UNIVERSITY OF TEXAS ARLINGTON

TxDOT Report 5-7008-01-1

Implementation of Electrical Resistivity Imaging Manual

Mohsen Shahandashti, Ph.D., P.E.
Sahadat Hossain, Ph.D., P.E.
Mina Zamanian, Ph.D.

Report Publication Date:	Submitted: August 2023 Published: November 2023
Project:	5-7008-01
Project Title:	Implementation of Electrical Resistivity Imaging Manual

Technical Report Documentation Page

1. Report No. FHWA/TX-24/5-7008-01-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Implementation of Electrical Resistivity Imaging Manual		5. Report Date August 2023
		6. Performing Organization Code
7. Author(s) Mohsen Shahandashti, Sahadat Hossain, Mina Zamanian		8. Performing Organization Report No. 5-7008-01-1
9. Performing Organization Name and Address The University of Texas at Arlington Department of Civil Engineering P.O. Box 19308 Arlington, TX 76019		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 5-7008-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Division P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report September 2021–August 2023
		14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract
Texas Department of Transportation (TxDOT) annually encounters a substantial number of claims and change orders that have a detrimental effect on project costs and schedules. State Departments of Transportation (DOTs) spend approximately $10 million annually on geotechnical-related change orders, accounting for about 7% of the total expenditures associated with claims, change orders, and cost overruns in highway and bridge projects. Insufficient subsurface information and soil mischaracterization significantly contribute to such cost overruns and delays in up to 50% of all infrastructure projects. Inadequate and inaccurate subsurface information results from inherent limitations of conventional geotechnical site investigation methods, as they are unable to provide a continuous assessment of subsurface conditions. Despite the advantages of advanced geophysical methods, such as Electrical Resistivity Imaging (ERI), in enhancing geotechnical analysis, these technologies are underutilized by state DOTs because of a lack of proven implementation details for different applications, geotechnical conditions, and operational environments.
This project aims to enhance TxDOT's existing subsurface investigations by highlighting the potential applications of the ERI technology and offering best practices for a successful implementation of the ERI by (1) implementing the ERI manual developed in TxDOT Project 0-7008 on 10-15 projects in Fort Worth and Dallas districts to improve geotechnical analysis, (2) refining the ERI manual to present lessons learned from the implementation of the ERI on real projects, (3) developing five case studies to illustrate the successful implementation of ERI for various project types and distributing them to all 25 TxDOT districts, (4) conducting cost analysis for implementing the ERI manual for all districts, and (5) conducting outreach activities to present the ERI manual and implementation results to potential TxDOT districts to facilitate the adoption of the manual.

17. Key Words	18. Distribution Statement
Electrical resistivity imaging, Continuous subsurface information, ERI applications, Implementation challenges, Case studies,	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	TBD	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

IMPLEMENTATION OF ELECTRICAL RESISTIVITY IMAGING MANUAL

by:

Mohsen Shahandashti, Ph.D., P.E.

Sahadat Hossain, Ph.D., P.E.

Mina Zamanian, Ph.D.

The University of Texas at Arlington

Report 5-7008-01-1

Project 5-7008-01

Project Title: Implementation of Electrical Resistivity Imaging Manual

Performed in cooperation with

Texas Department of Transportation and Federal Highway Administration

August 2023

UNIVERSITY OF TEXAS ARLINGTON | Department of Civil Engineering

425 Nedderman Dr., 416 Yates St.

Box 19308, Arlington, TX 76019

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGEMENT

This project was conducted in cooperation with TxDOT. The authors are grateful for the support and guidance provided by Ms. Jade Adediwura, Project Manager of Research and Technology Implementation (RTI). The authors are thankful for the technical guidance provided by the TxDOT staff, Natnael Asfaw, Prakash Chavda, Michael Dawidczik, Ryan Eves, Richard Izzo, Peyman Barghabany, Clover Clamons, Hugo Hernandez, Ben Mebarkia, Noel Paramanantham, Glenn Allbritton. The authors are also thankful for the technical support provided by the TxDOT Fort Worth and Dallas district offices. Their prompt assistance and collaboration have been central to the successful implementation of this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Texas Department of Transportation (TxDOT) annually encounters a substantial number of claims and change orders that have a detrimental effect on project costs and schedules. State Departments of Transportation (DOTs) spend approximately $10 million annually on geotechnical-related change orders, accounting for about 7% of the total expenditures associated with claims, change orders, and cost overruns in highway and bridge projects. Insufficient subsurface information and soil mischaracterization significantly contribute to such cost overruns and delays in up to 50% of all infrastructure projects. Inadequate and inaccurate subsurface information results from inherent limitations of conventional geotechnical site investigation methods, as they are unable to provide a continuous assessment of subsurface conditions. Despite the advantages of advanced geophysical methods, such as Electrical Resistivity Imaging (ERI), in enhancing geotechnical analysis, these technologies are underutilized by state DOTs because of a lack of proven implementation details for different applications, geotechnical conditions, and operational environments. This project aims to enhance TxDOT's existing subsurface investigations by highlighting the potential applications of the ERI technology and offering best practices for a successful implementation of the ERI by (1) implementing the ERI manual developed in TxDOT Project 0-7008 on 10-15 projects in Fort Worth and Dallas districts to improve geotechnical analysis, (2) refining the ERI manual to present lessons learned from the implementation of the ERI on real projects, (3) developing five case studies to illustrate the successful implementation of ERI for various project types and distributing them to all 25 TxDOT districts, (4) conducting cost analysis for implementing the ERI manual for all districts, and (5) conducting outreach activities to present the ERI manual and implementation results to potential TxDOT districts to facilitate the adoption of the manual.

The research team, in collaboration with the TxDOT Fort Worth and Dallas districts, selected 13 locations across these districts to examine the applicability of the ERI technology for various project types and capture implementation challenges and best practices in different geotechnical conditions and operational environments. A total of 60 ERI surveys were designed and implemented in the selected locations. Multiple soil samples were also collected as needed to validate the ERI results. Based on these implementations, the research team carefully documented the ERI implementation details, lessons learned, and recommendations for improving future

implementation of the ERI manual. The research team developed five case studies among 13 projects to illustrate the successful implementation of the ERI manual for various project types and distributed them among potential TxDOT districts. The research team also documented successful project planning and management practices for implementing the ERI manual derived from the gained experience and lessons learned by this project. Besides, an approach to estimate the detailed costs for implementing the ERI manual in the TxDOT districts was developed which can be used to establish the annual budget required for manual implementation in each district.

Moreover, following the district contacts' recommendations, the research team proposed an approach toward integrating electrical resistivity imaging and a machine learning classifier to estimate sulfate concentration levels in clayey soils. They established an experimental design and developed a random forest classifier to categorize the sulfate concentration levels into three levels low (below 3,000 ppm), moderate (between 3,000 and 8,000 ppm), and high (above 8,000 ppm) based on soil electrical resistivity and water content.

The research team organized and conducted statewide outreach activities in about one-third of the TxDOT districts including the maintenance division and different teams in Abilene, Dallas, El Paso, Fort Worth, Houston, and Paris districts to present the ERI manual and disseminate the implementation results to potential teams to facilitate the manual adoption. The project's findings can enhance TxDOT's existing subsurface investigations by highlighting the potential applications of the ERI technology and offering best practices for a successful implementation of the ERI in different geotechnical conditions and operational environments. The ERI technology offers an opportunity to help obtain a continuous assessment of subsurface conditions, locate problematic zones that require more consideration, and identify areas where traditional methods of site investigation, which are costly and time-consuming, may be unnecessary. Well-informed decisions can prolong transportation assets' service life and lower maintenance/rehabilitation costs.

CHAPTER 1 INTRODUCTION

Sufficient and accurate subsurface information is critical for designing transportation infrastructure systems and assessing the stability of operational assets, especially in locations with extreme wetting-drying cycles such as North Texas (Zamanian et al. 2023b; Shahandashti et al. 2022a). Texas Department of Transportation (TxDOT) annually encounters a considerable and yet increasing number of claims and change orders that has a detrimental effect on project costs and schedules (Shahandashti et al. 2021). State Departments of Transportation (DOTs) spend approximately $10 million annually on geotechnical-related change orders (Boeckmann and Loehr 2016). This amount accounts for approximately 7% of the total costs associated with claims, change orders, and cost overruns in highway and bridge projects. Insufficient subsurface information and soil mischaracterization significantly contribute to such cost overruns and delays in up to 50% of all infrastructure projects (Shrestha and Neupane 2020; Prezzi et al. 2011; Baynes 2010). Inadequate subsurface information may also lead to infrastructure failures caused by unforeseen circumstances (Zamanian et al. 2024; Shahandashti et al. 2019), leading to road maintenance expenses that significantly impact the state transportation budgets (Darghiasi et al. 2023b; Shahandashti et al. 2022b). Inadequate and inaccurate subsurface information results from inherent limitations of conventional geotechnical site investigation methods, as they are unable to provide a continuous assessment of subsurface conditions (Zamanian and Shahandashti 2022). Despite the advantages of advanced geophysical methods, such as Electrical Resistivity Imaging (ERI), in enhancing geotechnical analysis, these technologies are underutilized by state DOTs because of a lack of proven implementation details for different applications, geotechnical conditions, and operational environments (Rosenblad and Boeckmann 2020).

