*right*)

F.11.2 Parallel-plate loading tests of sliplined culverts with no voids or defects

Parallel-plate loading tests were conducted on grouted sliplined culverts for two grouts from Group A (Mix A and Mix A-5) to investigate the effect of several CLSM grout characteristics. Figure F.42 and Figure F.43 show the grout condition before and after parallel-plate loading tests for culverts grouted with Mix A and Mix A-5, respectively. The culvert grouted with the typical CLSM mix, Mix A, exhibited multiple cracks at the crown as well as at the springline, and a portion of the grout was spalled from the culvert during the test. In contrast, the sliplined culvert grouted using the modified CLSM mix, Mix A-5, exhibited only a few cracks at the crown and at one springline position.

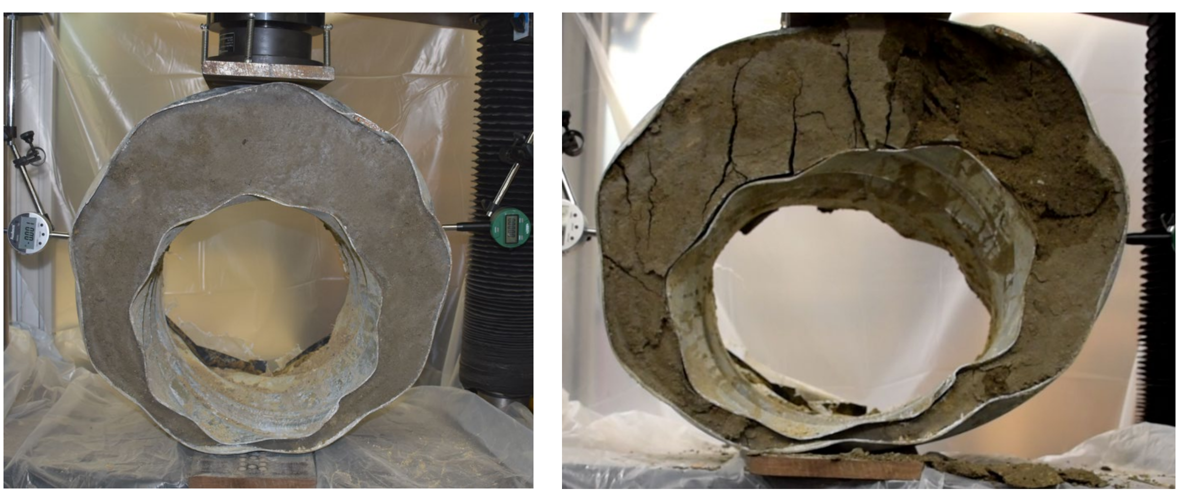

Figure F.42: Sliplined Culvert with CLSM grout Mix A Before (*left*) and After (*right*) the Parallel-Plate Loading Test.

Figure F.43: Sliplined Culvert with CLSM grout Mix A-5 Before (*left*) and After (*right*) the Parallel-Plate Loading Test.

A plot showing the applied load versus diameter change for the culverts grouted with Mix A and Mix A-5 is presented in Figure F.44. The first crack in the culvert grouted with Mix A occurred at the crown position of the culvert (Figure F.45) at 1300 lbf of applied load with a vertical diameter change of 0.11 inch. The first crack in the culvert grouted with Mix A-5 occurred at the crown position (Figure F.46) at an applied load of 3000 lbf (130% higher than the load for the culvert grouted with Mix A, which was higher by a factor of 2.3), with a vertical diameter change of 0.13 inch.

Based on the test results, the crown position is considered to be the most critical position on the culvert, because the first crack in the annulus material occurred at this position in both culverts. It is clear from Figure F.44 that the applied load and diameter change maintained a linear relationship until the first crack occurred. After that, both culverts slowly yielded. The ratios of vertical diameter change to horizontal diameter change were 3.15 and 4.5 for the culvert specimens grouted with Mix A and Mix A-5, respectively.

The load-carrying capacity of the sliplined culvert grouted with Mix A-5 was higher than that for the culvert grouted with Mix A. In particular, at a 5% vertical diameter change (0.9 in), the culvert grouted with Mix A had a load-carrying capacity of 4163 lbf, whereas the culvert grouted with Mix A-5 had a 19% higher load-carrying capacity (4959 lbf) at the same percentage change in vertical diameter. Similarly, for a 0.5-in. horizontal diameter change, the culvert grouted with Mix A (4350 lbf) had a 21% lower load-carrying capacity than the culvert grouted with Mix A-5 (5500 lbf). Although the stiffness of the host and liner pipes typically decreases after yielding, the stiffness of the culvert grouted with Mix A-5 increased suddenly after a change in vertical diameter of 1.12 in. and a change in horizontal diameter of 0.3 in. From this observation, it can be stated that the ultimate load-carrying capacity of the culvert grouted with Mix A-5 is significantly higher than that of the the culvert grouted with Mix A.

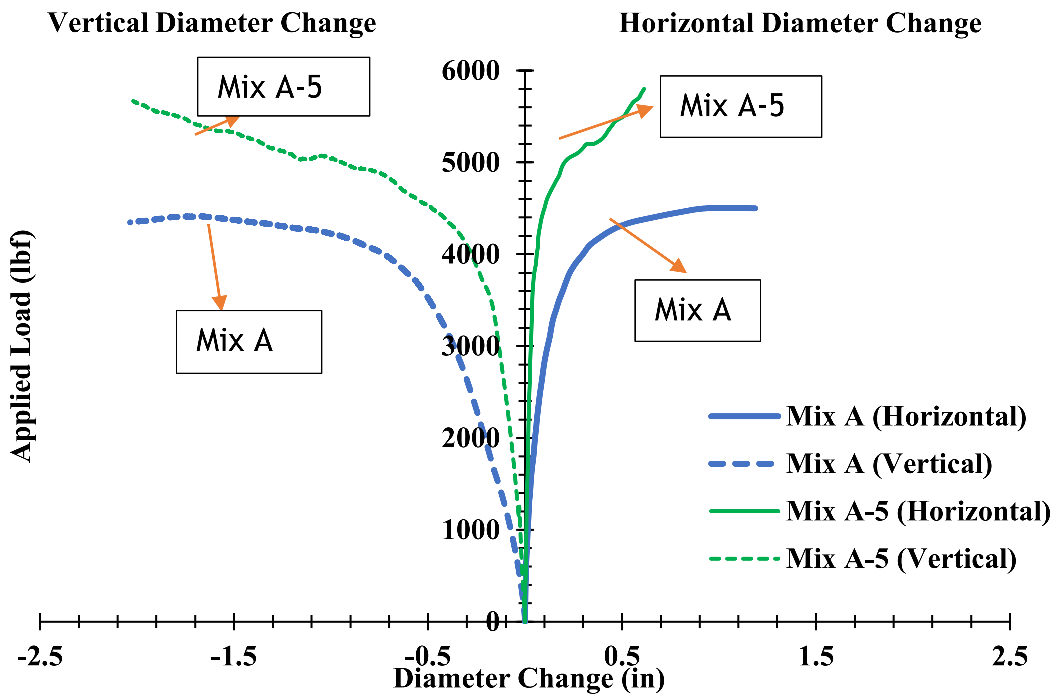

Figure F.44: Applied Load vs. Diameter Change in Sliplined Culverts Grouted with Mix A and Mix A-5.

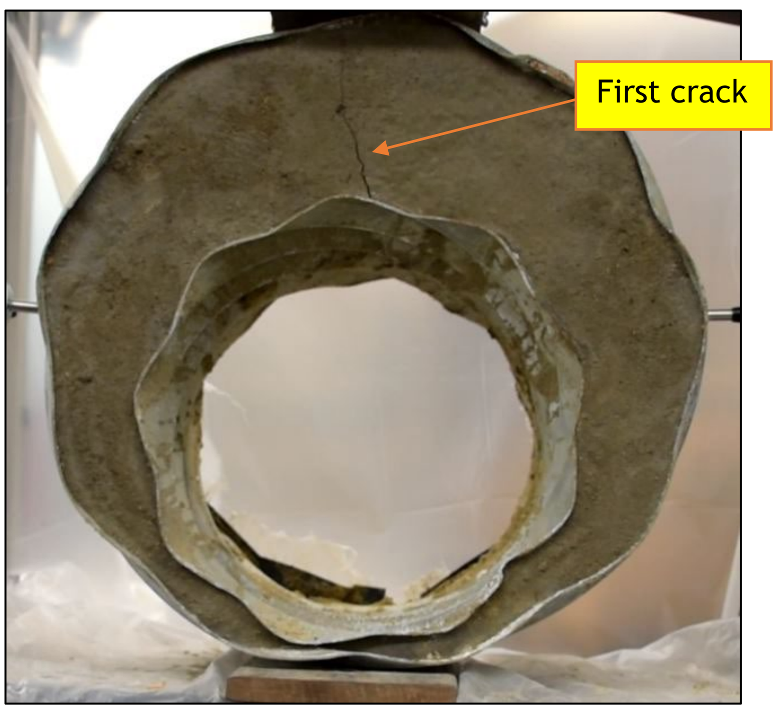

Figure F.45: First Crack in Culvert with No Voids Grouted with Mix A (at 1300 lbf).

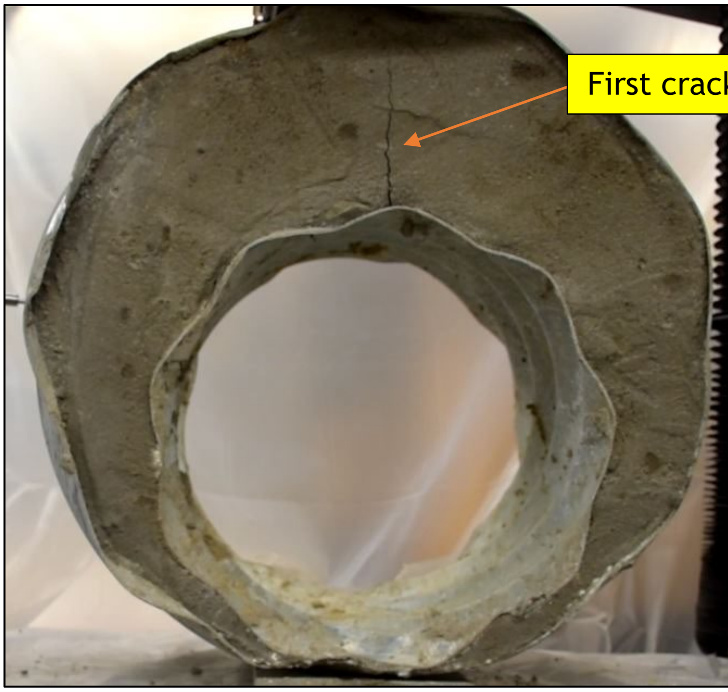

Figure F.46: First Crack in Culvert with No Voids Grouted with Mix A-5 (at 3000 lbf).

The contribution of CLSM grout to the load-carrying capacity of a sliplined culvert can be determined using the load-carrying capacity of the host and liner pipes, as shown in Figure F.49. The resulting load-carrying capacities for the two culvert samples, the contribution of the host and liner pipes, and the contribution of the two CLSM grouts (Mix A and Mix A-5) are presented in Table F.16. The results indicate that the grout has the greatest contribution to the load-carrying capacity of a sliplined culvert.

Table F.16: Contribution of Grout to the Load-Carrying Capacity of a Sliplined Culvert

Grout Mix	Load-Carrying Capacity of Culvert*, *A* (lbf)	Contribution of Host Pipe, *H* (lbf)	Contribution of Liner Pipe, *L* (lbf)	Contribution of Grout, *G* (lbf); (*G* = *A* − *H* - *L*)
Mix A	4163	584	423	3156
Mix A-5	4959	584	423	3952

*considering a 5% change in vertical diameter.

F.11.3 Parallel-plate loading tests of sliplined culverts with voids

As mentioned earlier, most of the voids found in a partially filled annulus of a sliplined culvert are found at the crown and at the springline. For this reason, parallel-plate loading tests were conducted on sliplined culvert samples grouted with Mix A-5 with voids introduced at either the springline or at the crown to investigate the effect of void position on the load-carrying capacity of the sliplined culvert. Figure F.47 and Figure F.48 show the culvert and grout conditions of a culvert with voids at the springline and a culvert with a void at the crown, respectively, both before and after a parallel-plate loading test. The sliplined culvert with voids at the springline has several cracks between the springline and the crown. In addition, a small portion of grout has spalled from the springline. In contrast, the host pipe of the sliplined culvert with a void at the crown deflected significantly, and the culvert exhibited delamination at both sides. Radial cracks occurred between the 10 o’clock and 2 o’clock positions, and a crack occurred at the springline.

Figure F.47: Sliplined Culvert with Voids at the Springline,
Before (*left*) and After (*right*) the Parallel-Plate Loading Test.