The ERI technology offers an opportunity to help obtain a continuous assessment of subsurface conditions, locate problematic zones that require more consideration, and identify areas where traditional methods of site investigation, which are costly and time-consuming, may be unnecessary. This project intends to assess the benefits, capture the implementation challenges, and provide the best practices for the successful implementation of the ERI technology. By having a comprehensive record of the benefits and limitations of this technology, TxDOT can effectively implement this technology on upcoming projects to reduce geotechnical-related cost overruns and delays due to inadequate subsurface information. This technical report is organized into 9 chapters and 5 appendices as follows:

Chapter 1 describes an overview of the issues that have prompted the necessity of this research and outlines the organization of the technical report.

Chapter 2 presents the implementation details of the ERI manual on 10-15 projects in the Fort Worth and Dallas districts.

Chapter 3 summarizes the lessons learned and future recommendations for ERI implementation improvement.

Chapter 4 provides five case studies to illustrate the successful implementation of the ERI manual on real projects for various project types.

Chapter 5 elaborates on the successful project and management practices for deploying the ERI technology in operational environments to facilitate the adoption of the ERI technology by the TxDOT districts.

Chapter 6 offers a cost analysis approach to determine detailed costs for implementing the ERI manual in the TxDOT districts.

Chapter 7 delivers a summary of the outreach activities conducted to present the ERI manual and disseminate the implementation results to potential TxDOT districts.

Chapter 8 evaluates the value of research by determining the qualitative and economic benefits of ERI technology in enhancing geotechnical analysis.

Chapter 9 presents the takeaways and conclusion of this project.

Appendix A provides borehole logs where the soil samples were collected.

Appendix B provides additional documents that were for cross-validating the ERI findings.

Appendix C shows typical ranges of resistivity of earth materials.

Appendix D presents the developed case studies.

Appendix E presents the outreach summary.

CHAPTER 2 IMPLEMENTATION OF ELECTRICAL RESISTIVITY IMAGING MANUAL ON REAL PROJECTS

2.1 Introduction

This chapter documents the implementation detail of ERI manual for 10 to 15 projects in the Fort Worth and Dallas districts to help enhance geotechnical analysis. These projects cover various applications (e.g., pavement, bridge, maintenance, forensics), geotechnical conditions, and operational environments. Relevant district sections and areas include but are not limited to pavement and materials, bridge, construction, project development, and area offices.

Following the district contacts' recommendations, the research team also established an experimental design to investigate the effects of sulfate concentration levels on the soil electrical resistivity. This chapter also presents the laboratory testing methods and results from the data analysis.

2.2 Implementation of ERI in Fort Worth and Dallas Districts

In cooperation with the Fort Worth and Dallas district representatives and receiving agency's advisory committee, 13 projects were selected to implement the ERI manual. These projects cover a variety of applications, including determining the depth of bridge foundations, identifying critical sulfate concentration zones, mapping topography and bedrock depth, determining water table depth, locating underground water lines, and assessing slope stability. Table 2.1 lists the selected project's names and applications for which ERI is implemented.

Table 2.1. Selected projects for implementing the ERI manual

No.	Project's Location	District	No. of Surveys	Max. Penetration Depth (ft.)	Application
1	US 67	FW	12	62	Critical sulfate concentrations
2	IH 20 at Clear Fork Trinity River	FW	5	39	Water table depth
3	Cedar Hill State Park	Dal	11	19	Critical sulfate concentrations
4	SH 170 at Westport Pkwy	FW	3	55	Water table depth Bridge foundation depth
5	SH 170 at N Main St	FW	3	40	Critical sulfate concentrations
6	IH 30 at Mary's Creek	FW	3	26	Water table depth Bridge foundation depth
7	IH 30 at Chapel Creek Blvd	FW	2	39	Retaining wall drainage Slope stability
8	IH 30 at Walsh Ranch Pkwy	FW	5	20	Water line location
9	IH 20 at Farmer Rd	FW	5	20	Water line location
10	SH 352 at White Rock Creek	Dal	3	13	Bridge foundation depth
11	Ronald Reagan Memorial Hwy (IH 20) – Site 1	FW	3	20	Critical sulfate concentrations
12	Ronald Reagan Memorial Hwy (IH 20) – Site 2	FW	1	104	Water table depth
13	IH 35W at Railroad	FW	4	22	Retaining wall drainage

The research team conducted a preliminary analysis of each project and planned for ERI implementation. The data collection plans were presented to and approved by the districts' contacts before field implementation. The following subsections elaborate on the ERI implementation details for the projects listed in Table 2.1, along with discussions on the obtained results.

2.2.1 US 67

The study area is located along highway US 67 in Johnson County, Fort Worth, Texas. Figure 2.1 shows the location of the study area on the Fort Worth map.

Figure 2.1. Location of US 67 on the Fort Worth map

The study area is situated in a region mapped with Woodbine formation. Woodbine formation consists primarily of sandstone and shale with a thickness of about 320 feet. A geotechnical report for this project (documented in December 2020) shows that lean and fat clayey soils (CL and CH) are dominant in the study area. Liquid limits range from 30 to 92, and plasticity indices range from 14 to 67. Clayey sandy (SC) soil overlays CL and CH soils at some locations; the depth of the SC layer varies from one to 9 feet. In some areas, borings reached a dense layer (shale) at least 9 feet below the ground surface. A trace of water was observed at four soil borings (B-2, B-3, B-4, and B-5) at a minimum depth of 10 feet. High concentrations of sulfate (>16,000 ppm) were reported at boreholes B-5, B-6, B-7, and B-11. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.2 illustrates the ERI data collection plan and borehole locations for US 67. This implementation aimed to assess the sulfate concentration levels at the study area and identify the extent of critical zones prone to sulfate-induced heaving.

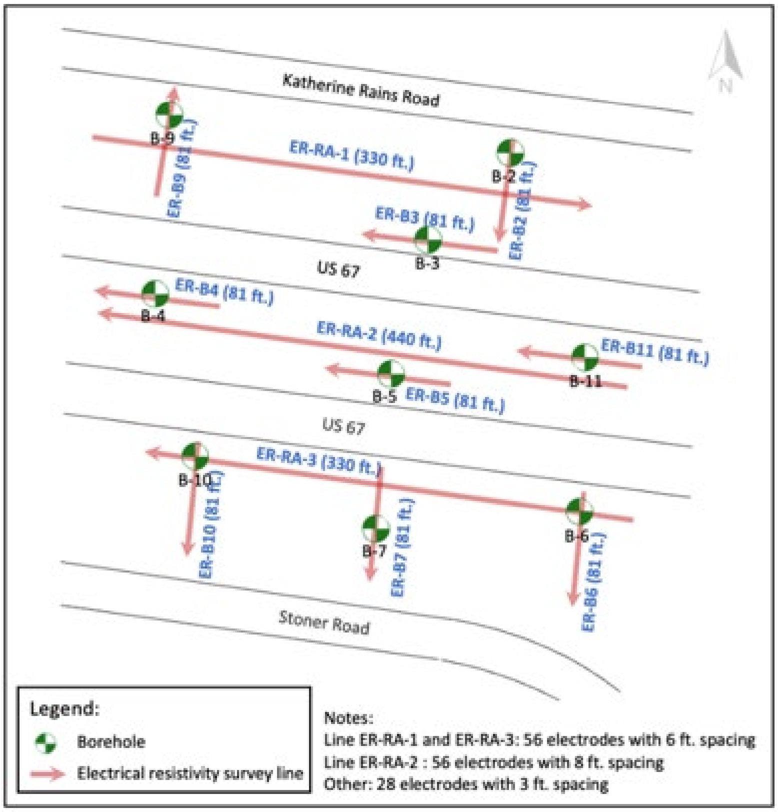


Figure 2.2. ERI data collection plan and borehole locations for US 67

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for US 67 project on December 2nd and 3rd, 2021. Twelve ERI surveys were conducted using 28 and 56 electrodes with 3-, 6-, and 8-feet spacings. In addition, six soil samples were collected from locations of high sulfate concentrations to be tested in the laboratory. Borings were advanced to a maximum depth of 2.5 feet using an electric hand auger. Figure 2.3 shows the implementation of ERI along highway US 67 and soil sample collection. Two days before conducting the ERI surveys, 0.33 inches of precipitation were recorded at the study area (Weather Underground 2022).

Figure 2.3. Implementation of ERI along highway US 67 and soil sample collection

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous subsurface resistivity images. Elevation data were also extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling. Based on the obtained subsurface resistivity images, the minimum and maximum depths of investigation are 20 feet with 3 feet electrode spacing (Line ER-B3) and 62 feet with 8 feet electrode spacing (Line ER-RA-2). The research team assessed the subsurface conditions and identified possible earth materials and anomalies (i.e., underground cavities) using the obtained subsurface resistivity images and borehole results. The research team also used the equations developed in the TxDOT Project 0-7008 along with the continuous resistivity images and borehole results in characterizing the subsurface conditions.

Figure 2.4 shows an overall view of the subsurface conditions along boreholes B-2, B-3, and B-9 obtained by 6 feet electrode spacings (inverted resistivity profile of Line ER-RA-1). The resistivity image shows heterogeneous conditions through the depth and length of the profile in Figure 2.4. The maximum electrical resistivity value is about 150 Ω.m, indicating the presence of dry stiff clayey soil at the shallow subsurface and sand or shale at the bottom of the profile. Intermittent zones of low electrical resistivity values (<5 Ω.m) are attributed to zones of high moisture content.