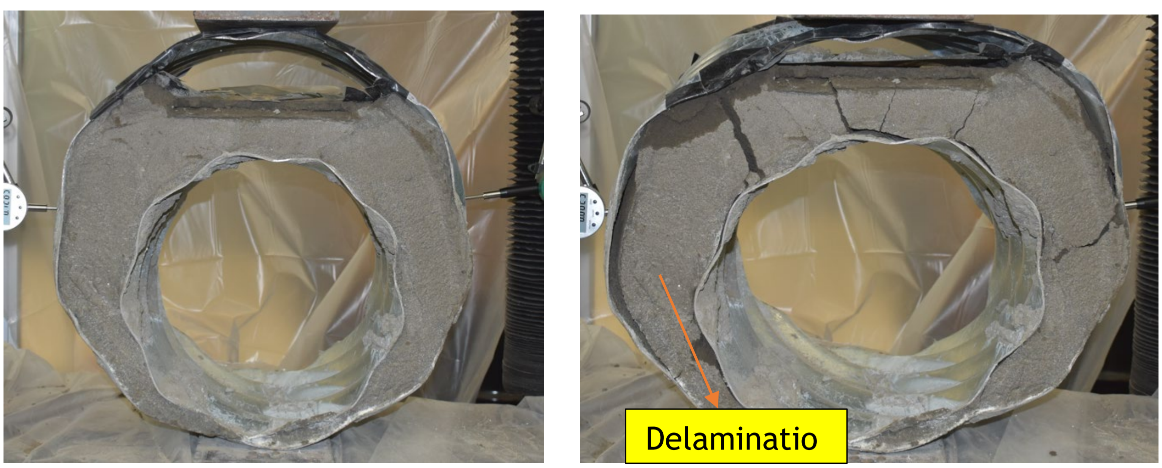

Figure F.48: Sliplined culvert with a Void at the Crown,
Before (*left*) and After (*right*) the Parallel-Plate Loading Test.

Figure F.49 shows the applied load versus diameter change for sliplined culverts with three culvert types: no voids on the grout (Type I), voids at the crown (Type II), and voids at the springline (Type III). In the culvert with voids at the springline (shown in Figure F.50), the first hairline crack occurred at 1700 lbf. However, in the culvert with a void at the crown (shown in Figure F.51), the first hairline crack occurred at an applied load that was about 65% lower (600 lbf).

The plot in Figure F.49 shows that the load-carrying capacity of a completely full sliplined culvert is higher than that for sliplined culverts with voids at the springline or at the crown. For example, the load-carrying capacity at a 5% vertical diameter change (0.9 in) of the sliplined culvert with voids at the springline was 4283 lbf. In contrast, at the same percentage (5%) of vertical diameter change, the load-carrying capacity of the sliplined culvert with a void at the crown was 60% lower (1700 lbf) than that for the culvert with voids at the springline. Similarly, by comparing the load-carrying capacities for a 0.5-in. horizontal diameter change, it is clear that sliplined culvert with voids at the springline had a 115% higher load capacity than the culvert with a void at the crown. These results indicate that the position of voids in a partially filled annulus can affect the load-carrying capacity of the grout. In addition, a void at the crown position has a more detrimental effect on the load-carrying capacity of a sliplined culvert than voids at the springline.

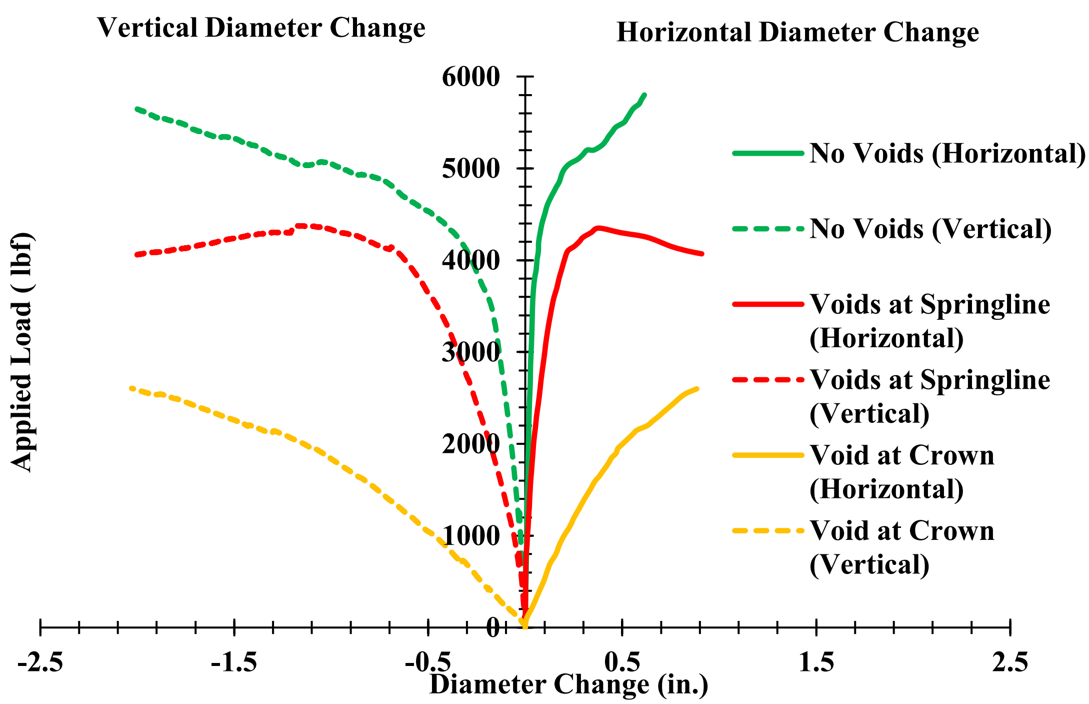

Figure F.49: Load-Carrying Capacity of Sliplined culverts with No Voids, Voids at the Springline Positions, and a Void at the Crown.

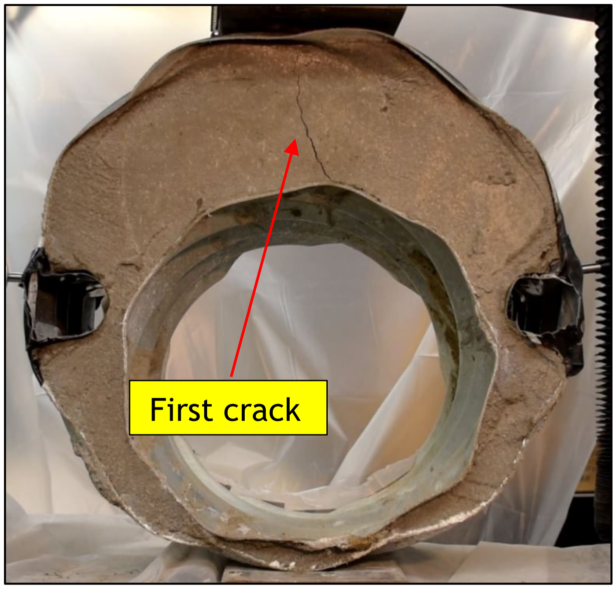

Figure F.50: First Crack in a Sliplined Culvert with Voids at the Springline.

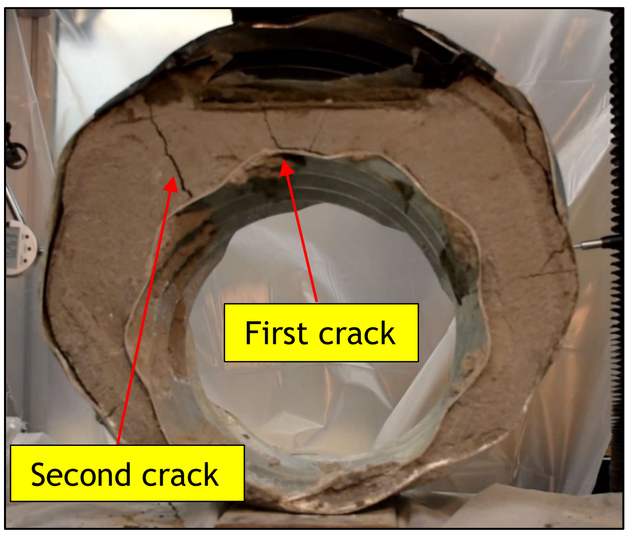

Figure F.51: Cracks in a Sliplined Culvert with Voids at the Crown.

Table F.17 summarizes the contribution of the grout to the load-carrying capacity for the three types of sliplined culverts tested in this project (i.e., a culvert with a completely full annulus, a culvert with a void at the crown position, and a culvert with voids at the springline). It can be noticed from this table that the contribution of grout can be reduced significantly when voids are present. For example, grout contribution was reduced by 17% when voids were present at the springline than when the annulus was completely full. In contrast, the contribution of the grout was drastically reduced (an 82% reduction) when the void was at the crown position. These results suggest that voids at the crown could be the main cause for the vertical and horizontal distortion of the sliplined culvert as well as the delamination on the sides.

Table F.17: Load-carrying Capacities of Sliplined Culverts and Their Components at a Change of 5% in Vertical Diameter

Culvert Sample	Applied load at first crack (lbf)	Load-Carrying Capacity of Sliplined Culvert*, *A* (lbf)	Contribution of Host Pipe, *H* (lbf)	Contribution of Liner Pipe, *L* (lbf)	Contribution of Grout, *G* (lbf); (*G* = *A* − *H* − *L*)
Culvert w/ Mix A-5 (No Void)	3000	4959	584	423	3952
Culvert w/ Mix A-5 (Void at Springline)	1700	4283	584	423	3276
Culvert w/ Mix A-5 (Void at Crown)	600	1700	584	423	693

* considering a 5% change in vertical diameter.

F.12 Summary and Conclusions

This study was primarily undertaken to develop improved mix proportions for CLSM grout used for filling the annular spaces of sliplined culverts. Several new CLSM mix designs were proposed in this project that were created by modifying potentially important characteristics for annulus fill applications: flowability, bleeding, unconfined compressive strength, drying shrinkage, and cost. Characteristics of the modified CLSM mixtures were compared to those for traditional CLSM mixes that are generally used as annulus void fill materials for sliplined culverts. Four optimum CLSM mix designs were selected based on this evaluation.

One of the best mix designs was utilized as an annulus void fill material in the sliplined corrugated steel pipe samples to investigate the effect of the modified grout on the load-carrying capacity of a sliplined culvert by conducting parallel-plate loading tests. Another key objective of this project was to explore the effect of a partially filled annulus on the load-carrying capacity of a sliplined culvert, as the presence of annulus voids is a common problem that is observed and reported by field inspectors. Parallel-plate loading tests were performed on three sliplined culvert test specimens (i.e., one with no voids, one with a void at the crown, and one with voids at the springline) to investigate the effect of the void position on the load-carrying capacity of the culverts. The following specific conclusions were drawn based on the findings of this study:

- Fill Flow admixture was effective in producing flowable CLSM mixes with no noticeable segregation. Moreover, the use of this admixture reduced the water demand of the CLSM mixtures, resulting in a flowable mix with zero bleeding.

- The wet densities of modified mixtures from Group A and Group B (i.e., Mix A-4, Mix A-5, and Mix B-2), were reduced by the addition of Fill Flow admixture. The reduction in wet density can make these grouts more pumpable and provide a more cost-effective solution for annulus filling of sliplined culverts.
- All modified CLSM mixtures developed in this study had a minimum compressive strength of 100 psi, which is the minimum compressive strength recommended by most state transportation agencies. The compressive strength of the CLSM mixes was improved by increasing the cement content, while higher porosity in the CLSM mixtures was found to somewhat reduce the compressive strength.
- The reduction or absence of fine aggregate and the higher water content in a CLSM mixture results in an increase in shrinkage.
- The ultimate load-carrying capacities of sliplined culverts grouted with a modified CLSM mixture were considerably greater than culverts grouted with a traditional CLSM mixture. Moreover, it was found that the hardened grout had the maximum contribution to the load-carrying capacity of culverts sliplined with corrugated metal pipes. This indicates the importance of complete grout filling of the annulus of a sliplined culvert.
- For a sliplined culvert with a partially filled annulus, a void at the crown has a more adverse effect on the structural performance of the culvert than a void at the springline. The contribution of the grout to the load-carrying capacity is reduced substantially, and the sliplined culvert exhibits significant deflection as well as delamination when voids are present in the annulus. The sliplined culverts can distort vertically and horizontally in the presence of a void at the crown position.

On a final note, the research conducted in this project provides modified CLSM mixture proportions for a grout that can be used to better fill the annulus of a sliplined culvert. Moreover, this research provided a better understanding of the importance of complete grout filling of the annulus and the contribution of the grout to the load-carrying capacity of the culvert.

F.13 Recommendations for future work

In this project, parallel-plate loading tests were conducted on unburied sliplined culverts. A buried sliplined culvert, which has additional support from the surrounding soil and would be subjected to lateral soil pressure, may exhibit a stiffer response and have a higher load-carrying capacity than an unburied culvert. In the future, large-scale tests may be conducted on sliplined corrugated steel pipes in a buried condition. In addition, only corrugated steel liner pipes were considered in this project. Different liner pipe materials, such as high-density polyethylene (a commonly used liner) should be considered in future research. Finally, the optimal CLSM mixes proposed in this study for use as grouts in sliplined culverts were validated in the field, and field evaluations were conducted to verify their performance as grouting materials for sliplined culverts (see Appendix G).

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Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX G

Pumping Tests

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Prepared for:
The Ohio Department of Transportation,
Office of Research and Development

State Job Number 135965
February 2023
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APPENDIX G

PUMPING TESTS

G.1 Introduction

This chapter describes pumping tests that were conducted to demonstrate the pumping performance of three grouts proposed for filling the annulus voids of sliplined culverts. A typical CLSM grout traditionally used by ODOT (CLSM Mix A, as described in Appendix F), the improved CLSM grout developed in this project (CLSM Mix A5, also described in Appendix F), and the recommended cellular grout (Mix C40, as described in Appendix E) were included in the testing program. These three grouts were selected for evaluation because they satisfy most ASTM standard tests for fresh and hardened grout properties and, more crucially, they have good flowability, which is the key property for grouts used in sliplined culverts.

The pumping tests in this research project were conducted in three stages. In the first phase, a batching plant was engaged to mix 3 yd^3 of each of these three grouts. If the prepared amount of grout satisfied the detailed requirements of relevant ASTM standard tests, then it was to be used in the next phase of testing. In the second phase of testing, a large quantity of grout was pumped across a considerable distance (200 ft) through a polyvinyl chloride (PVC) pipe with a small diameter (2 inches). The wet and hardened grout properties were determined before and after pumping. The third phase involved the pumping of grouts into the annulus voids of actual culvert test specimens. The fresh and hardened properties of the grouts were examined for each phase before and after pumping to assess the grout properties for the large batches of grout and to facilitate a comparison between the results for the large batches and those obtained for the same grout mixes when prepared in smaller amounts in our laboratory. Furthermore, the flowability of the grouts was verified as well as the ability of the grouts to fully fill the annulus voids of two large-scale test specimens that emulated field trials. More details about the phases of the study and the pumping test results are reported in the following sections.

G.2 Phase 1 Testing

G.2.1 Material information and test setup

When conducting the pumping tests, it was necessary to use larger quantities of grout than the amount tested in the laboratory (which was approximately 1 cubic foot of each grout). The amount of grout recommended for use in each pumping test was three cubic yards (3 yd^3). This amount reflects the minimum quantity that would be mixed in a batching plant and pumped to fill the sliplined culvert test specimens in Phase 3. Tables G.1 and G.2 present the mixture proportions used to prepare the three grouts.

Table G.1: Grout Mix Proportions for 1 yd^3 of CLSM Grouts in Phase 1

Grout Mix	Cement Type I (lb/yd^3)	Fly Ash	Fine Aggregate Type	Fly Ash (lb/yd^3)	Fine Aggregate (lb/yd^3)	Water (gallons)	Fill Flow (lb)	W/C
CLSM Mix A	66.7	Class C	No. 4 (100% Passing)	261.7	3086.7	60.3	N/N	1.533
CLSM Mix A5	100	Class C	No. 4 (100% Passing)	348.3	2700	39	4+0.6*	0.726

**An additional 0.6 lb of Fill Flow was added to the mix to help the grout flow during flow cone tests.*

Table G.2: Grout Mix Proportions for 1 yd^3 of Cellular Grout in Phase 1

Grout Mix	Cement Type I (lb/yd^3)	Water (gallons)	Foam (yd^3)	W/C
Cellular Grout Mix C40	701.6	42.3	0.6	0.503

Grout mixes were prepared at a batching facility of Mack Ready Mix Concrete in Akron, Ohio (Figure G.1a). The mix trials were conducted in December 2021, when the weather in Ohio is typically cool (average ambient temperature of 46° F). Once the grout materials were placed into separate concrete mixer trucks, the ingredients were blended for an extended period of time until a uniform mixture was achieved. Additives were introduced to the wet grout mix in the rotating drum of the truck, as shown in Figure G.1(b). Fill Flow (an admixture produced by Fitz-Pak Corporation that improves the flowability of grout) was added to CLSM Mix A5, and foam prepared using AERLITE-R™ (a foaming agent produced by Aerix Industries that is specifically formulated for annulus void filling) was added to cellular grout Mix C40. No additives were used in the typical CLSM mixture (Mix A).

The tests listed in Table G.3 were performed at the batching facility using the setup shown in Figure G.2 to determine if the physical properties of the large batches of grouts would be comparable to the results for tests conducted in the laboratory for smaller-sized batches. In order to decide whether or not to proceed with the mix design, it was crucial to measure each grout's cast wet density (i.e., fresh density) using ASTM C796/C796M. In this test, a standard steel cylinder (12 inches tall and 8 inches in diameter) is filled with grout and leveled off at the top. An electronic scale is then used to determine the mass of the grout, and the density of the grout is calculated from the mass of the grout. The density is considered to be acceptable when the fresh wet density is within ± 3 lb/ft^3 of the design density. Another conventional container, a vertical air chamber that conforms to the requirements of ASTM C23, was employed to determine the air content of the grout. Next, the flow properties of the grout were evaluated using a flow cone test in which grout was poured into a flow cone with a volume of 1,725 ± 5 mL and the grout was permitted to flow under its own self-weight through a flow cone with a ½-inch diameter. A spread test was also conducted according to ASTM D6103. In this test, a 6-in.-long plastic bottomless cylinder with a diameter of 3 in. is filled with grout and is then lifted vertically to allow the grout to spread. The resulting spread of the grout is measured using a tape measure.

(a) Mack Ready Mix Concrete Facility

(b) Adding Fill Flow to CLSM Mix A5

(c) Creating Foam with a Foam Generator

(d) Adding Foam to the Mixer Drum

Figure G.1: Preparation of Large Batches of Grout Mixtures.

Figure G.2: Test Station for Tests on Fresh and Hardened Properties of the Cellular Grout and CLSM Grouts.

Table G.3: Experimental Tests Conducted in Phase 1

Test	ASTM Reference
Fresh Properties: Fresh Density	ASTM C138
Fresh Properties: Fluidity	ASTM C939
Fresh Properties: Flowability/Slump	ASTM D6103
Fresh Properties: Air Content	ASTM C138
Fresh Properties: Temperature	ASTM C1064
Fresh Properties: Stability/Bleeding Test*	ASTM C940
Hardened Properties: Compressive Strength	ASTM D4832
Hardened Properties: Split Tensile Strength	ASTM C496
Hardened Properties: Drying Shrinkage	ASTM C596
Hardened Properties: Water Absorption	ASTM C796
Hardened Properties: Oven Dry Density	ASTM C495

** Stability tests were conducted for cellular grout; bleeding tests were conducted for CLSM Grouts.*

G.2.2 Phase 1 test results on grout properties

Table G.4 presents the results for tests to determine both fresh and hardened properties of large batches of all three grouts. CLSM Mix A did not flow through the flow cone as shown in Figure G.3(a); this result is consistent with the lab test results. However, the results for the spread test for the large batch showed no spread (Figure G.3(b)), while the lab results showed about 7 inches of spread. As the large batch of this mix showed no flow and no spread, it exhibited less bleeding as compared to the lab results (about 20% lower) as well as a higher compressive strength (higher by a factor of 1.8). Similarly, the large batch of CLSM Mix A5 did not flow through the flow cone even though an additional amount of Fill Flow additive was added to the truck mixture. However, it showed a good spread of 8 inches. The large batch of Cellular Grout Mix C40 showed excellent results, with a spread of about 12 inches (Figure G.4); it also performed well in the flow cone test, as the grout was able to flow through a ½-in.-diameter flow cone. However, the cellular grout was prepared during cold weather, when the concrete batching plants typically prepare mixes with hot water (between 100 °F and 150 °F), and the use of hot water during cold weather was later determined to cause cellular grout to exhibit collapse. Based on this observation, we investigated the effect of the use of high-temperature water on the cellular grout mix. This investigation is discussed in Appendix E ("Cellular Grout"), where it was reported that mixing cellular grout with hot water at an approximate temperature of 100°F would cause the grout to collapse before reaching the hardening stage, as shown in Figure G.5.

Table G.4: Properties of Grouts from Phase 1 Tests

Property Type/Test	CLSM Mix A	CLSM Mix A5	Cellular Grout Mix C40
Fresh Property: Fresh Density (lb/ft^3)	125.6 (123 ± 3)	97 (93 ± 3)	44 (40±3)
Fresh Property: Temperature (°F)	100 (68 °F to 72 °F)	100 (68 °F to 72 °F)	100 (68 °F to 72 °F)
Fresh Property: Spread Test (in.)	No (7)	8 (11.5)	12 (10.5)
Fresh Property: Flow Cone Test (sec)	No (No)	No (37)	75 (62)
Fresh Property: Air Content (%)	3 (1.5)	30 (30)	70 (70)
Fresh Property: Stability/Bleeding Test (%)	2 (2.5)	No (No)	1.25* (No)
Hardened Property: Compressive Strength (psi)	162 (92)	220 (278)	312 (264)
Hardened Property: Split Tensile Strength (psi)	--	--	--
Hardened Property: Oven-Dry Density (lb/ft^3)	--	--	--
Hardened Property: Water Absorption (%)	--	--	--

( ) = Lab test results;   -- = Not considered in Phase 1.

(a) Flow Cone Test for CLSM Mix A   (b) Spread Test for CLSM Mix A

Figure G.3: Flow Tests for CLSM Mix A.

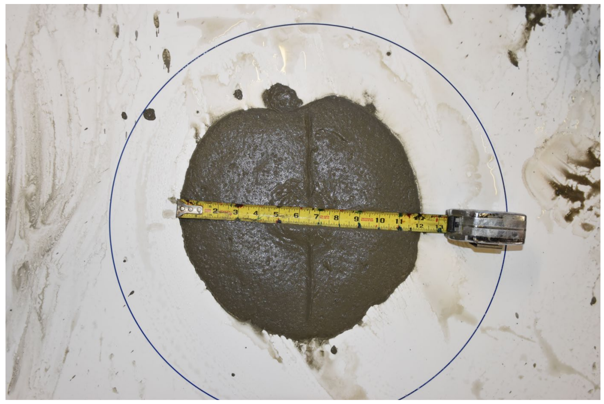
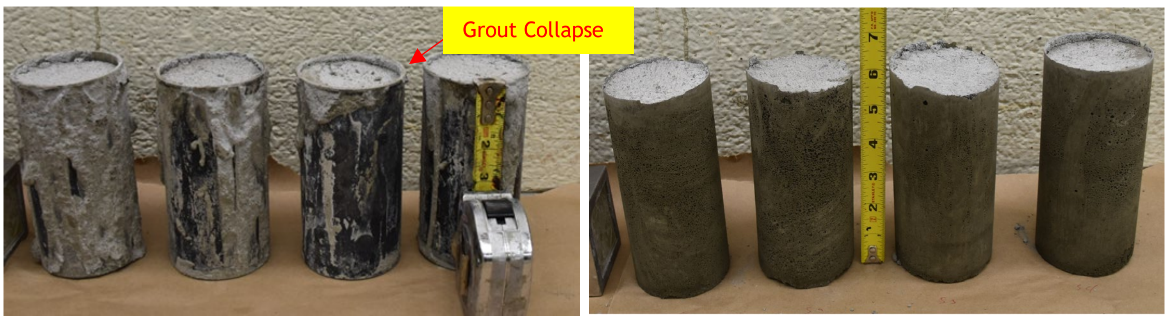


Figure G.4: Spread Test for Cellular Grout Mix C40.



(a) Before Demolding (b) After Demolding

Figure G.5: Collapse of Cellular Grout.

G.3 Phase 2 Testing

G.3.1 Material information and test setup for Phase 2 tests

The second phase of this study involved the pumping of grouts over a 200-ft. distance. As these tests require large open areas that can accommodate the machines and pipes required to pump the grouts over long distances, the pumping tests were conducted at the facilities of Grout Systems Inc. (Wadsworth, Ohio). For practical installations, the annulus void of a sliplined culvert is generally filled by pumping grout through 2-inch PVC pipes. Therefore, it was proposed to pump the grouts through 2-inch PVC pipes over a distance of 200 ft with a positive slope of 2.5% and examine the grout properties before and after pumping in order to evaluate the pumpability of grouts over a long distance. Figure G.6 presents a diagram showing the testing setup for the pumping tests conducted in Phase 2. For the Phase 2 tests, the grout selections were narrowed to two grouts, CLSM Mix A5 and Cellular Grout Mix C40 (CLSM Mix A was excluded from this phase because the grout did not flow through the flow cone and did not spread during tests conducted in Phase 1). The wet and hardened grout tests performed on the grouts were similar to those conducted in Phase 1, with the addition of tests on hardened properties such as tensile splitting strength, drying shrinkage, water absorption, and dry density. The mix proportions used for CLSM Mix A5 and

Cellular Grout Mix C40 are shown in Table G.5 and Table G.6, respectively. A total of 3 yd^3 of each grout was made in this phase.