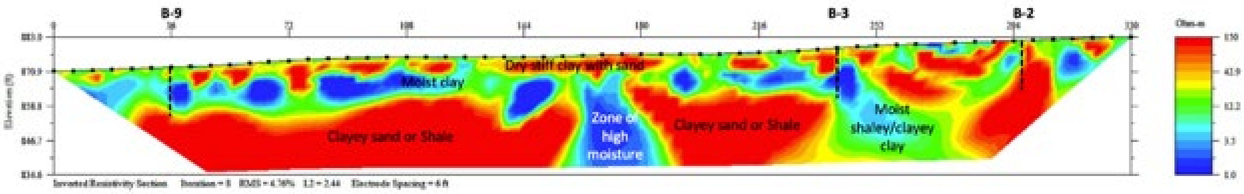


Figure 2.4. Subsurface resistivity image of Line ER-RA-1 (12 feet away from borehole B-2, 48 feet away from borehole B-3, 28.5 feet away from borehole B-9)

Figure 2.5 shows the inverted resistivity profiles of Lines ER-B2, ER-B3, and ER-B9 obtained by 3 feet electrode spacings to further investigate the subsurface conditions in this area. Borehole results are also shown in the approximate borehole locations on each resistivity image. Zones of high electrical resistivity values at the shallow subsurface of the profiles are attributed to dry stiff clayey, or sandy soil. Zones of high electrical resistivity values (between 50 to 150 Ω.m) at the bottom of the profiles represent shale or sand. Areas with electrical resistivity values below 5 Ω.m are associated with zones of high moisture (shown with dashed lines).

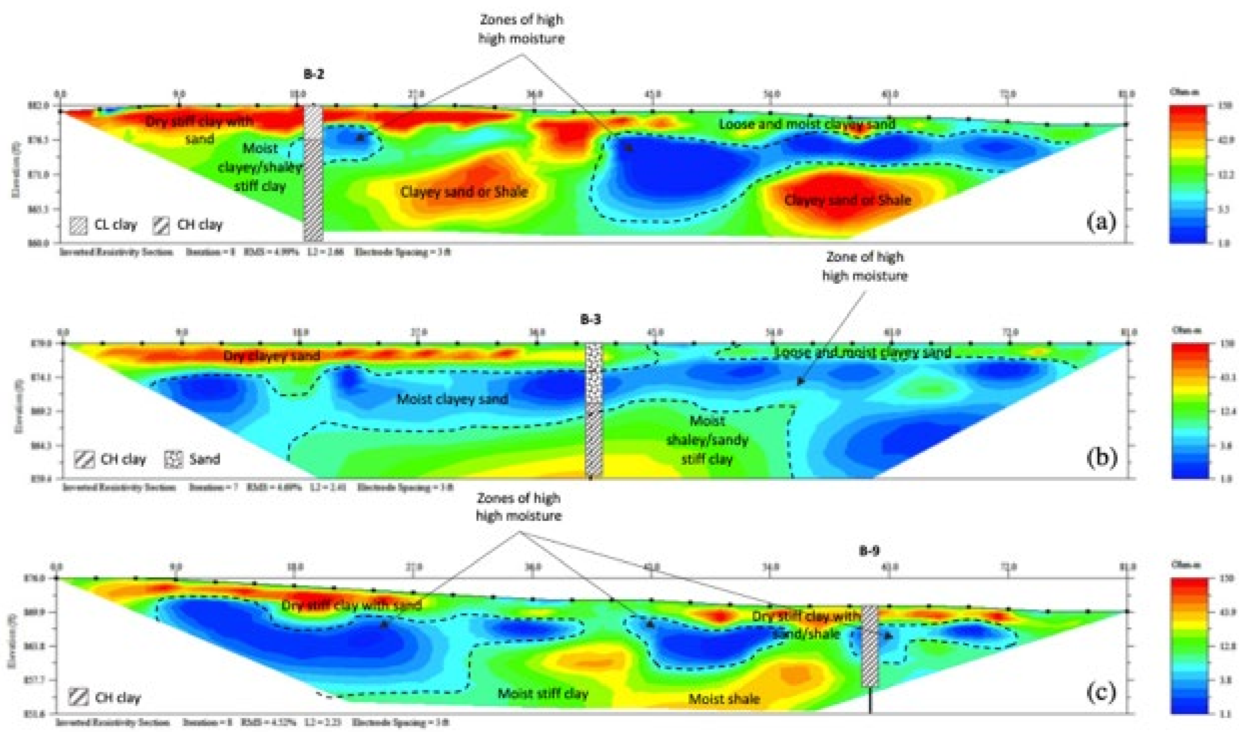


Figure 2.5. Subsurface resistivity image; (a) Line ER-B2, (b) Line ER-B3, and (c) Line ER-B9

Figure 2.6 shows an overall view of the subsurface conditions along boreholes B-4, B-5, and B-11 obtained by 8 feet electrode spacings (inverted resistivity profile of Line ER-RA-2). The resistivity image illustrates relatively consistent subsurface conditions through the depth and length of the profile with low electrical resistivity variations from 1 to 40 Ω.m. Low variations of electrical resistivity values imply the existence of similar earth materials with similar geotechnical properties. However, according to the borehole results, a variety of earth materials (e.g., sand, shale, and clay) can be found in this area up to 20 feet. It is worth noting that soluble sulfate in earth materials can significantly decrease their resistance to a flow of electric current. In other words, the electrical resistivity of earth materials decreases as the sulfate concentration increases. Thus, since the electrical resistivity values in Figure 6 are inconsistent with the typical ranges of electrical resistivity of different earth materials (refer to Appendix B) found by geotechnical analysis, more detailed ERI surveys with smaller electrode spacings were conducted to study the subsurface conditions in detail.

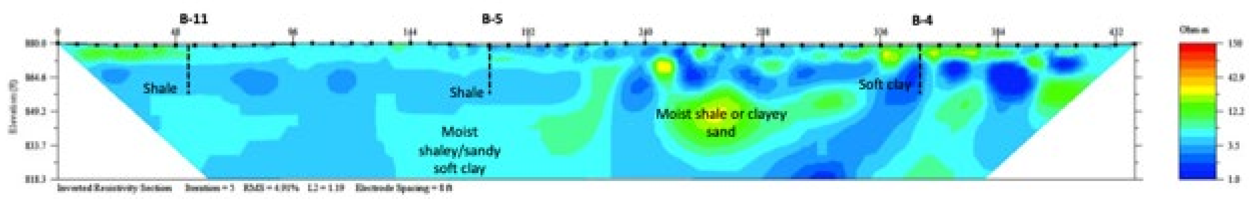


Figure 2.6. Subsurface resistivity image of Line ER-RA-2 (11 feet away from borehole B-4, 15 feet away from borehole B-5, 9 feet away from borehole B-11)

Figure 2.7 shows the inverted resistivity profiles of Lines ER-B4, ER-B5, and ER-B11 obtained by 3-feet electrode spacings. Borehole results are also shown in the approximate borehole locations on each resistivity image. Figure 2.7a shows relatively high variations from 1 up to 150 Ω.m, indicating that the soil type and moisture content vary through the depth of the profile. Areas with high electrical resistivity values at the shallow subsurface are attributed to dry stiff clayey, and sandy soils. On the other hand, Figures 2.7b and 2.7c show slight variations in the electrical resistivity values, ranging from 3 to 18 Ω.m, through the depth and length of the profiles. Compared to the borehole results, areas with electrical resistivity values below 10 Ω.m can be attributed to zones of high moisture and high sulfate concentrations (shown with dashed lines in Figures 2.7b and 2.7c). The large extent of low electrical resistivity zones indicates a considerable amount of sulfate minerals in this area. The borehole results also show high sulfate concentrations (above 20,000 ppm) at depths of 2 to 4 feet at boreholes B-5 and B-11.

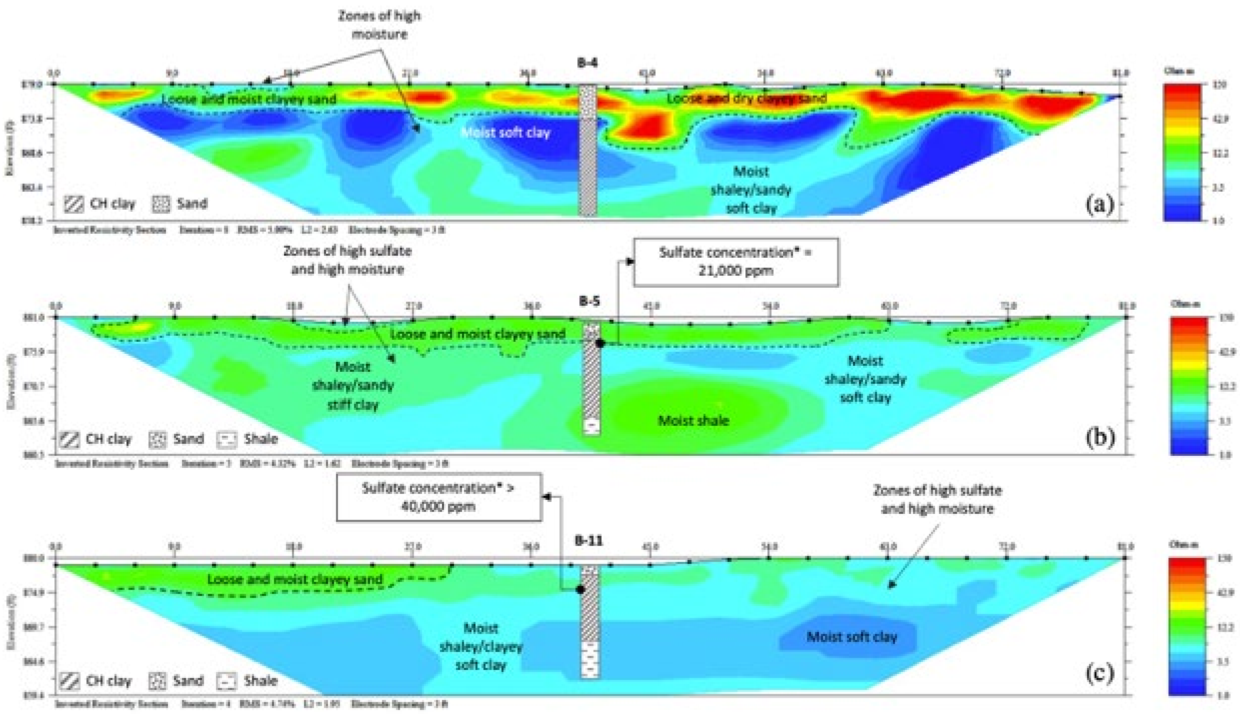


Figure 2.7. Subsurface resistivity image; (a) Line ER-B4, (b) Line ER-B5, and (c) Line ER-B11

Figure 2.8 shows an overall view of the subsurface conditions along boreholes B-6, B-7, and B-10 obtained by 6 feet electrode spacing (inverted resistivity profile of Line ER-RA-3). Although areas with high electrical resistivity values (up to 200 Ω.m) are observed in Figure 2.8, especially at the shallow subsurface, the resistivity image shows relatively consistent subsurface conditions through the depth and length of the profile with low variations in the electrical resistivity values. According to the borehole results, low variations in the electrical resistivity values (from 1 to 40 Ω.m) imply that the earth materials contain a high amount of moisture and sulfate.