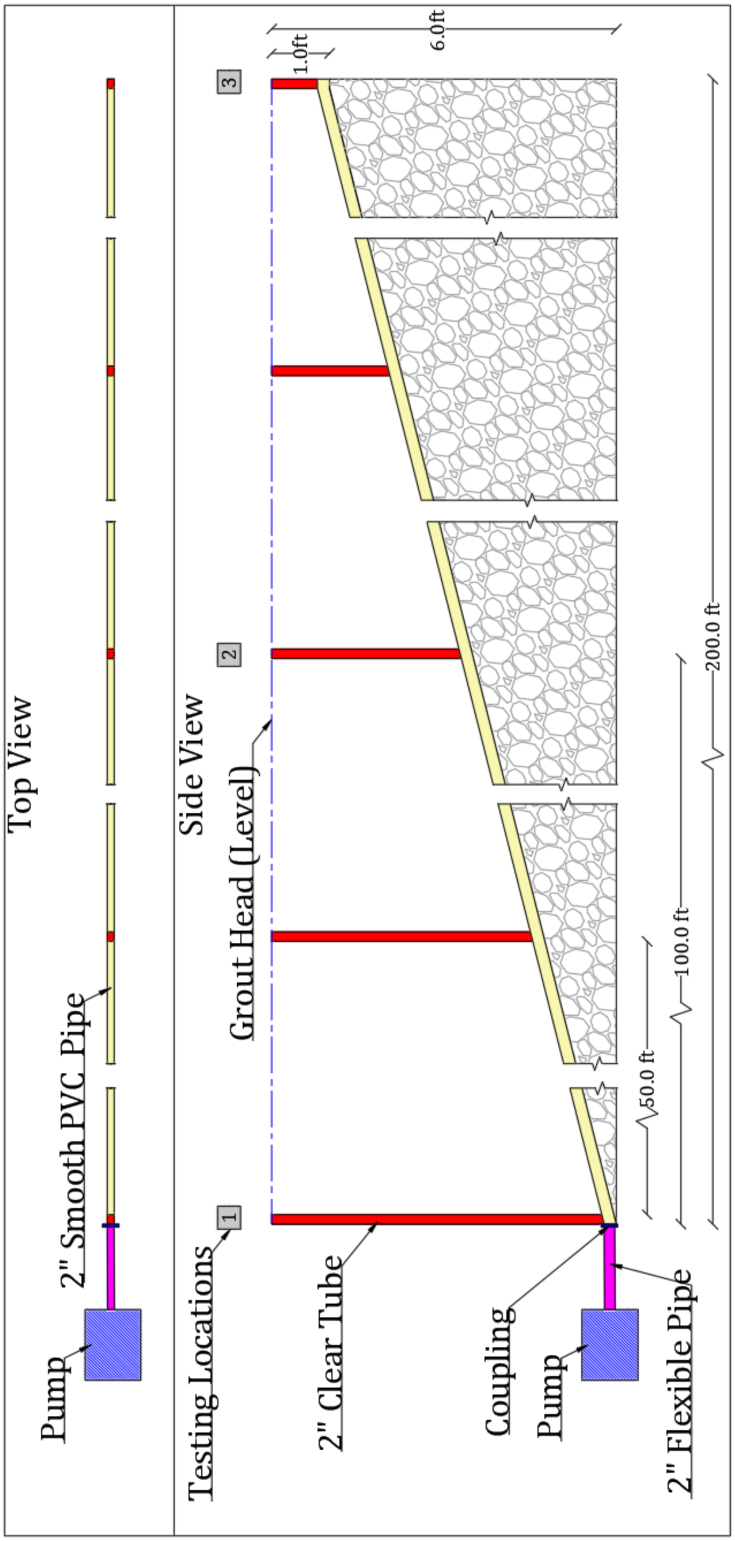


Figure G.6: Layout for Grout Pumping in Phase 2.

To investigate the pumpability of the grout mixtures, grouts samples were collected at three different points along the pumping route (Figure G.7). Prior to pumping, the density of the grout at Point 1 (the start location) was measured to ensure that the mix design achieved the required density; if not, adjustments were made to the mix before pumping proceeded. Point 2 was located approximately midway along the length of the pipe (approximately 100 ft from the start point), while Point 3 (the discharge end) was located approximately 200 ft from the start point. Prior to beginning each test, the PVC pipe was flushed with water to ensure that grout would not stick to the walls of the pipe. Transparent 2-inch tubes were fixed to the pipe at different locations to observe the grout as it was pumped. The top vents of the transparent tubes were capped off to allow the grout to continue traveling the entire length of the pipe.

(a) Start Location (Point 1) (b) Discharge End (Point 3)

Figure G.7: Pumping Test in Phase 2.

Table G.5: Grout Mix Proportions for 1 yd^3 of CLSM Grout in Phase 2

Mix Type	Cement Type I (lb/yd^3)	Fly Ash	Fly Ash (lb/yd^3)	Fine Aggregate Type	Fine Aggregate (lb/yd^3)	Water (gallon)	*Fill Flow (lb)	*Air Entraining Agent Admixture (oz)	W/C
CLSM Mix A5	103.3	Class F	370	No. 4 (100% Passing)	2733.3	35.6	4	2.6	0.628

**Added at the site*

Table G.6: Grout Mix Proportions for 1 yd^3 of Cellular Grout in Phase 2

Mix Type	Cement Type I (lb/yd^3)	Water (gallons)	*Foam (yd^3)	W/C
Cellular Grout Mix C40	693.3	39	0.6	0.469

**Added at the site*

G.3.2 Phase 2 test results

G.3.2.1 *CLSM Mix A5*

The results of pumping tests in Phase 2 are presented in Table G.7. Prior to pumping, the fresh density of CLSM Mix A5 was measured. Ten bags of Fill Flow (10 lb) were added based on the laboratory tests; this resulted in a density of 110 lb/ft^3. Tis. Therefore, an additional two bags of Fill Flow (2 lbs) were added to the mix to further reduce the fresh density. However, as the additional Fill Flow only reduced the density of the mix to 100 lb./ft^3 which is still above the limit of the target fresh density for CLSM A5, a total of 8 oz. of an air entraining agent was added to the mix to attain the target density of 93.3 lb/ft^3. Once the fresh density of CLSM Mix A5 met the requirements, the grout was pumped through the 2-inch PVC pipes using an Olinpump SC 25 S-tube grout pumping machine.

Spread test results of 11.5 inches for grout samples collected at Points 2 and 3 satisfied the lab spread result , and the results were nearly the same as those for Point 1. However, while flow cone tests on all samples collected required longer test times than those for the mixes tested in the lab, the grout still flowed continuously through a ½" flow cone. No bleeding was noted in any CLSM Mix A5 samples, and the hardened properties of the samples were found to satisfy the relevant ASTM hardened grout requirements, as shown in Table G.7. Moreover, the drying shrinkage for the grout used in the pumping test was lower than that for the same mix as tested in the lab (see Figure G.8). In summary, it was possible to pump CLSM Mix A5 through the PVC pipe at a slope of +2.5% over a distance of 200 ft without observing any bleeding before or after pumping.

G.3.2.2 *Cellular Grout C40*

A cement mixer truck delivered 3 yd^3 of slurry mix (cement and water) to the test site, and about 54 ft^3 the generated foam was added to the truck to prepare Cellular Grout Mix C40. The initial fresh density was 34 lb/ft^3, which was lower than the cellular grout fresh density limits (40 ± 3 lb/ft^3). Because of this, a second sample was collected from the mix truck after the grout was mixed for an additional 5 minutes. The density was then determined to be within the allowable limits. The second sample was collected prior to pumping and was recorded as 42 lb/ft^3; for this reason, no additional foam or other admixtures were added to the mix. It was noted that the density measurements varied for different samples of cellular grout, as the samples included various amounts of foam. Nonetheless, an overall density of 38 lb/ft^3 was achieved, which is within the limit of 40 ± 3 lb/ft^3. After confirming that the density of the freshly mixed grout was acceptable, the grout was pumped through the PVC pipe using the Olinpump SC 25 S-tube pumping machine. From the results shown in Table G.7, the outcomes of the spread and flow cone tests for samples collected at all three sampling points were comparable to the outcomes of the tests in the laboratory.

It is worth noting that no collapse of the large batches of grout occurred after 24 hours for samples collected at any of the sampling locations along the PVC pipe; the grout temperature at the placement point (Point 1) was 65°F. Because making and placing cellular grout at high temperatures might lead to collapse, it is essential to monitor the temperature during mixing and placement (the deleterious effects of high temperatures were demonstrated in the laboratory and during Phase 1 of the project).

All hardened property results for the large batches of grouts met the criteria required by the relevant ASTM tests. Moreover, as shown in Figure G.8, the results for drying shrinkage for grouts collected at different points in the pumping test were lower than those for smaller batches prepared in the lab. The most important finding is that pumping cellular grout with a density of 40 lb/ft^3 up a slope of +2.5% over a distance of 200 feet resulted in an air loss of 4.5% (Table G.8), which is within the maximum air loss limit for cellular grout according to ASTM C869/C869M-11 (calculated in Eq. (G.1)), and no stability issues were observed at any of the three sampling points.

$$\text{Air Loss } \% = 100 \times \frac{D_{ex2} - D_{ex1}}{D_{th}} \qquad (G.1)$$

where D_{ex1} is the experimental density of the grout before pumping (lb/ft^3), D_{ex2} is the experimental density of the grout after pumping (lb/ft^3), and D_{th} is theoretical density of the plastic mix based on the absolute volume (lb/ft^3).

Table G.7: Results for Phase 2 Experimental Tests

Property Type/Test	CLSM A5 Point 1	CLSM A5 Point 2	CLSM A5 Point 3	Cellular Grout C40 Point 1	Cellular Grout C40 Point 2	Cellular Grout C40 Point 3
Fresh Property: Fresh Density (lb/ft^3)	93.3 (93±3) *ASTM C38*	91.8	90.8	38 (40±3) *ASTM C138*	36.0	36.2
Fresh Property: Temperature (°F)	70	70	70	65	65	65
Fresh Property: Spread (inches)	11 (11.5)	14	12	19.5 (10.5)	16.25	11.5
Fresh Property: Flow Cone Test (sec)	77 (37)	49	46	24 (62)	19	34
Fresh Property: Air Content (%)	26 (30)	28	28	60 (70)	50	60
Fresh Property: Bleeding or Stability (mL)	0	0	0	0	0	0
Hardened Property: Compressive Strength (psi)	214 (278)	219	205	376 *(200) ASTM C869*	373	368
Hardened Property: Tensile Splitting Strength (psi)	29	--	33	61.0 *(25) ASTM C869*	--	62.17
Hardened Property: Oven-Dry Density (lb/ft^3)	88.6 (91)	92	95	31.0 *(30±3) ASTM C869*	29.4	28.2
Hardened Property: Water Absorption (%)	15 (15.2)	14.4	13.8	24 *(25) ASTM C869*	23	23.3

Notes: ( ) = lab results; -- = Not determined at these locations.

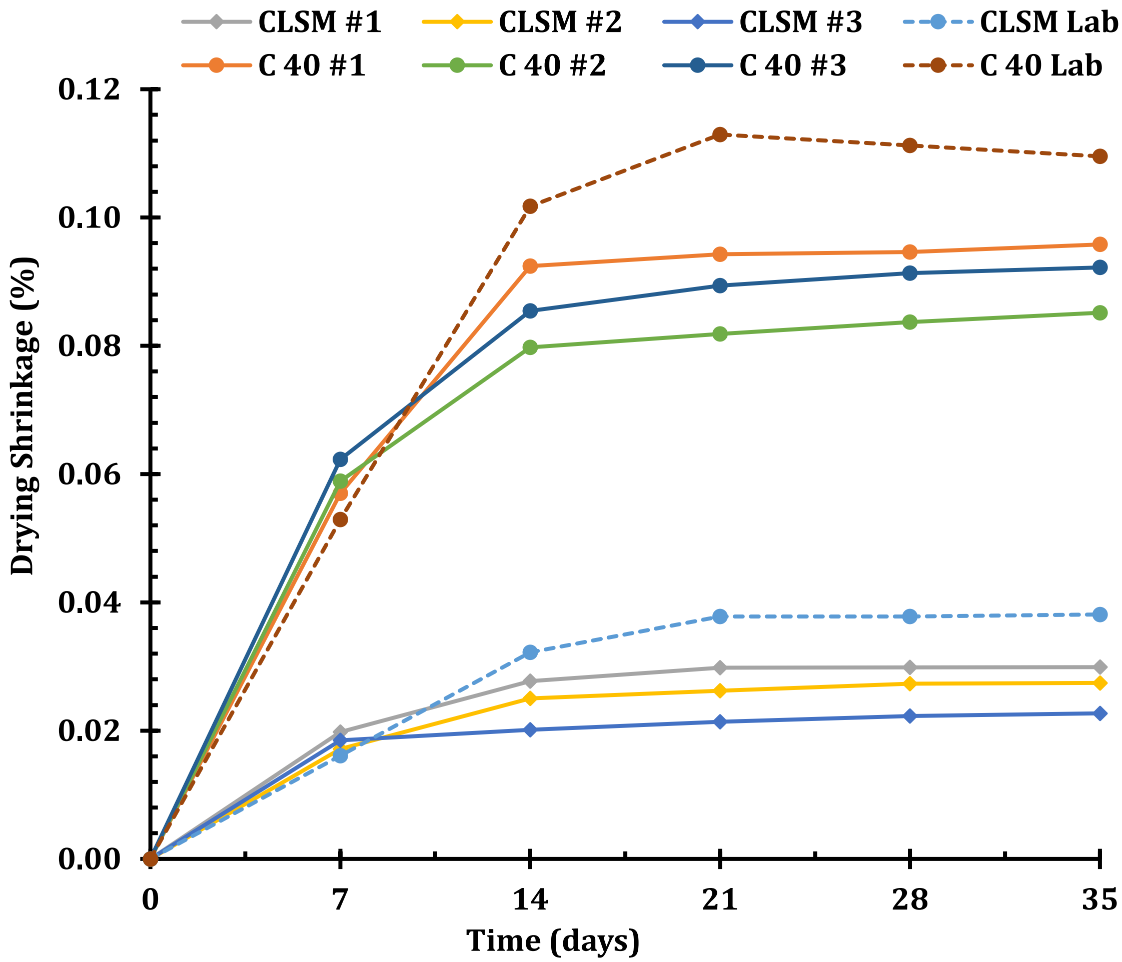


Figure G.8: Drying Shrinkage for Grouts Tested in Phase 2.

Table G.8: Air Loss Before and After Pumping for Phase 2

Property (Timepoint)	CLSM Mix A5 (Before Pumping)	CLSM Mix A5 (After Pumping)	Cellular concrete Mix C40 (Before Pumping)	Cellular concrete Mix C40 (After Pumping)
Density (lb./ft^3)	93.3	90.84	38	36.20
Air Loss (%)	−2.5	−2.5	−4.5	−4.5

G.4 Phase 3 Test Results

G.4.1 Test setup and materials used in Phase 3

Phase 3 of the project involved pumping the grouts into sliplined culvert test specimens that met ODOT specifications and had 48-in. diameter galvanized corrugated host pipes and liner pipes made from 36-in. diameter spiral rib pipe. The conduits were selected based on the culvert inspections conducted earlier in the project (Appendix C), which revealed that these were some of the common materials used for host pipes and liner pipes in the inspected culverts.

The Phase 3 tests were conducted using the setup shown in Figure G.9, where grout was pumped through a 2-in.-diameter flexible pipe that is 100 ft in length. Plywood bulkheads supported by 2 in. × 4 in. wooden runners were installed at the inflow and outflow ends of the sliplined culvert test specimens (Figure G.10). Silicone sealant was used to provide a tight seal between the bulkhead and the sliplined culverts, and Dywidag steel anchor bars were used to secure the bulkheads at the ends of the host and liner pipes by reinforcing the connection between the sliplined culvert test specimens and the end bulkheads. Three pieces of clear Plexiglass windows (3 in. × 4 in.) were placed at approximately the 9, 12, and 3 o'clock positions of the host pipe to allow for the inspectors to watch the grouting process during pumping. For each sliplined culvert test specimen, two PVC feed tubes were used: the main tube (Inlet Pipe 1) was located at the one o'clock position. The pipes were 10 ft. long so that the grout was discharged at a location 10 feet inside the culvert from the inlet end of the culvert. Another pipe (Inlet Pipe 2) was installed at the 11 o'clock position to discharge grout at a location that was 5 feet from the culvert inlet. Grouting was mainly conducted using the primary pipe, and the secondary pipe was only to be used as a backup in the event that the first pipe should become obstructed.

To monitor the temperature and the flow of grout during the pumping, wireless cameras and temperature sensors were placed in each culvert at the 12 o'clock position (Figure G.11). The cameras were installed one day prior to testing, and all devices were linked to a WiFi hotspot so that the research team could use the software app *Soliom+* to monitor the grout flow within the annulus void via a live streaming video. The wireless camera has a capacity to swivel up to 320° horizontally and up to 90° vertically, and it has 3X zoom, making it possible to record images of the grouting from various angles. SmartRock concrete temperature sensors were procured from GIATEC and were connected via Bluetooth wireless technology. These sensors can sense temperatures ranging from −22 °F to 181 °F.

The mix proportions for CLSM Mix A5 and Cellular Grout Mix C40 are shown in Tables G.9 and G.10, respectively. At the site, additives such as Fill Flow and air-entraining agents were applied to the grout as needed. Because different mixes included different additives (Fill Flow or foam, for example) and additives are known to affect the final volume of the grout after mixing. The quantity of grout that was ordered from the batching plant was different for each grout type. The volume of CLSM Mix A5 that was ordered from the batching plant was 6 yd^3, including all primary ingredients (cement, fly ash, fine aggregate, and water), while only 5 yd^3 of slurry grout for Cellular Grout Mix C40 was ordered. According to the findings from the laboratory experiments, Fill Flow can increase the volume of CLSM grout by up to 30%, while foam can increase the volume of slurry grout by up to 60%.

Table G.9: Grout Mix Proportions for 1 yd^3 of CLSM Grout in Phase 3

Mix Type	**Cement Type I (lb/yd^3)**	**Class F Fly Ash (lb/yd^3)**	**Fine Aggregate Type**	**Fine Aggregate (lb/yd^3)**	**Water (gallons)**	***Fill Flow (lb)**	***Air Entraining Agent Admixture (oz)**	**W/C**
CLSM Mix A5	130	350	100% Passing No. 4 (100% Passing)	2743.3	38	4	2.6	0.661

** Added at the site, not at the batching plant.*

Table G.10: Grout Mix Proportions for 1 yd^3 of Cellular Grout in Phase 3

Mix Type	**Cement type I (lb/yd^3)**	**Water (gallons)**	**Foam* (ft^3)**	**W/C**
Cellular Grout Mix C40	698	41.2	18	0.492

** Added at the site, not at the batching plant.*

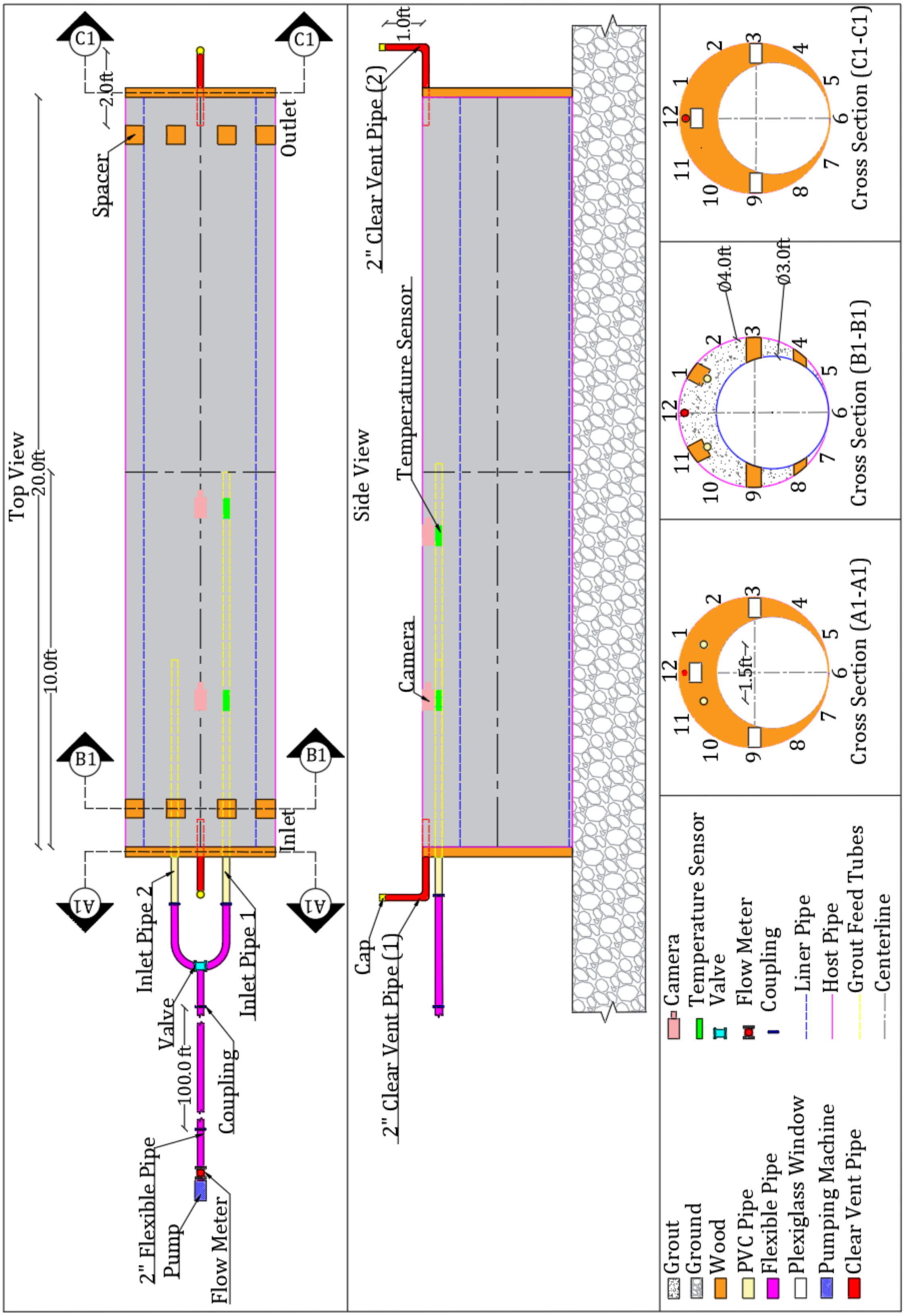


Figure G.9: Layout for Grout Pumping Tests in Phase 3.

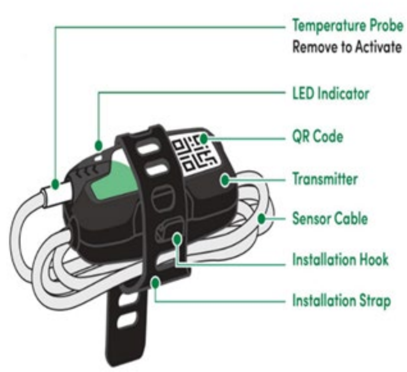
(a) Side view of culvert

(b) Inlet side of culvert inlet

(c) Outlet side of culvert

Figure G.10: Preparation of Culverts for Phase 3 Testing.

(a) Soliom wireless camera



(b) SmartRock temperature sensor

Figure G.11: Camera and Sensors used for Phase 3 Tests.

G.4.2 Results for Phase 3 pumping tests

Phase 3 test results are summarized in Table G.11 and are described below.

G.4.2.1 *Results for CLSM Mix A5*

The initial fresh density of the as-delivered CLSM Mix A5 exceeded the density limit for this mix of 93 ± 3 lb/ft^3. A total of 18 bags (18 lb) of Fill Flow were added to the mix delivered to the site, but the fresh density was only reduced to 114 lb/ft^3. After the addition of another six bags (6 lb) of Fill Flow, the fresh density was further reduced to 98 lb/ft^3. However, as this was still beyond the fresh density limit for CLSM Mix A5, 16 oz of an air-entraining agent was added to obtain a density of 96.5 lb/ft^3. After ensuring that the fresh density met the requirements, an Olinpump SC 25 pump was used to pump the grout through the feed tube (which consisted of 100 ft of a 2-in. high pressure–resistant flexible hose). The wireless cameras were able to record the grout as it came out of the feed tube and began to fill the annulus void (Figure G.12), and the grout flow was also observed through the Plexiglass windows installed in the bulkheads.

The CLSM Mix A5 grout was filled to a nearly equal level at the bulkheads, taking into consideration the 2.5% slope. However, since the liner pipe was only supported at locations near the bulkheads, the middle portion of the liner pipe was lifted by the grout. The grouting process was paused for a short time while the bottom of the liner pipe was secured to the host pipe by screws, and additional support was provided by placing steel I-beams on the inside of the liner pipe to ensure that the liner pipe would be held in the correct position. Pumping of the grout was then re-started, and the pumping continued until grout was observed to come out of the vent tubes at both ends of the culvert. The time required to fill the annulus void of the sliplined culvert test specimen with grout was about 22 minutes, and the total amount of grout pumped was approximately 5.2 yd^3 (determined from the number of pump piston strokes).

The fresh properties of the CLSM Mix A5 grout were characterized for grout samples collected at two locations: one from the ready mix truck (Point 1, prior to pumping) and another from the vent tubes at the outlet (Point 2, after pumping), and the test results are presented in Table G.11. It is interesting to note that even though the grout did not flow through the ½" stem of the funnel in the flow cone test, it was still possible to smoothly pump the grout through a 2" flexible hose. The grout showed a spread of 9 in. before pumping and 12 in. after pumping; these spread results satisfy the minimum spread of 8 in. stipulated by ACI Committee 229 (2013).

Testing the hardened properties of CLSM Mix A5 grout required collecting specimens of hardened grout from the grout used to fill the annulus of the culvert test specimens at the site and transporting them to the University of Akron for testing. Most tests for hardened properties were performed within or after 28 days of grout installation. As can be seen from the results in Table G.11, the hardened properties satisfy ASTM and lab requirements. Figure G.14 shows the drying shrinkage of the grout over 30 days; it can be noticed that the shrinkage values for grout samples collected before and after pumping are still lower than the lab results and are within the acceptable range. The peak temperature developed within the grout during the first 24 hours after casting (Figure G.15(a)).

G.4.2.2 *Results for Cellular Grout Mix C40*

A concrete ready mix truck delivered 5 yd^3 of slurry mix (mixture of cement and water) to the test site, and foam produced at the site was added to the mix to prepare Cellular Grout Mix C40. At the initial stage, only 80% of the generated foam was added to the truck to avoid over foaming the mix in the truck. Next, the fresh density of the grout was measured using a standard container; the first reading was 56.8 lb/ft^3, which is above the required fresh density for this grout mix (40 ± 3 lb/ft^3). Additional foam was added to the truck from the remaining supply of generated foam, and the truck mixer agitated the grout for at least 5 minutes to allow the foam to be fully incorporated into the mix. The second fresh density measurement obtained for the grout was about 45 lb/ft^3, which was decided to be acceptable (even though it is outside the tolerance of 40 ± 3 lb/ft^3) because the appropriate amount of foam (90 ft^3) had been added to the slurry mix. The grout sample obtained from the first sampling location (Point 1) flowed through the flow cone for 46 seconds, which is less than was required for this grout in the lab tests, and the spread of 12.5 in. was greater than the spread for the grout tested in the lab tests. The temperature of the grout was 74.3 ^oF, and this helped the cellular grout to remain stable even after the first 24 hours of placement.

As the amount of cellular grout from the first mixer truck was insufficient to completely fill the annulus void of the sliplined culvert test specimen (it filled only 75% of the total volume of the annulus), a second batch of grout was ordered. The second mixture truck arrived at the site 90 minutes later. For this batch, the required amount of foam was added at one time and was mixed for about 5 minutes. The first fresh density measurement was about 30 lb/ft^3, which was below the acceptable tolerance. A second density measure was made to obtain an average value for the mix in the second truck. A grout sample was obtained just ahead of the culvert inlet, and the result was about 42 lb/ft^3; this yielded an average value of 36 lb/ft^3 (average of 30 and 42 lb/ft^3), which was within the acceptable limit for fresh density. Some amount of foam may have dissipated between the pump and the inlet point of the culvert test specimen because of pumping.

Once the grout density was considered to be acceptable, the pumping process was re-started, and the remaining portion of the annulus of the sliplined culvert was filled smoothly. The pumping was stopped when grout came out from the vent tubes on both sides of the culvert (Figure G.13). Grout was collected from the vent tube located at the outlet of the culvert (Point 2), and a fresh density of 46 lb/ft^3 was obtained. At the outlet, the grout showed perfect flow; a flow test took 14.54 seconds, and a spread of 12.5 in. was measured. It took approximately 14 minutes to fill the total volume of the annulus (4 yd^3) with cellular grout. At 24 hours after placement, the grout showed good stability.