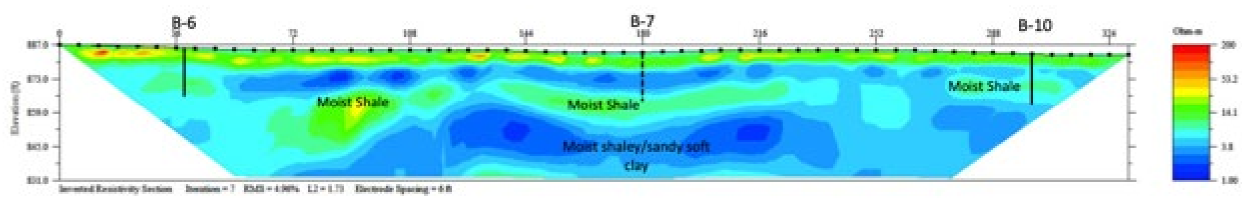


Figure 2.8. Subsurface resistivity image of Line ER-RA-3 (35 feet away from borehole B-7)

Figure 2.9 illustrates the inverted resistivity profiles of Lines ER-B6, ER-B7, and ER-B10 obtained by 3 feet electrode spacing to further investigate the subsurface conditions in this area. The borehole results are also shown in the approximate borehole locations on each resistivity image. Figures 2.9a, 2.9b, and 2.9c indicate a relatively similar pattern compared to one another. The electrical resistivity varies from 1 to 200 Ω.m, indicating that the soil type and moisture content vary significantly through the depth of the profile. The areas with high electrical resistivity values are attributed to dry clay and sand at the shallow subsurface and shale at the bottom of the profiles. Areas with electrical resistivity values below 10 Ω.m are associated with high moisture and sulfate concentration zones (shown by a dashed line in Figure 2.9). The borehole results also confirm high sulfate concentrations (above 17,000 ppm) at depths of 2 to 4 feet at boreholes B-6 and B-7.

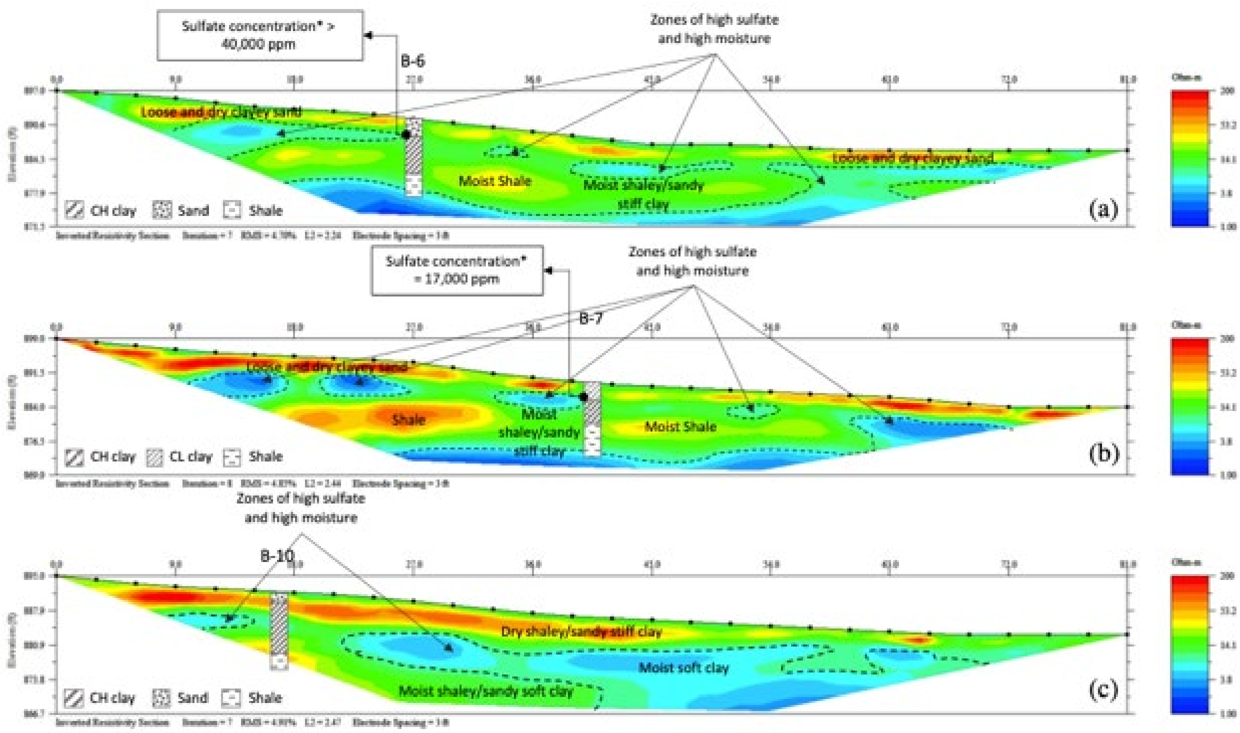


Figure 2.9. Subsurface resistivity image; (a) Line ER-B6, (b) Line ER-B7, and (c) Line ER-B10

Laboratory Tests on Collected Samples from US 67

Six soil samples were collected from US 67 to validate the ERI findings. Actual sulfate concentrations of the collected soil samples were determined using a colorimetric method based on TxDOT 145-E. Moisture contents of the soil samples were also determined according to ASTM

D2216-90. The actual sulfate concentrations and moisture contents are presented in Table 2.2. According to Table 2.2, the measured sulfate concentrations were lower than those reported in the geotechnical report for this project, possibly due to seasonal fluctuations in sulfate concentrations.

Table 2.2. Summary of the laboratory tests of the collected samples from the US 67 in the Fort Worth district

Borehole No.	Soil Type	Depth (feet)	Sulfate Concentration (ppm)	Actual Moisture Content (%)
B-5	Clay	1.0 - 1.5	550	28.3
B-5	Clay	1.5 - 2.5	1,250	30.1
B-6	Sand	1.0 - 1.5	5,900	28.1
B-7	Clay	1.0 - 1.5	250	9.1
B-11	Clay	1.0 - 1.5	3,800	25.9
B-11	Clay	1.5 - 2.5	17,000	29.7

In addition, the research team conducted 96 laboratory electrical resistivity tests on the collected samples from US 67 at different moisture contents with various compaction efforts. The research team followed a Wenner four-electrode method to conduct the laboratory electrical resistivity tests (ASTM G57 2020). The obtained data were used to validate the equations developed in the TxDOT Project 0-7008.

2.2.2 IH 20 at Clear Fort Trinity River

The study area is located along Interstate 820 Loop in Tarrant County, Fort Worth, Texas. Figure 2.10 shows the location of the study area on the Fort Worth map.

Figure 2.10. Location of the IH 20 at Clear Fort Trinity River on the Fort Worth map

The study area is situated on Alluvium deposits, including sand and clay with gravel and silts overlying the Fort Worth limestone, Kiamichi Formations, and Goodland limestone. A geotechnical report for this project (documented in July 2019) identifies that lean clay (CL with liquid limits in the range of 22 and 43 and plasticity indices in the range of 12 and 28), clayey sand (SC), and gravel consist subsurface materials up to a depth of maximum 24 feet. Borings reached limestone at a minimum of 11 feet below the ground surface. At the time of drilling, groundwater was observed at a depth of approximately 23 feet at boreholes B-3 and B-4.

Data Collection

Figure 2.11 illustrates the ERI data collection plan and borehole locations for IH 20 at Clear Fort Trinity River. This implementation aimed to determine the study area's water table depth and subsurface conditions.