At three days after grouting, temperature readings from the culvert were obtained for those three days. Figure G.15(b) shows the readings obtained for the cable and body of the sensor. The temperature reading from the cable was about 137 ^{o}F, while the reading from the body of the sensor was about 92 ^{o}F. This large difference between the temperatures of the cable and outer pipe (host pipe) indicates that the cable was in direct contact with the grout, as the grout temperature begins to rise within 24 hours of casting due to the heat of hydration. Thus, monitoring the temperature inside the annular space can also assist in determining that the space is filled with grout and the grout is hydrating; this another way to verify that the space is filled with grout.

At three days following installation, cellular grout test specimens were collected from the site test station and were carefully transported to the lab at the University of Akron. The specimens were tested 28 days after the installation, and the results are presented in Table G.11. The grout properties determined from laboratory tests satisfied ASTM requirements and the requirements based on earlier lab tests on small batches of grout. Figure G.14 shows the drying shrinkage of the grout over 30 days. It can be stated that the shrinkage values at Points 1 and 2 in the field are lower than the values recorded from the corresponding lab tests performed on smaller batches, which indicates that the shrinkage obtained for the installed grout is acceptable, and less than that for the small quantity of grout prepared in our laboratory.

Table G.11: Test Results for Phase 3 Pumping Tests

Test	CLSM Mix A5 Point 1	CLSM Mix A5 Point 2	Cellular Grout Mix C40 Point 1	Cellular Grout Mix C40 Point 2
Fresh Property: Fresh Density Test (lb/ft^3)	96.5 *(90 ± 3 lb/ft^3 per ASTM C138)*	95.1	Avg *45, **42.4 *(40 ± 3 lb/ft^3 per ASTM C138)*	46
Fresh Property: Temperature (°F)	80.4	82.8	74.3	78
Fresh Property: Spread Test (in.)	9.0 (11.5 per lab)	12	12.25 (10.5 per lab)	12.5
Fresh Property: Flow Cone Test (sec)	No (37 per lab)	No 46	46.0 (62 per lab)	14.5
Fresh Property: Air Test (%)	30 (30 per lab)	30	70 (70 per lab)	65
Fresh Property: Bleeding or Stability Test (mL)	0	0	0	0
Hardened Property: Compressive Strength (psi)	244 (278 per lab)	226	*481 (min. 200 psi per ASTM C869*	376
Hardened Property: Tensile Splitting Strength (psi)	39	35	*84 (25 psi per ASTM C869*	38
Hardened Property: Oven-Dry Density (lb/ft^3)	93 (91 per lab)	89	*32 (30±3*Lb./ft^3 *per ASTM C869)*	28
Hardened Property: Water Absorption (%)	18.6 (15.2 per lab)	16	*24 (25 per ASTM C869)*	22

Figure G.12: Grout Flow During the Filling of the Annulus (CLSM A5).

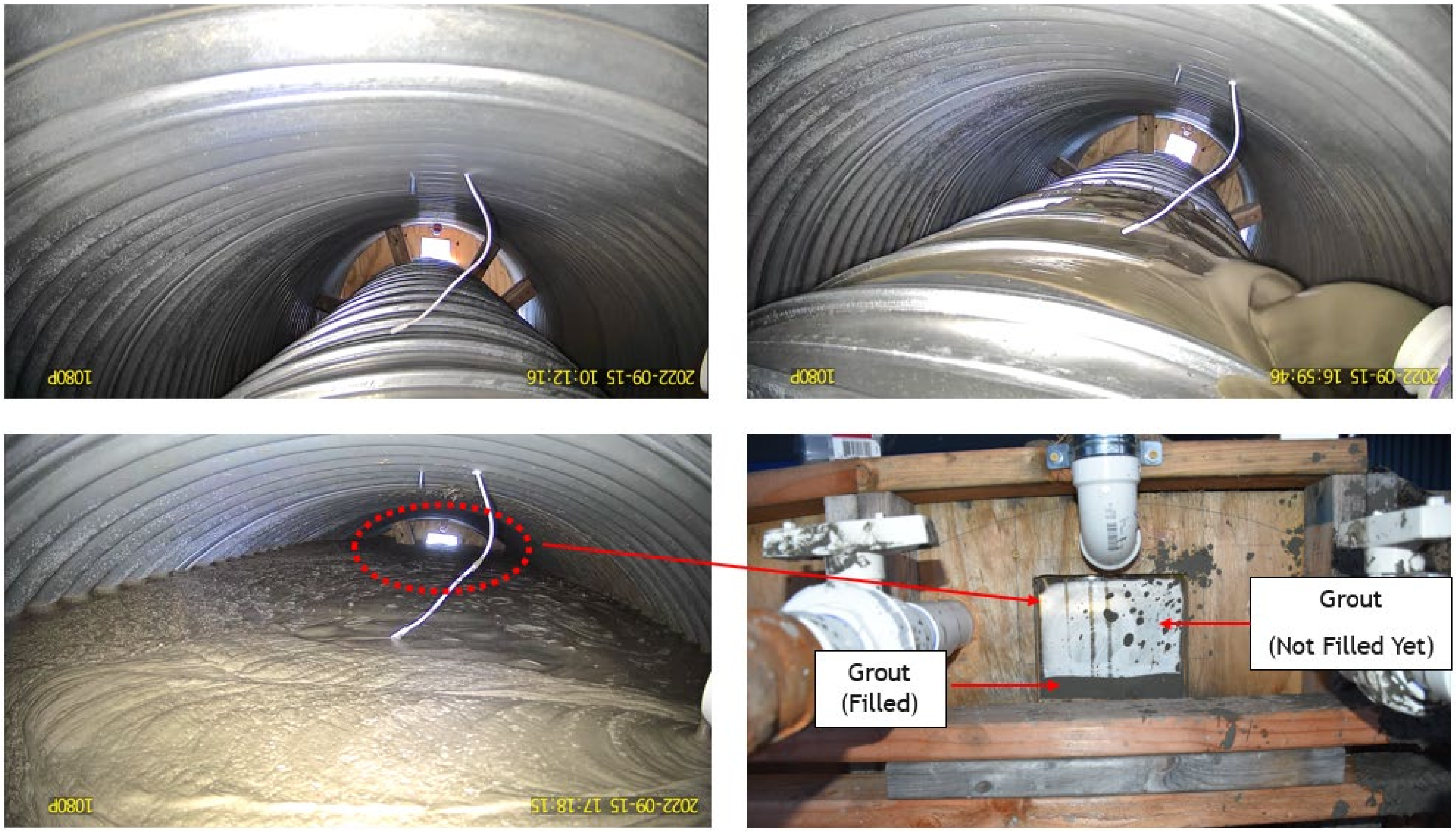


Figure G.13: Grout Flow During the Filling of the Annulus with Cellular Grout Mix C40.

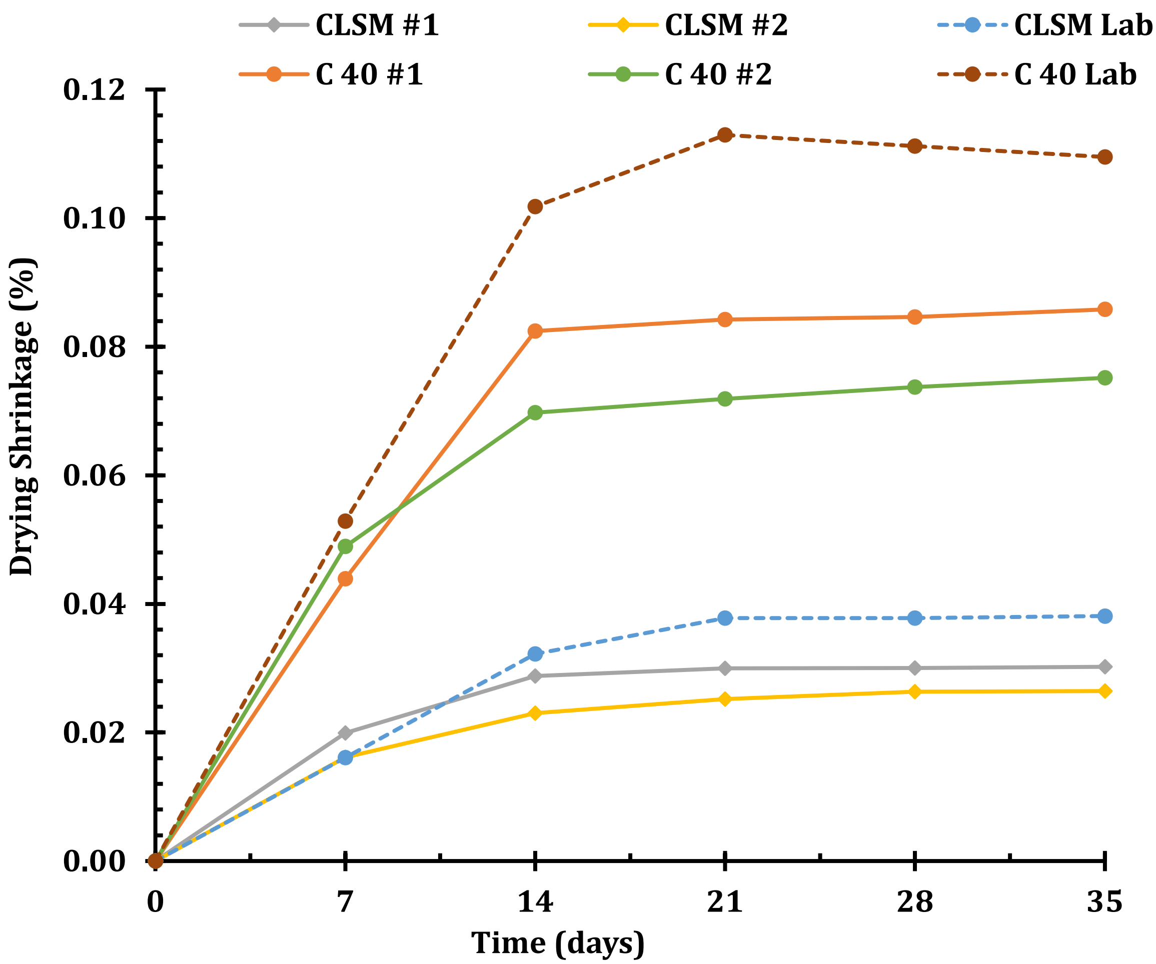
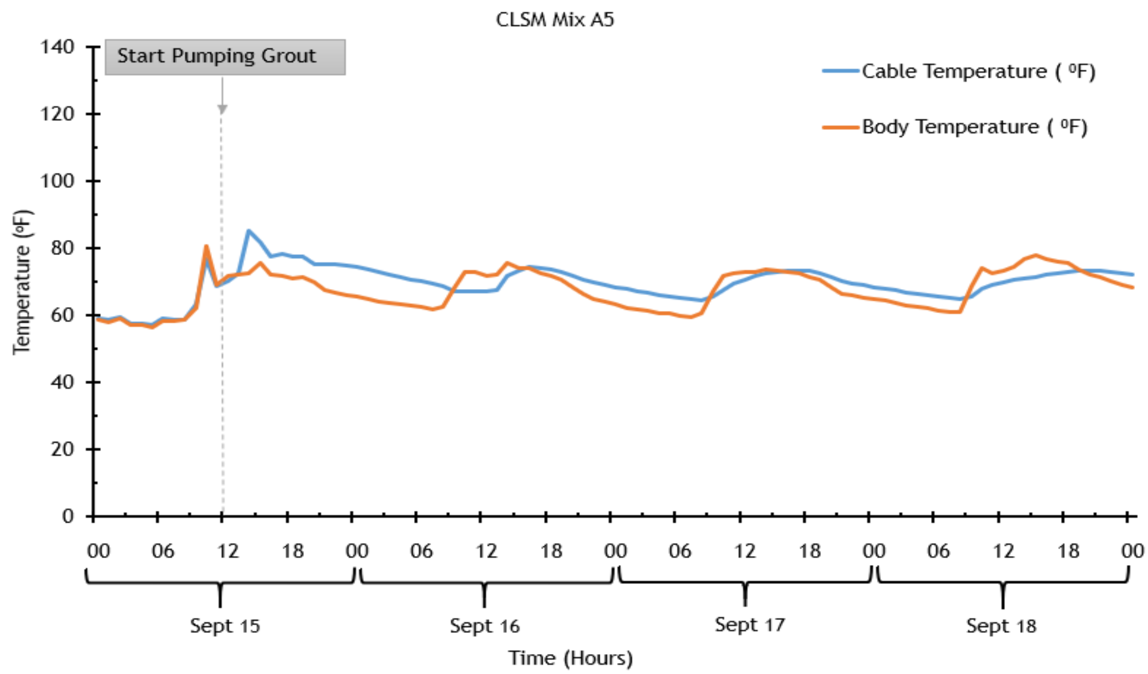
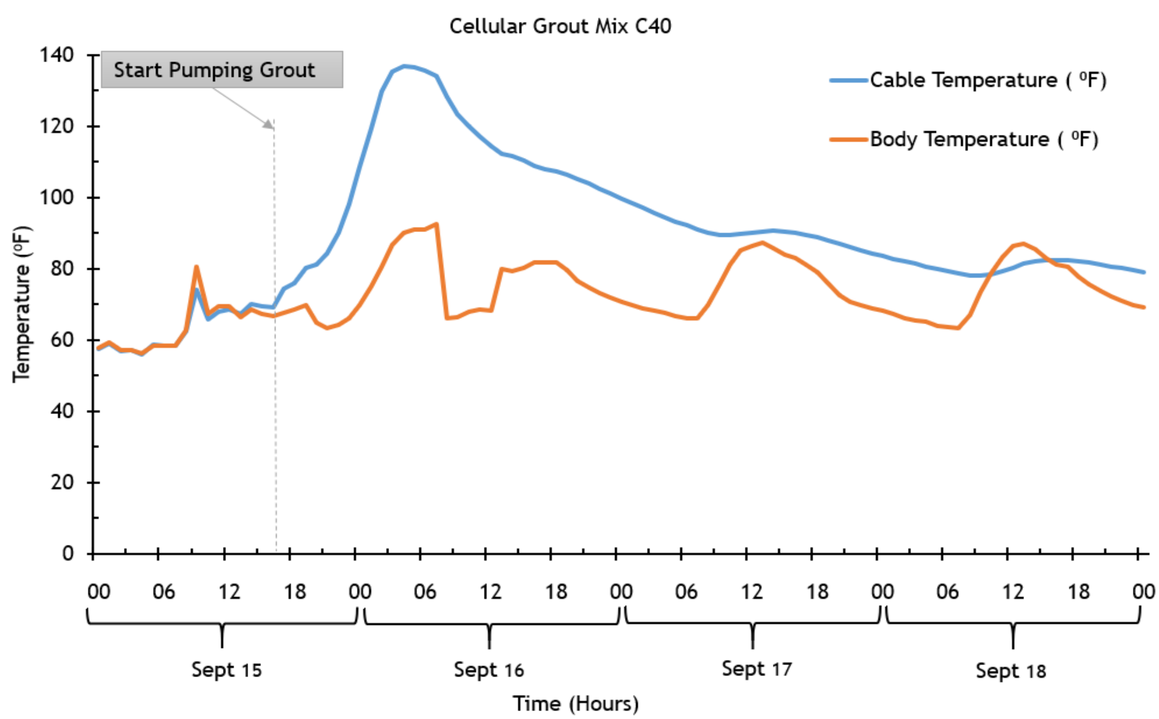


Figure G.14: Drying Shrinkage Results for Grouts in the Phase 3 Tests.



(a) CLSM Mix A5



(b) Cellular Grout Mix C40

Figure G.15: Mix Temperatures for Grouts in Phase 3
(Note: The cable temperature is the temperature within the annulus grout, while body temperature is the ambient temperature outside of the host pipe).

G.5 Inspection of the Grouted Culverts

At 28 days after grout installation, visual checks were made to determine if the grouts were able to completely fill the annulus voids and harden as designed. This was accomplished by removing the bulkheads at the inlets and outlets of the culverts to expose the grouts and allow a visual examination to be conducted (Figure G.16). For both sliplined culvert test specimens, the annular spaces at the two ends of the culvert were found to be completely filled with grout, and no voids were present. Using a commercial concrete cutting saw, each sliplined culvert was then cut into four pieces (at the cutting locations shown in Figure G.17) by a skilled crew from Concrete Cutting Systems (Akron, Ohio) to allow examination of the grouts at the interior locations within the culvert test specimens. Cuts in each culvert were first made from the 9 o'clock position to the 3 o'clock position through the crown position at three locations. Each culvert was then turned using a crane in order to allow the crew to cut the remaining portions. The cut ends of all four segments of both pipes were then inspected, and all segments of the two sliplined culverts were found to be completely filled with grout (Figure G.18).

(a) Cellular Grout C40 at inlet

(b) Cellular Grout C40 at outlet

(c) CLSM Mix A5 at inlet

(d) CLSM Mix A5 at outlet

Figure G.16: Ends of the Culverts After Bulkheads Were Removed.

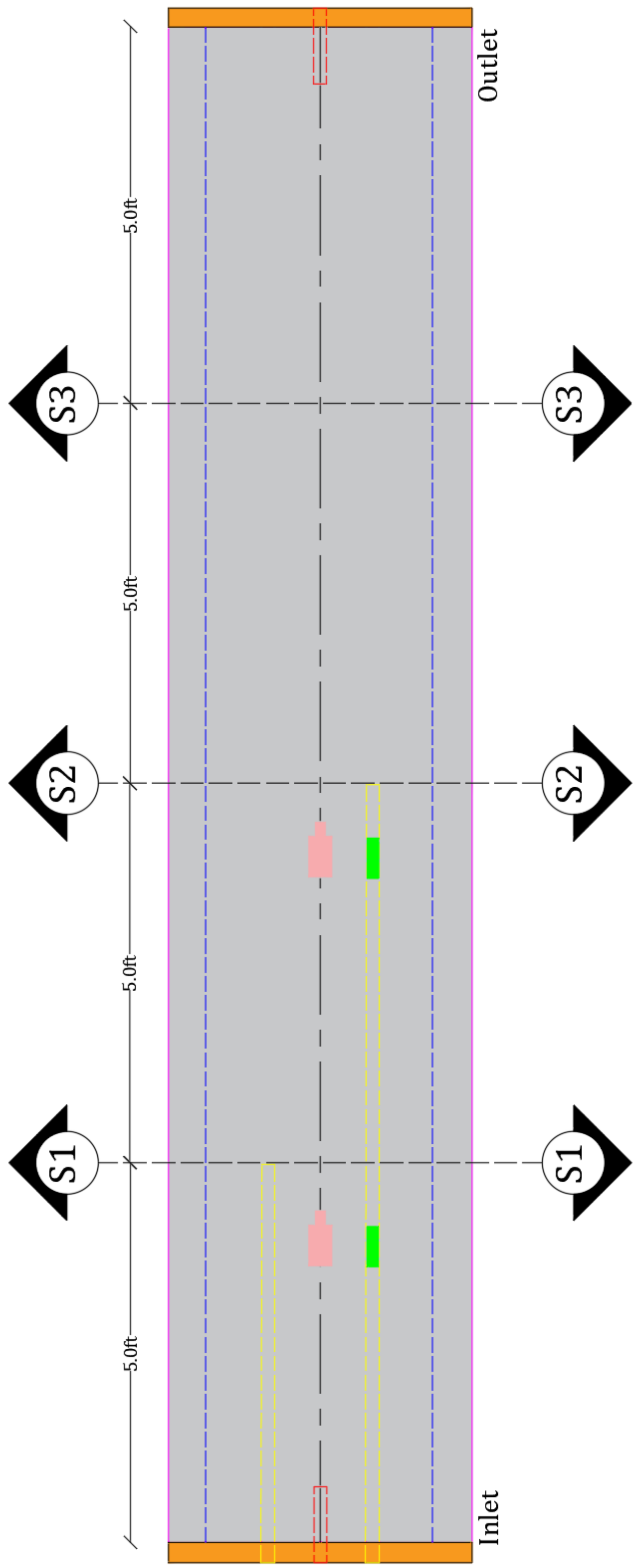


Figure G.17: Conduit Segment Cutting Locations.

(a) Lifting of culvert specimens

(b) Cutting of culvert specimens

(c) CLSM Mix A5 segments

(d) Cellular Grout Mix C40 segments

Figure G.18: Cutting of the Culverts into Segments.

G.6 Conclusions

The effectiveness of the two grout mixtures developed in this study for annulus void filling of sliplined culverts was demonstrated using results from laboratory tests of small batches of grout, pumping tests conducted in the field, and installation of grout in large-scale culvert tests. The complete filling of grout for the two large-scale culvert test specimens was successfully verified during and after the grouting operation. The following conclusions are drawn based on the results of the field culvert grouting tests:

- A typical CLSM grout (Mix A) was unable to achieve the needed flow for pumping, while a modified CLSM grout with a Fill Flow admixture (CLSM Mix A5) and Cellular Grout Mix C40 achieved adequate flowability. Both these mixes are suitable for annulus void filling of sliplined culverts.
- In Phase 1 and Phase 3 tests, CLSM Mix A5 and Cellular Grout Mix C40 performed well when subjected to spread tests. While CLSM Mix A5 made in a batching plant for field tests did not flow through a ½-in. discharge tube of the standard funnel in the flow cone tests, Cellular Grout Mix C40 flowed smoothly through the cone and discharge tube. Regardless, both CLSM Mix A5 and Cellular Grout Mix C40 were able to be pumped through a 2-in. PVC pipe with a 2.5% positive slope over a 200-ft distance in Phase 2, and both grouts were found to retain their wet and hardened grout properties after pumping. Both grouts were also able to be pumped through a 2-in. flexible flow hose in the annulus filling conducted in Phase 3. For CLSM Mix A5, it is preferred to specify a spread test rather than a flow cone test; for cellular grouts, it is appropriate to specify a flow cone test and the spread test.
- Both grouts performed very well in filling the annular spaces of large-sized sliplined culvert test specimens, with excellent flow and filling ability. Complete filling of the annulus voids was demonstrated when the grout flowed out of the vent tubes at both ends of the culvert. Visual inspection of the inlet and outlet ends of the culvert test specimens, as well as the ends of culvert segments after the culverts were cut, showed that the annulus of each culvert was entirely filled with hardened grout. Therefore, both CLSM Mix A5 and Cellular Grout C40 are demonstrated to be suitable for filling the annular spaces of sliplined culverts.
- In Phase 3 tests, where grouts were used to fill the annular spaces of large-scale culverts, temperature sensors were installed at various locations prior to the pumping of the grout installation. The cable temperature readings from the sensors indicate the temperature of the grout once the hydration process begins, as was seen with the cellular grout after 24 hours of casting. Temperature sensors can be installed at specific locations of interest along the culvert where it might be critical for the annulus to be filled (e.g., the 12 o'clock crown position) to verify that grout has filled the annulus at a particular location. The response of sensors would demonstrate that the grout has reached the locations where the sensors are emitting signals.

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Annulus Void Fill Material for Rehabilitated Sliplined Culverts

APPENDIX H

Recommendations on Specification Changes

Prepared by:
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Prepared for:
The Ohio Department of Transportation,
Office of Research and Development

State Job Number 135965
February 2023
Draft Final Report

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APPENDIX H

RECOMMENDATIONS ON SPECIFICATION CHANGES

H.1 Introduction

This appendix provides information regarding potential changes to ODOT Supplemental Specification (SS) 837, which specifies furnishing liner pipe, filling voids around existing conduits, installing liner pipe and grouting liner pipe into existing conduits for the sliplining of culverts. The majority of annulus voids of sliplined culverts are grouted in accordance with the most current ODOT specifications, which employ cementitious grouts (Item 613, Item 602, or cellular grout). However, the findings of the field inspections (Appendix C) performed on multiple sliplined culverts in various districts across Ohio revealed that many of the inspected sliplined culverts had incomplete filling. As a result, it was necessary to undertake experimental testing to revisit the existing requirements and make necessary improvements. Our laboratory tests of two different grouts, a controlled low strength mortar (CLSM Mix A5) and a cellular grout (Cellular Grout Mix C40), validated that the wet and hardened grout properties obtained were suitable for grouts used for filling the annular spaces of sliplined culverts. Larger quantities of grout (3 yd^3) were mixed in a batching plant to verify that the grouts are able to maintain their properties even when they are mixed at a large scale. Our field pumping tests and culvert grouting tests demonstrated that the suggested grouts were able to completely fill the annular spaces of two culvert test specimens having a length of 20 ft. with a 4 ft. outer conduit and a 3 ft. liner pipe. Based on these demonstrations, it is recommended that the new grouts proposed from this study be incorporated into the next revision of SS 837. The following sections provide an overview of fresh and hardened properties of CLSM Mix A5 and Cellular Grout Mix C40 as well as their mix proportions.

H.2 Grouts

The proposed grouts are referred to as CLSM Mix A5 and Cellular Grout C40 in the associated reports compiled for this project. The grouts were evaluated in three phases. During the first phase, the batching plant at Mack Ready Mix Concrete (Akron, OH) successfully prepared trial batches of three cubic yards of each grout. The second phase consisted of pumping the two grouts over a distance of 200 feet through PVC pipes that were 2 inches in diameter. The third and final phase involved pumping the grouts through a 2-inch flexible pipe and placing them in the annular spaces of sliplined culverts, as described in Appendix G.

H.2.1 CLSM Grout Mix A5

The mix proportions for the CLSM Mix A5 grouts used in the three phases of field testing are presented in Tables H.1 to H.3.

Table H.1: Mix Proportions for 1 yd^3 of CLSM Mix A5 Grout in Phase 1

Cement Type I (lb/yd^3)	Fly Ash	Fine Aggregate Type	Fly Ash (lb/yd^3)	Fine Aggregate (lb/yd^3)	Water (gallons)	*Fill Flow (lb)	W/C
100	Class C	No. 4 (100% Passing)	348	2700	39	4 + 0.6**	0.726

*Added to the truck before discharging.

**An additional 0.6 lb of Fill Flow was added to the mix to help the grout flow through in the flow cone test.

Table H.2: Mix Proportions for 1 yd^3 of CLSM Mix A5 Grout in Phase 2

Cement Type I (lb/yd^3)	Fly Ash	Fly Ash (lb/yd^3)	Fine Aggregate Type	Fine Aggregate (lb/yd^3)	Water (gallon)	*Fill Flow (lb)	*Air Entraining Agent Admixture (oz)	W/C
103	Class F	370	No. 4 (100% Passing)	2733	36	4	2.6	0.628

* Added to the truck at the site, not at the batching plant.