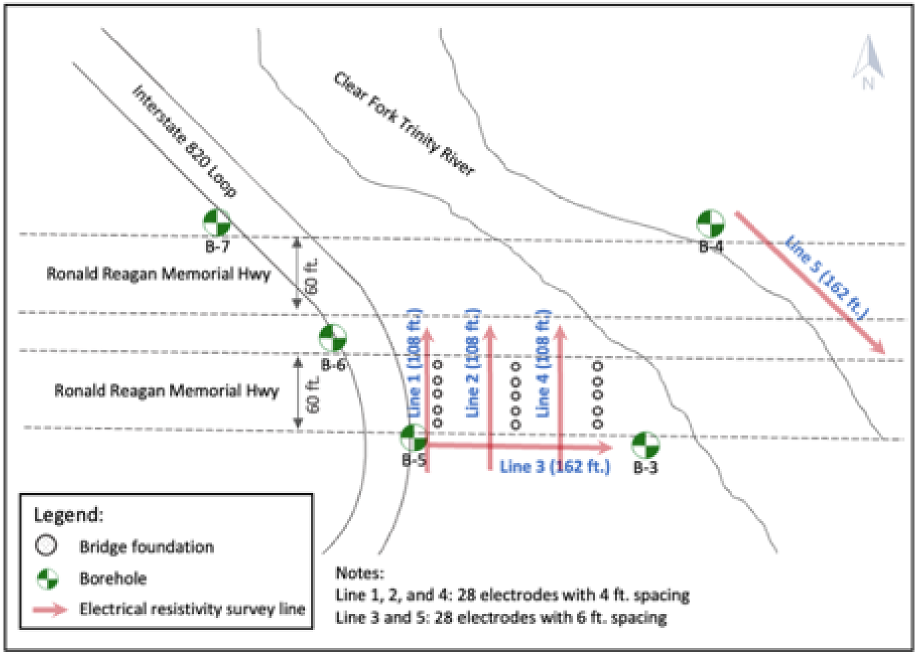


Figure 2.11. ERI data collection plan and borehole locations for IH 20 at Clear Fort Trinity River

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 20 project on January 20th, 2022. Five ERI surveys were conducted using 28 electrodes with 4- and 6-feet spacings. Figure 2.12 shows the implementation of ERI for the IH 20 at Clear Fort Trinity River along Interstate 820 Loop. During 15 days before implementing the ERI surveys, no precipitation was observed at the study area (Weather Underground 2022).

Figure 2.12. Implementation of ERI for IH 20 project; (a) on the crest of the slope at the river's West bank, (b) on the crest of the slope perpendicular to the river, (c) on the middle of the slope on the river's West bank, and (d) on the crest of the slope on the river's East bank.

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the minimum and maximum depths of investigation are 26 feet with 4 feet electrode spacing (Line 4) and 39 feet with 6 feet electrode spacing (Lines 3 and 5). The research team assessed the subsurface conditions and identified possible earth materials and anomalies (i.e., underground cavities) using the obtained subsurface resistivity images, borehole results, and developed equations for the TxDOT Project 0-7008.

Figure 2.13 shows the inverted resistivity profiles of Lines 1, 2, 3, and 4 obtained by 4- and 6-feet electrode spacings on the river's West bank. Figure 2.13a illustrates relatively consistent subsurface conditions through the length of the profile with a maximum electrical resistivity of 170 Ω.m, indicating hard earth materials with low moisture content. According to the borehole results, the zones of high electrical resistivity values are attributed to stiff clay and sand at the shallow subsurface and limestone at the bottom of the resistivity image.

Figure 2.13b illustrates heterogeneous conditions through the depth and length of the profile with relatively significant variations in the electrical resistivity values from 1 to 250 Ω.m. Areas with electrical resistivity values between 50 to 250 Ω.m at the shallow subsurface indicate dry stiff clay with sand or dry sand. Areas with electrical resistivity values below 5 Ω.m are attributed to zones of high moisture content (shown by a dashed line in Figure 2.13b). A zone of high electrical resistivity is also observed in the middle of the profile and continues to the right side, indicating limestone or gravel.

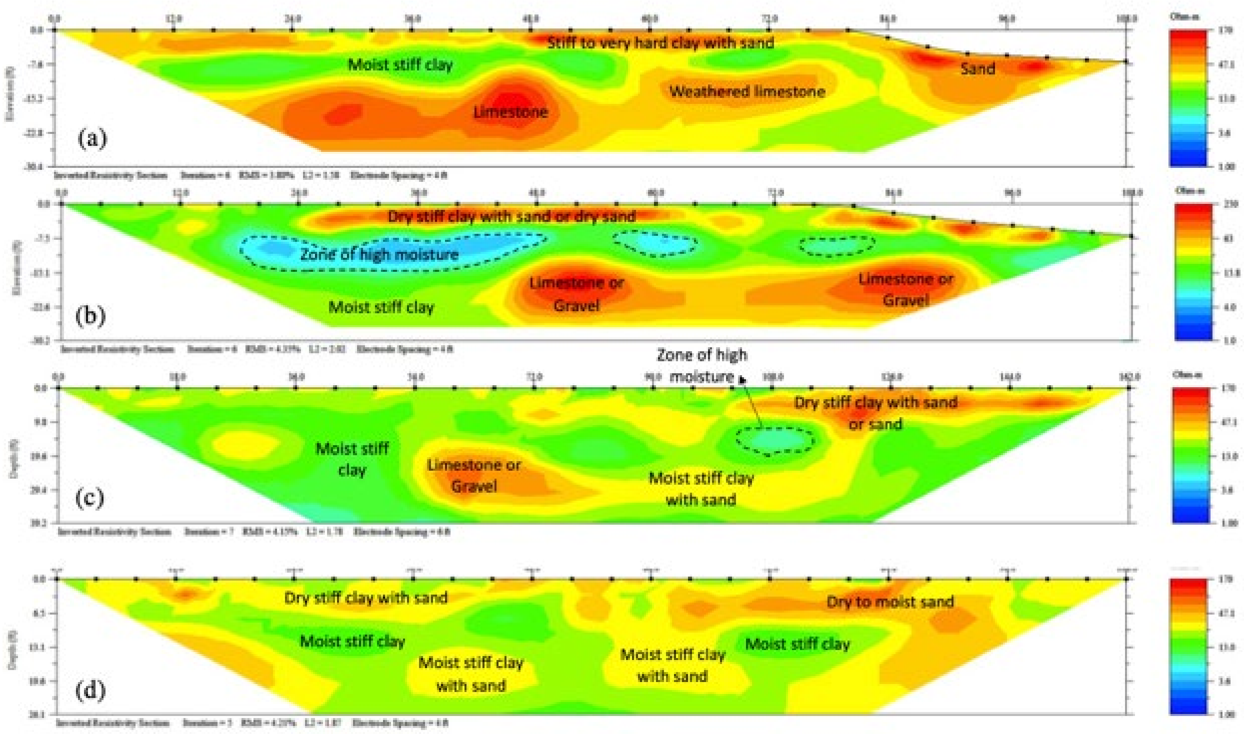


Figure 2.13. Subsurface resistivity image on the West bank of the river; (a) Line 1 on the crest of the slope, (b) Line 2 on the crest of the slope, (c) Line 3 on the crest of the slope perpendicular to the river, and (d) on the middle of the slope.

Figures 2.14c and 2.14d show a similar pattern compared to one another. The electrical resistivity values range from 10 to 110 Ω.m through the depth of the profiles, indicating relatively hard earth materials with low moisture contents. The areas with electrical resistivity in the range of 40 to 110

Ω.m at the shallow subsurface are associated with dry stiff clay with sand or sand. Zones with low electrical resistivity values (< 40 Ω.m) can also be attributed to moist, soft to stiff clayey soil.

Figure 2.14 shows the inverted resistivity profile of Line 5 obtained by 6 feet electrode spacing on the river's East bank. The electrical resistivity values vary significantly from 10 to 1000 Ω.m through the depth of the profile. Areas of high electrical resistivity values are attributed to unweathered limestone or loose gravel. A zone of low electrical resistivity values at the bottom of the resistivity image (shown by a dashed line in Figure 2.14) is attributed to subsurface groundwater at a depth of approximately 30 feet.

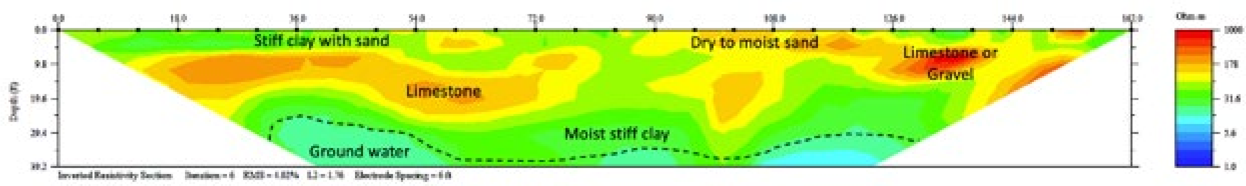


Figure 2.14. Subsurface resistivity image on the crest of the slope on the river's East bank.

2.2.3 Cedar Hill State Park

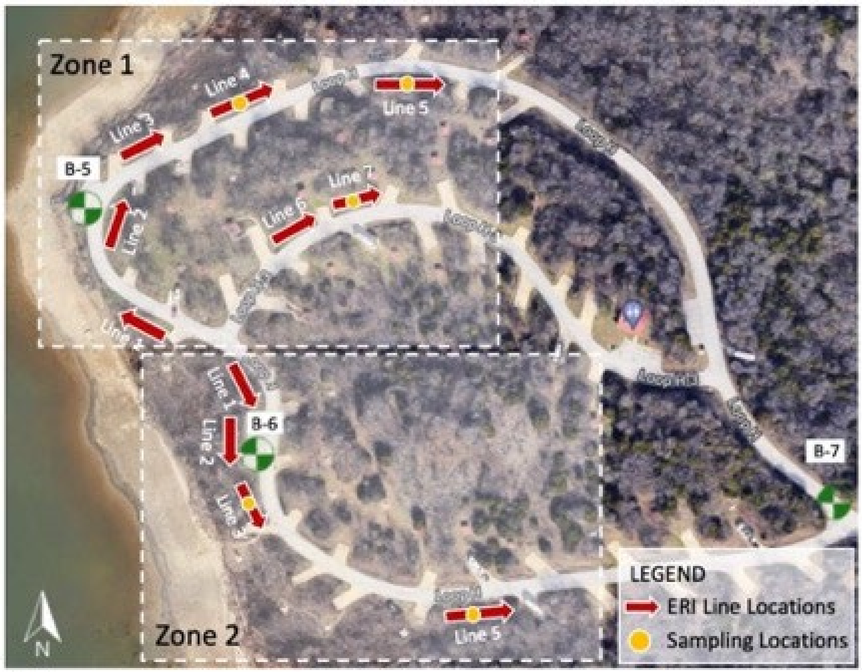
The study area is located along Eagle Ford and Shady Ridge loops in Dallas County, Dallas, Texas. Figure 2.15 shows the location of the study area on the Dallas map.

Figure 2.15. Location of Cedar Hill State Park on the Dallas map

The study area is situated in a region mapped with the Eagle Ford formation and is bound by a lake to the west. The Eagle Ford formation consists of shale, siltstone, and limestone and has an estimated thickness of 300 to 400 feet in north Texas. A geotechnical report for this project (documented in September 2021) shows that the existing asphalt pavements consist of a dense crushed limestone layer (<1.5 feet depth) at the surface. Directly beneath the crushed limestone, stiff to hard, fat (CH) and lean (CL) clays are extended to a depth of 20 feet. The plasticity indices were measured in the range of 14 to 45. No groundwater was encountered in any soil test borings at the site during drilling. High concentrations of sulfate (up to 22,080 ppm) were reported at boreholes B-5 and B-6. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.16 illustrates the ERI data collection plan and borehole locations for Cedar Hill State Park. This implementation aimed to assess the sulfate concentration levels at the study area and determine the critical zones prone to sulfate-induced heaving.



Notes:
Three ERI lines (Line Z1-L4, Z1-L5, and Z2-L5), using 28 electrode with 3-feet spacings (81 feet long) to a depth of 15 feet.
Other ERI lines, using 28 electrode with 2-feet spacings (54 feet long) to a depth of 10 feet.

Figure 2.16. ERI data collection plan and borehole locations for Cedar Hill State Park

In coordination with the Dallas district contacts, the research team implemented the ERI plan for Cedar Hill State Park on April 21st, 2022. Eleven ERI surveys were conducted using 28 electrodes with 2- and 3-feet spacings. In addition, six soil samples were collected from multiple locations, as shown in Figure 2.16, to be tested in the laboratory. Borings were advanced to a maximum depth of 2.5 feet using an electric hand auger. Section 2.3.3 describes laboratory electrical resistivity tests and presents sulfate testing results. Figure 2.17 shows the implementation of the ERI at Cedar Hill State Park and soil sample collection. During 15 days before implementing the ERI surveys, no precipitation was observed at the study area (Weather Underground 2022).

Figure 2.17. Implementation of ERI for Cedar Hill State Park; (a) Line 1 in Zone 1, (b) Line 2 in Zone 2, (c) Line 2 in Zone 2, and (d) soil sampling.

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Elevation data were also extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling. Based on the obtained resistivity images of the subsurface, the minimum and maximum depths of investigation are 13 feet with 2 feet electrode spacing and 19 feet with 3 feet electrode spacing. The research team assessed the subsurface conditions and identified possible earth materials and different sulfate concentration levels using the obtained subsurface resistivity images, borehole results, and developed equations for TxDOT Project 0-7008.

Figure 2.18 shows the inverted resistivity profiles of Lines 1 to 5 obtained by 2- and 3-feet electrode spacings along Loop H in Zone 1. Figure 2.18a shows a consistent profile throughout the length of the profile. A resistive layer at the shallow subsurface with electrical resistivities of

60 to 500 Ω.m is associated with the crushed limestone. There are significant changes in the electrical resistivity values through the depth of the profile. A conductive layer at the bottom of the profile identifies the saturated zone and water table depth at 5 feet. The electrical resistivities below 3 Ω.m are attributed to saline water (water with high soluble salts).

Figure 2.18b illustrates the inverted resistivity profile of Line 2. Borehole results are also shown in the approximate borehole locations on each resistivity image. Borehole BH-1 at a 14 feet distance shows a layer of limestone at the top, underlaid by stiff to very stiff clays up to a depth of 20 feet. On the other hand, the profile shows low variations in the electrical resistivity between 1 and 50 Ω.m through the length and depth of the profile, indicating the existence of similar earth materials. Inconsistencies between the observations imply that high moisture and sulfate concentration levels exist in the shallow subsurface; note that the typical ranges of electrical resistivity for limestone are larger than 50 Ω.m. It is worth mentioning that soluble sulfate in soils can significantly decrease the resistance of earth materials to a flow of electric currents. In other words, the electrical resistivity decreases as the soluble sulfate in the soil increases. The borehole result also shows a sulfate concentration of 22,080 ppm at a depth of 1.2 feet. A zone with relatively higher electrical resistivities (between 30 and 50 Ω.m) at the top left corner of the profile can be attributed to the soils with sulfate concentrations below 8000 ppm.

Based on the finding from previous profiles, different anomalies are identified in Figure 2.18c. Figure 2.18d shows a conductive area in the middle of the profile at the shallow subsurface, indicating a high sulfate concentration and moisture zone. Testing results show low sulfate concentrations (below 250 ppm) at the transition zone from low to high electrical resistivities at a 36 feet distance. The resistivity profile also shows a higher range of electrical resistivity between 30 and 50 Ω.m, which can be attributed to the zones of low to moderate sulfate concentrations.

Figure 2.18e shows the inverted resistivity profile of Line 5. Similarly, a resistive layer is expected at the top of the profile shown in Figure 2.18e, which should represent limestone. Laboratory test results indicate sulfate concentrations of 13,650 and 33,550 ppm at 1- and 2-feet depths, respectively. The electrical resistivities show higher variations through the profile depth at 6 to 21 feet distance, ranging from 83 to 8 Ω.m. A conductive layer is observed directly beneath the resistive layer, denoting accumulated sulfate concentrations.

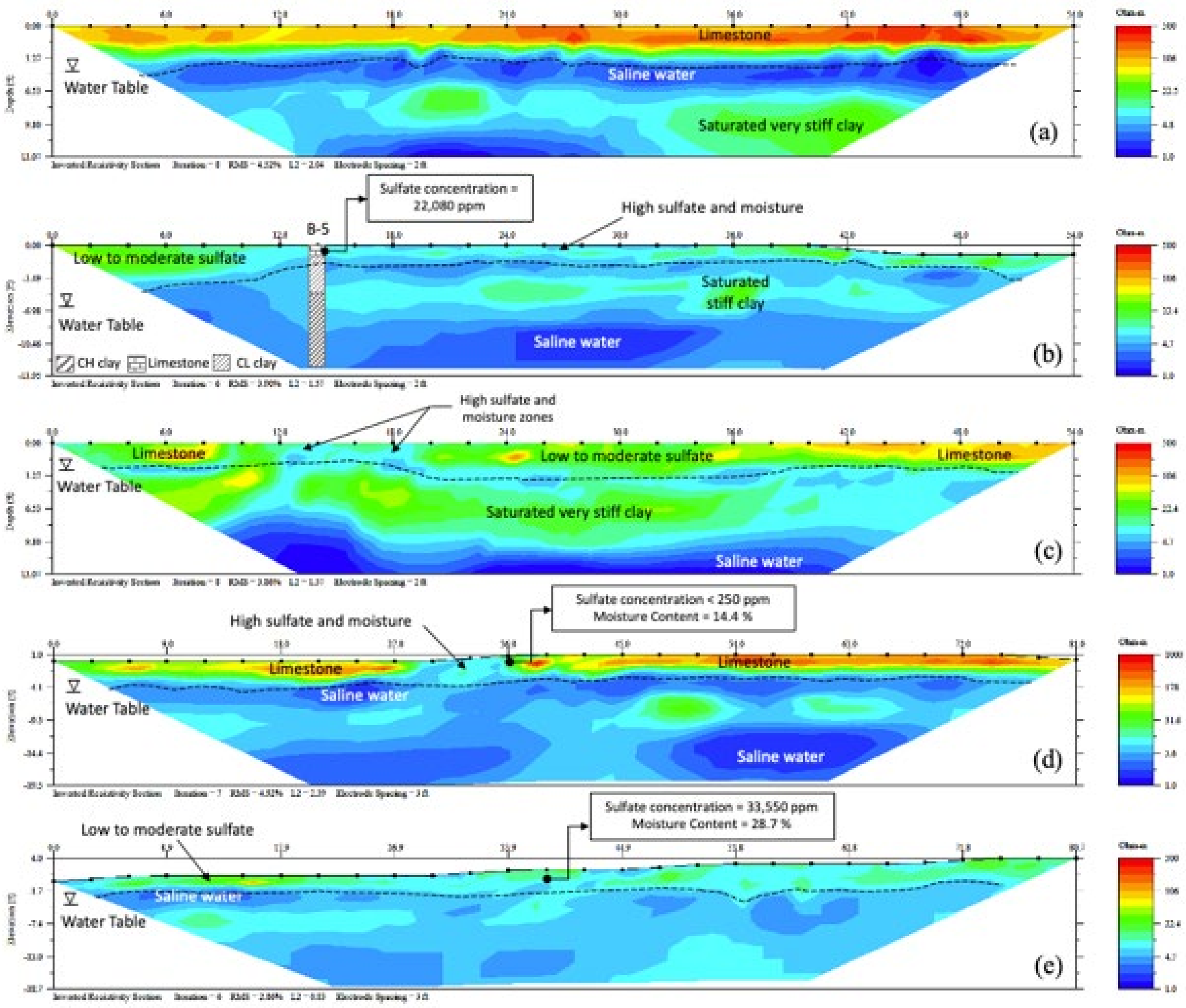


Figure 2.18. Subsurface resistivity image in Zone 1; (a) Line 1, (b) Line 2, (c) Line 3, (d) Line 4, and (e) Line 5