Table H.3: Mix Proportions for 1 yd^3 of CLSM Mix A5 Grout in Phase 3

Cement Type I (lb/yd^3)	Class F Fly Ash (lb/yd^3)	Fine Aggregate Type	Fine Aggregate (lb/yd^3)	Water (gallon)	*Fill Flow (lb)	*Air Entraining Agent Admixture (oz)	W/C
130	350	100% Passing No. 4 (100% Passing)	2743	38	4	2.6	0.661

* Added to the truck at the site, not at the batching plant.

After preparing three large batches of grouts with different quantities (*e.g., 3 yd^3 for Phase 1, 3 yd^3 for Phase 2, and 6 yd^3 for Phase 3*), the mix proportions given in Table H.4 are proposed for the revised CLSM Mix specification.

Table H.4: Grout Mix Proportions Proposed for 1 yd^3 of CLSM

Materials	**Amount**
Cement Type I (lb/yd^3)	100–130
Fly Ash, Class C (preferred) or Class F (lb/yd^3)	350–370
Fine Aggregate (lb/yd^3)	2700–2750
Water (gallon)	35–40
W/C	0.6–0.7
*Volume-expanding admixture (lb/yd^3)	4 to 5
**Air Entraining Agent Admixture (oz)	As needed
Target Density (lb/ft^3)	93 ± 4

** Minimum 30% volume expansion is needed; add admixture at the site, not at the batching plant.*

*** Can be added to the mix to meet the target density after adding the required amount of admixture.*

Table H.5 shows the results of the tests conducted in all phases, including descriptions of the fresh and hardened properties of the CLSM Mix A5 grout. In addition, the tests that are being suggested for future specifications are shown in Table H.6.

Table H.5: CLSM Mix A5 Test Results from Pumping Tests

Phases	1	2			3	
Locations	Out of Truck	Before Pumping	Middle Length	After Discharge	Before Pumping	After Discharge
Fresh Properties Tests						
Fresh Density (lb/ft^3)	97 (93 ± 3)	93.3	91.8	90.8	96.5	95.1
Temperature (^{o}F)	100 (68 to 72)	70	70	70	80.4	82.8
Spread Test (in)	8 (11.5)	11	14	12	9.0	12
Flow Cone Test (sec)	No (37)	77	49	46	No	No
Air Content (%)	30 (30)	26	28	28	30	30
Stability/Bleeding Test (%)	No (No)	0	0	0	0	0
Hardened Property Tests						
Compressive Strength (psi)	220 (278)	214	219	205	244	226
Split Tensile Strength (psi)	--	29	--	33	39	35
Oven-Dry Density (lb/ft^3)	--	88.6	92	95	93	89
Water Absorption (%)	--	15	14.4	13.8	18.6	16

( ) = Lab test results;   -- = Not considered in this Phase.

Table H.6: Proposed Test Requirements for CLSM Mixes

Test	ASTM Reference	Limits
Fresh Grout Properties to be Met Before Pumping is Allowed at Site		
Fresh Density	ASTM C138	Before Pumping: 93 ± 4 (lb/ft^3)
Flowability/Spread	ASTM D6103	Minimum 9 in.
Air Content	ASTM C138 /C231	30% ± 3%
Temperature	ASTM C1064	60 – 70 (^oF)
Hardened Grout Properties		
Bleeding Test	ASTM C940	No Bleeding (0 ml)
Compressive Strength	ASTM D4832	Minimum 200 psi
Split Tensile Strength	ASTM C496	Minimum 25 psi
Water Absorption	ASTM C796	Maximum 25% by Volume
Oven Dry Density	ASTM C495	90 ± 4 (lb/ft^3)

H.2.2 Cellular Grout Mix C40

The mix proportions for Cellular Grout C40 for the three phases of field testing are presented in Tables H.7 to H.9.

Table H.7: Mix Proportions for 1 yd^3 of Cellular Grout in Phase 1

Cement Type I (lb/yd^3)	Water (Gallon)	*Foaming Agent (yd^3)	W/C
701.6	42.3	0.6	0.503

** Added to the concrete truck at the site, not at the batching plant.*

Table H.8: Mix Proportions for 1 yd^3 of Cellular Grout in Phase 2

Cement Type I (lb/yd^3)	Water (Gallon)	*Foaming Agent (yd^3)	W/C
693.3	39	0.6	0.469

** Added to the concrete truck at the site, not at the batching plant.*

Table H.9: Mix Proportions for 1 yd^3 of Cellular Grout in Phase 3

Cement type I (lb/yd^3)	Water (Gallon)	*Foaming Agent (yd^3)	W/C
698	41.2	0.6	0.492

** Added to the concrete truck at the site, not at the batching plant.*

After preparing three batches of grouts (3 yd^3 for Phase 1, 3 yd^3 for Phase 2, and 3.5 yd^3 for Phase 3), the proposed mix proportions for Cellular Grout C40 shown in Table H.10 are suitable for inclusion in a revised specification.

Table H.10: Mix Proportions Proposed for 1 yd^3 of Cellular Grout C40

Materials	Amount
Cement Type I (lb/yd^3)	Minimum 700
Water (gallons)	39 – 42
W/C	0.46 – 0.50
*Foaming Agent (lb/yd^3)	0.6
Target Density (lb/ft^3)	40 ± 3

** Added at the site, not at the batching plant.*

The test results for the fresh and hardened properties of Cellular Grout C40 in the three phases of field tests are presented in Table H.11. The list of tests presented in Table H.12 are recommended to be specified as the required tests for C40 cellular grouts.

Table H.11: Cellular Grout C40 Test Results from Pumping Tests

Phase	**1**	**2**			**3**	
Locations	Out of Truck	Before Pumping	Mid Length	After Dischaging	Before Pumping	After Discharging
Fresh Properties Tests						
Fresh Density (lb/ft^3)	44 (40±3)	38	36.0	36.2	45	46
Temperature (^{o}F)	100 (68 to 72)	65	65	65	74.3	78
Spread Test (in)	12 (10.5)	19.5	16.25	11.5	12.25	12.5
Flow Cone Test (sec)	75 (62)	24	19	34	46.0	14.5
Air Content (%)	70 (70)	60	50	60	70	65
Stability (%)	1.25 (No)	0	0	0	0	0
Hardened Properties Tests						
Compressive Strength (psi)	312 (264)	373	373	368	*481*	376
Split Tensile Strength (psi)	--	61.0 (25)	--	62.17	*84*	38
Oven-Dry Density (lb/ft^3)	--	29.4	29.4	28.2	*32*	28
Water Absorption (%)	--	23	23	23.3	*24*	22

( ) = Lab test results;   -- = Not considered in this Phase.

Table H.12: Proposed Required Tests for Cellular Grout C40

Test	ASTM Reference	Limits
Fresh Grout Properties to be Met Before Pumping is Allowed at Site		
Fresh Density	ASTM C138	Before Pumping: 40 ± 3 (lb/ft^3)
Fluidity	ASTM C939	Can vary between 35 and 60 seconds
Flowability/Spread	ASTM D6103	Minimum 10 in.
Air Content	ASTM C138 /C231	50% to 70 %
Temperature	ASTM C1064	50 to 75 ^{o}F
Stability Test	ASTM C940	No Collapse (0 in. height change)
Hardened Grout Properties		
Compressive Strength	ASTM D4832	Minimum 200 psi
Split Tensile Strength	ASTM C496	Minimum 25 psi
Water Absorption	ASTM C796	Maximum 25% by Volume
Oven Dry Density	ASTM C495	30 ± 3 (lb/ft^3)

H.3 Annulus Void Inspections

It is recommended that inspections of the annulus of sliplined culverts be performed during and after installation.

A. During grouting

During grouting, conduct a hammer sounding test (or "sounding test"), in which the inspector taps the interior wall of the liner with a hammer and listens to the sound that is produced when the wall responds. During a sounding test, the response of a culvert with voids behind the pipe wall will have a different sound than that for a culvert where the materials behind the pipe are solid (i.e., without voids). This test is useful for evaluating the condition of the cementitious grout in the annular space behind the liner pipe wall of a sliplined culvert. Furthermore, to accomplish compliance of full or mostly full filling of the annulus void, the inspector may drill a ½-inch hole in the liner pipe (if it is possible, depending on the liner pipe material) and insert an endoscope probe into the hole to inspect the physical condition behind the liner pipe wall by viewing and recording images received from the camera attached to the end of the probe. For the best gathering of information, these holes may be drilled between the 9 o'clock to 3 o'clock positions (through the crown) at approximate distances of ¼, ½, and ¾ of the length of the culvert from one end of the culvert. These holes can be plugged once the grout comes out of these holes. Holes must be plugged adequately to prevent any leakage of grout after the inspection is complete. For large culverts, it is recommended to fill the annulus with grout in lifts.

Install at least three (3) vent pipes on each of the bulkheads at both ends of the culvert: one at the 9 o'clock position, one at 12 o'clock, and one at 3 o'clock. The pipes must be at least 2 inches in diameter and straight, except at the 12 o'clock position, where the vent pipes must be 90-degree elbows to accommodate the difference in elevation at the ends. Close the ends of the vent pipes with caps once the grout comes out from the pipes. Continue grouting until the grout comes out both bulkheads through the elbows of the vent pipes at the 12 o'clock position.

Install wireless cameras on the bulkheads to remotely monitor the filling of grout on the inside of the annulus void.

Install temperature sensors at specific locations of interest along the culvert where it might be critical for the annulus to be filled (e.g., the 12 o'clock position) to verify that grout has filled the annulus at those particular locations. The response of sensors would demonstrate that the grout has reached the locations where the sensors are picking up temperature signals and are transmitting signals from those locations.

In addition, vents of a suitable diameter may be installed from the 9 o'clock position to the 3 o'clock position through the crown throughout the entire length of the culvert. The purpose of these vents is to monitor the grout levels. After the grout comes out of these vent pipes, they should be plugged. Vent tubes may also be provided on the bulkheads at 12 o'clock with a 90-degree elbow.

B. After grouting

The simplest method to inspect the annulus after the grout has hardened is to conduct a sounding test of the liner using a hammer. Hammer tests must be performed as described in Section H.3.A. Hammer tests will provide a reasonably good indication of the extent of annulus void filling of the grout even though sometimes the resulting sound can be misleading to an inexperienced inspector particularly when cellular grout is used as the filler or non-metallic liners are used. The field inspections (as described in Appendix C) demonstrated that there would be a clear difference in the sound produced by hammer tap between a solid annulus and an empty one. Also, if it is possible to drill a hole with a diameter of less than ½ inch along the length of the culvert, the inspector can visually inspect the grout using an endoscope camera. These holes may be drilled in the liner pipe at positions from 9 o'clock to 3 o'clock (through the crown) at a distance of ¼, ½, and ¾ of the length of the culvert or at other locations where it is suspected that the annulus is not completely full. After hardening, the bulkhead can be removed (if possible) to physically observe the grout fill levels.

The actual volume of the grout pumped and the theoretical grout volume from calculations based on the cross-sectional area and culvert length must be compared at the site to detect any discrepancies and any possibility of excessive voids or escape paths behind the host pipes.

H.4 Recommended Specifications

The culvert inspections in this project indicated that many inspected culverts had several segments with empty or partially empty annulus voids (see Appendix C). Common grouting practices and the grout materials included in ODOT SS 837 were used to fill the annular spaces of these sliplined culverts. The annulus of the sliplined culverts were grouted using low strength mortar (LSM) backfill (Item 613), mortar (Item 602), or cellular grout as specified in ASTM C869 and Item 499. However, the laboratory tests performed in this project (Appendix F) showed that the grouts made with the recommended mix proportions of Item 613 or Item 602 did not show good spread of the grout or good flowability. The lack of flowability makes it difficult to pump the grout into the annular space of the sliplined lined culvert. Contractors will generally add water to these grouts at the site when they are not pumpable, despite the fact that adding water to the grouts will cause a severe bleeding problem and complete loss of strength.

The mix proportions in Item 613 were modified by introducing volume expansion admixtures to the mix, which improved the flowability of the grout and made it easily pumpable, as demonstrated at a large scale during the pumping tests. The mix proportions of CLSM Mix A5 that are presented in Table H.4 are a good alternative to the currently specified Item 613 if the test requirements given in Table H.6 are satisfied. The mortar described in Item 602 is not suitable for annulus void filling of sliplined culverts, and it may not be intended for use as an annulus void grout. It is recommended that Item 602 not be included as an acceptable mortar for sliplined culverts. A new CLSM item as described in this appendix may be introduced exclusively for the filling of annulus voids of sliplined culverts.

Per SS 837, the use of cellular grout is also allowed for filling annular spaces in sliplined culverts. However, detailed specifications for the use of cellular grouts are not included in SS 837; the supplier is merely directed to ASTM C869. In this study, many grades of cellular grouts with unit weights ranging from 10 to 75 lb/ft^3 were evaluated. The results of the laboratory tests and the pumping tests indicated that a grade of cellular grout with a unit weight of 40 lb/ft^3 as currently recommended by ODOT is suitable for use in sliplined culverts. This grade of cellular grout performed very well in the laboratory and in pumping tests.

In contrast, it was discovered that cellular grout is unstable at high temperatures (about 100 °F). Therefore, when grouting sliplined culverts, it is important to take into consideration the cellular grout mix proportion that is described in Table H.10 in addition to keeping a control on the temperature of the fresh mix. The fresh and hardened properties of the cellular grouts used for annulus void filling must satisfy the requirements presented in Table H.12.

H.5 Summary

In summary, grouts and mortars made using Items 613 and 602 are not suitable for sliplined culverts and may be removed from SS 837. Recommendations for a new CLSM grout specification have been presented in this appendix. Specific requirements in addition to those given in ASTM C869 for cellular grouts were also recommended.