Figure 2.19 illustrates the inverted resistivity profiles for Lines 6 and 7 along Loop H-3 in Zone 1. By generalizing the findings from previous profiles, high and low to moderate sulfate concentration zones are delineated at the top left corner of Line 6; however, no testing results confirm these findings. Figure 2.19a shows a relatively consistent profile to the left side of the profile without any evidence of high sulfate concentrations. Figure 2.19b specifies three layers in the subsurface: a resistive layer at the top with electrical resistivities >60 Ω.m (limestone), a transition layer with electrical resistivities of about 30 Ω.m, and a conductive layer with electrical resistivities <9 Ω.m. A sharp drop in the electrical resistivities through the depth indicates the water table level at approximately 8 feet below the ground surface. The low electrical resistivities (below 3 Ω.m) are associated with saline water (water with high soluble salts). No evidence of high sulfate concentration is observed through the length of the profile up to a depth of 3 feet. However, there is a potential risk of the movement of salts from the underlying water-saturated layer to the top layer due to capillary rise during the dry season. The results of laboratory tests confirm that the subsurface materials contain low water and sulfate concentrations at a 24 feet distance.

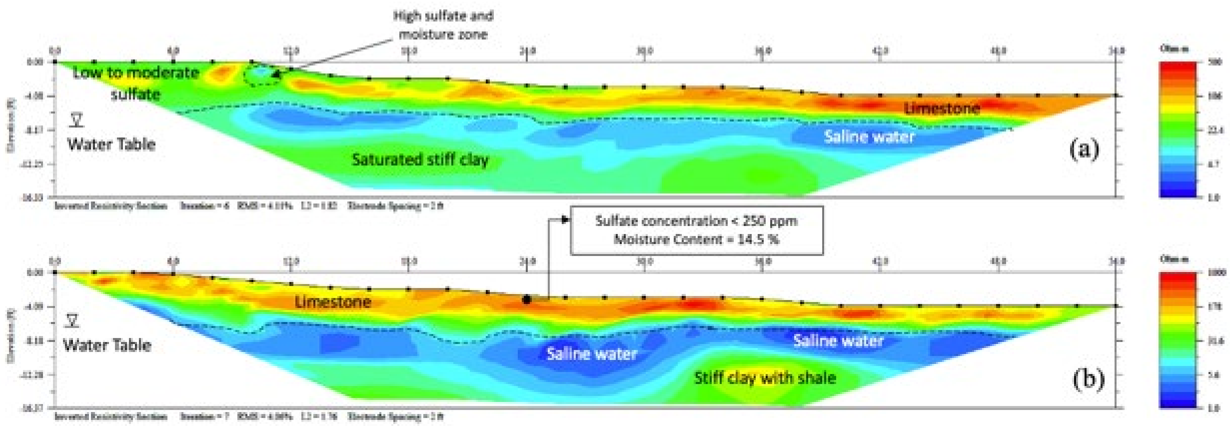


Figure 2.19. Subsurface resistivity image in Zone 1; (a) Line 6 and (b) Line 7

Figure 2.20 shows the inverted resistivity profiles of Lines 1 to 5 obtained by 2- and 3-feet electrode spacings along Loop H in zone 2. Figures 2.20a and 2.20b illustrate an inconsistent subsurface condition at the shallow subsurface through resistivity profiles. Borehole BH-2 at a 2 feet distance shows a layer of limestone and stiff to very stiff clays to a depth of 18 feet. Two conductive zones with electrical resistivities below 10 Ω.m indicate high moisture and sulfate concentration levels. The borehole results also show high sulfate concentrations (17,835 ppm) at a 2 feet distance from Line 2, which is associated with the electrical resistivity of 6 Ω.m. Zones with electrical resistivities above 50 Ω.m show no evidence of high sulfate concentrations. Figure 2.20c also agrees with the findings from Line 4 in Zone 1.

Although Figure 2.20d indicates conductive areas in the shallow subsurface from the middle to the right side of the profile, with electrical resistivities below 20 Ω.m, the testing results show a sulfate concentration of 350 ppm at a 36 feet distance. It shows that the areas with low electrical resistivities are associated with other soluble salts than sulfate. Based on the findings from the previous profiles, very low electrical resistivities (below 5 Ω.m) at the top right side of the profile can be attributed to the high sulfate and moisture zones. It is recommended that more tests be conducted at 45 to 81 feet distance to obtain more confidence regarding the extent of critical sulfate concentration.

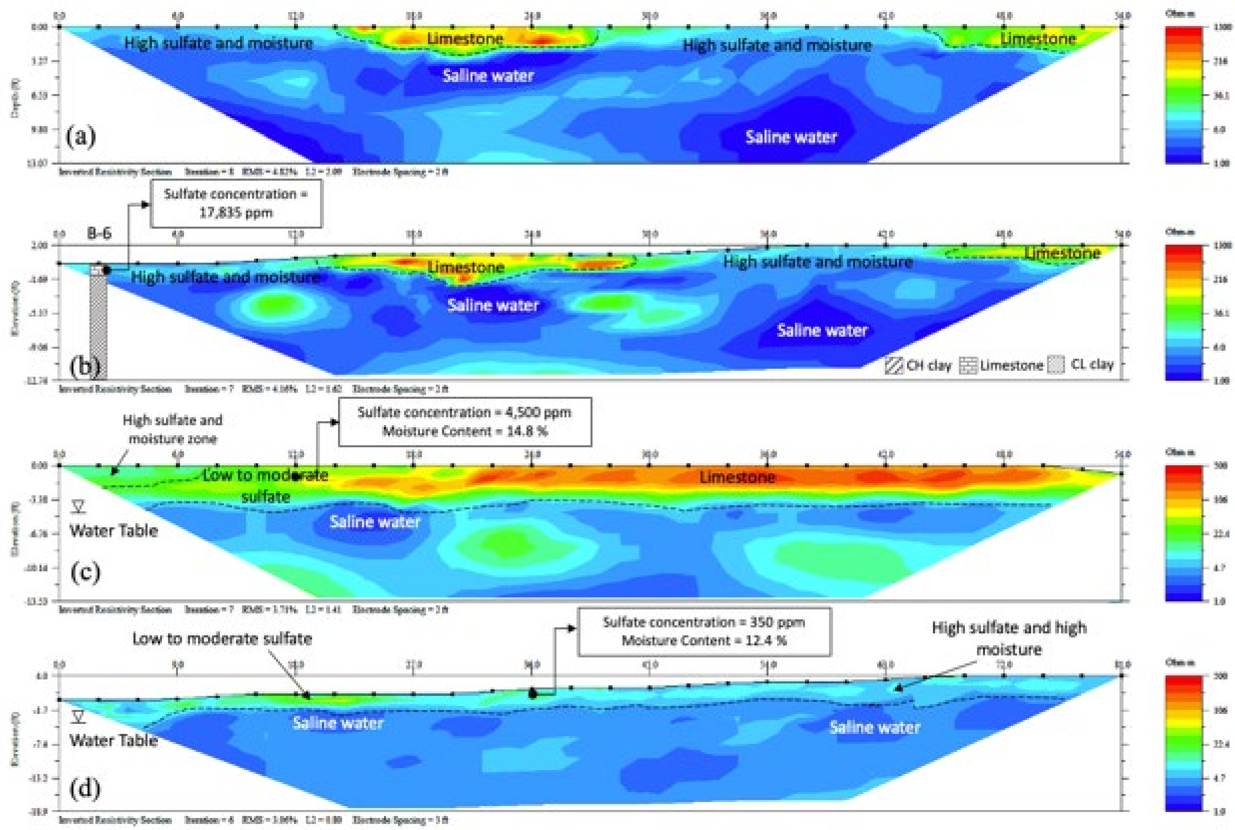


Figure 2.20. Subsurface resistivity image in Zone 2; (a) Line 1, (b) Line 2, (c) Line 3, and (d) Line 4

Figure 2.21 shows a comprehensive overview of the extent of critical zones with the risk of sulfate-induced heaving. As indicated in Figure 2.21, the extent of critical sulfate concentration zones along Loop H goes beyond zone 1 and 2 limits. However, there is a low risk of sulfate-induced heaving along Loop H-3.

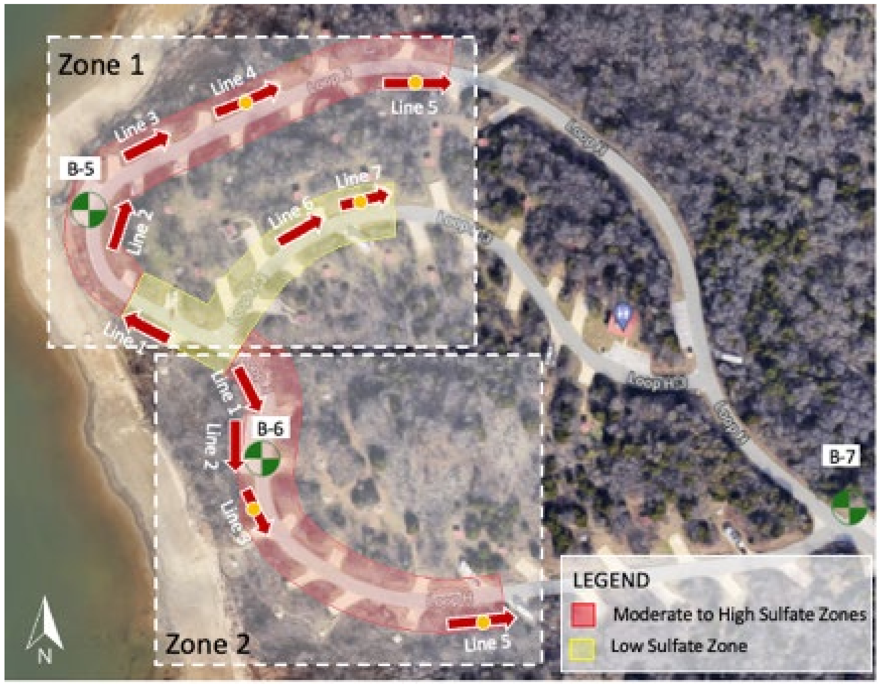


Figure 2.21. Overview of the extent of critical zones with the risk of sulfate-induced heaving

Laboratory Tests on Collected Samples from Cedar Hill State Park

Six soil samples were collected from Cedar Hill State Park to validate the ERI findings. The research team performed a colorimetric method based on TxDOT 145-E to obtain actual sulfate concentrations of the collected soil samples. Moisture contents of the soil samples were also determined according to ASTM D2216-90. The actual sulfate concentrations and moisture contents are presented in Table 2.3. According to Table 2.3, the measured sulfate concentrations were consistent with those reported in the geotechnical report for this project.

Table 2.3. Summary of the laboratory tests of the collected samples from the Cedar Hill State Park project in the Dallas district

Borehole No.	Soil Type	Depth (feet)	Sulfate Concentration (ppm)	Actual Moisture Content (%)
Line 4 – Zone 1	Crushed Limestone	0 – 1.0	Below 250	14.4
Line 5 – Zone 1	Crushed Limestone	0.5 – 1.5	13,650	23.3
Line 5 – Zone 1	CL	1.5 – 2.5	33,550	28.7
Line 7 – Zone 1	Crushed Limestone	0 – 1.0	Below 250	14.5
Line 3 – Zone 2	Crushed Limestone	0.5 – 1.5	4,500	14.8
Line 3 – Zone 2	CL	1.0 – 2.0	3,000	16.6

In addition, the research team conducted 96 laboratory electrical resistivity tests on the collected samples from Cedar Hill State Park at different moisture contents with various compaction efforts. The research team followed a Wenner four-electrode method to conduct the laboratory electrical resistivity tests (ASTM G57 2020). The obtained data were used to validate the equations developed in the TxDOT Project 0-7008.

2.2.4 SH 170 at Westport Pkwy

The study area is located at SH 170 at Westport Pkwy in Tarrant County, Fort Worth, Texas. Figure 2.22 shows the location of the study area on the Fort Worth map.

Figure 2.22. Location of West Port Parkway on the Fort Worth map

The study area is situated in a region mapped with Grayson Marl and Main Street Limestone, an undivided Formation. Graystone Marl formation consists of marl and shale with a thickness of 15 to 60 feet, which forms residual clays of high plasticity. Main Street Limestone is composed of limestone with a thickness of about 10 to 20 feet. A geotechnical report for this project (documented in December 2020) indicates that the subsurface materials consisted of soft to very stiff, fat (CH), and lean (CL) clays with a thickness of at least 22 feet. Clay layers are underlaid by shale and limestone to a depth of about 50 feet. The plasticity indices were measured in the range of 32 to 45. A trace of water was observed during drilling at 21.5 feet at borehole WP-03. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.23 illustrates the ERI data collection plan and borehole locations for SH 170 at Westport Pkwy. This implementation aimed to identify the water table depth (ER-1 and ER-2 in Figure

2.23). Moreover, the research team planned to study the application of the ERI for determining the bridge foundation depth (ER-3 in Figure 2.23).

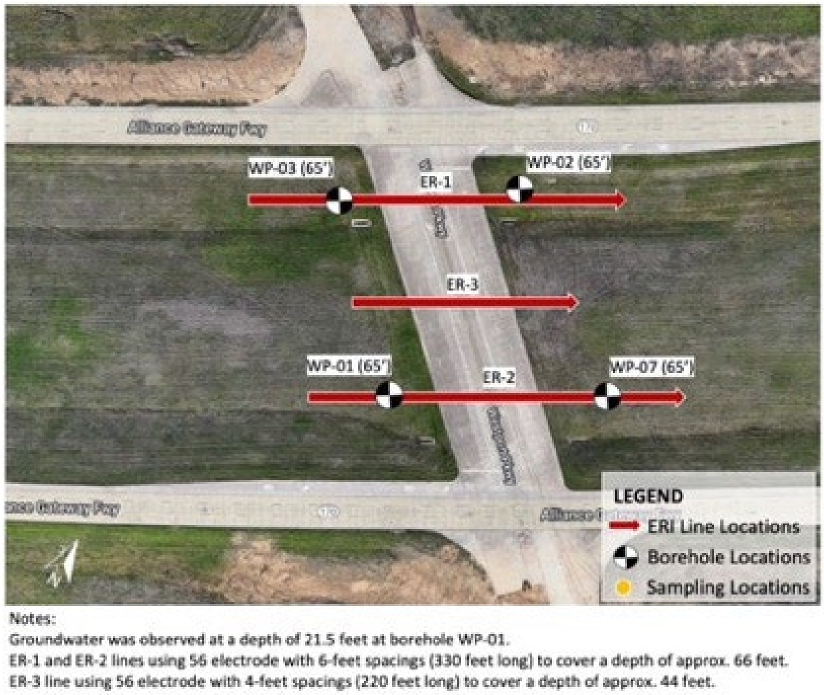


Figure 2.23. ERI data collection plan and borehole locations for SH 170 at Westport Pkwy

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for SH 170 project on July 13th, 2022. Three ERI surveys (ER-3 was performed in parallel with bridge piles.) were conducted using 56 electrodes and 4- and 6-feet spacings. Figure 2.24 shows the implementation of the ERI at Westport Pkwy. During 15 days before implementing the ERI surveys, no precipitation was observed at the study area (Weather Underground 2022). The average maximum temperature for a week before implementation was about 100˚F.

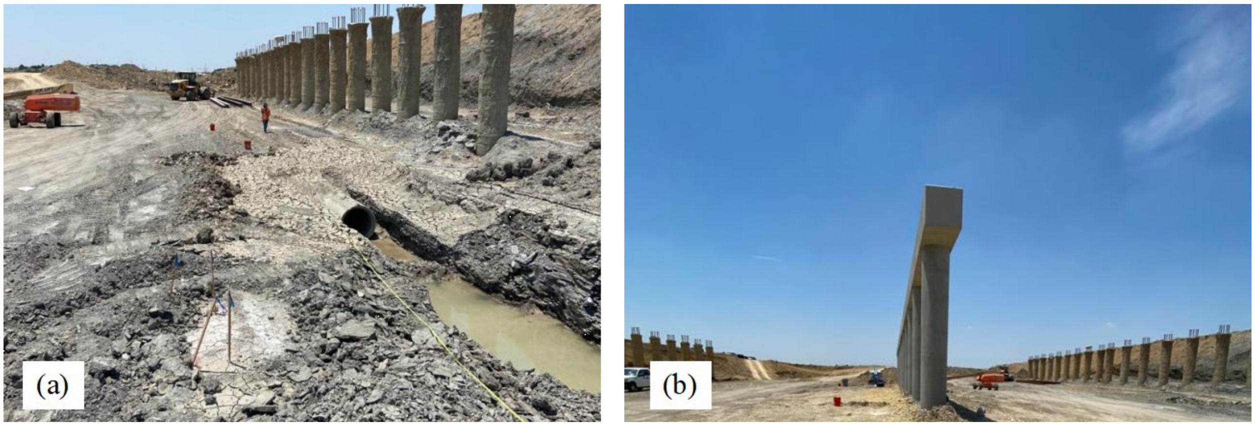


Figure 2.24. Implementation of the ERI at SH 170 at Westport Pkwy; (a) ER-1 and (b) ER-3 within a small distance from the bridge piles

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Elevation data were also extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling. Due to the extreme weather conditions, some of the obtained data was noisy that was removed from modeling. Based on the obtained resistivity images of the subsurface, the minimum and maximum depths of investigation are 30 feet with 4 feet electrode spacing and 55 feet with 6 feet electrode spacing. The research team assessed the subsurface conditions and identified possible earth materials and water table depth using the obtained subsurface resistivity images, borehole results, and the developed equations for the TxDOT Project 0-7008.

Figure 2.25 illustrates the inverted resistivity profile of Lines ER-1 and ER-2 obtained by 6 feet electrode spacing. Figure 2.25a shows consistent subsurface conditions with electrical resistivities of 3.9 to 27.5 Ω.m, indicating similar earth materials. High moisture zones at the shallow subsurface are due to standing water at the study area (Figure 2.24). Areas with electrical resistivities of about 10 Ω.m are associated with moist, soft clays. The water table was not detected up to 33 feet deep. There is, however, a potential sign of a groundwater table close to 33 feet, shown with dashed lines on the profile at 144 feet distance. Figure 2.25b shows an isolated area with high electrical resistivity contrast to the background, centered at 152 feet distance and extending to 41 feet depth. The background electrical resistivity varies slightly from 1 to 20 Ω.m, indicating moist, soft clays. It is perceived that this anomaly interfered with the ERI measurements and created noisy readings. Field observations suggest that the anomaly may represent a subsurface void or an underground concrete structure.

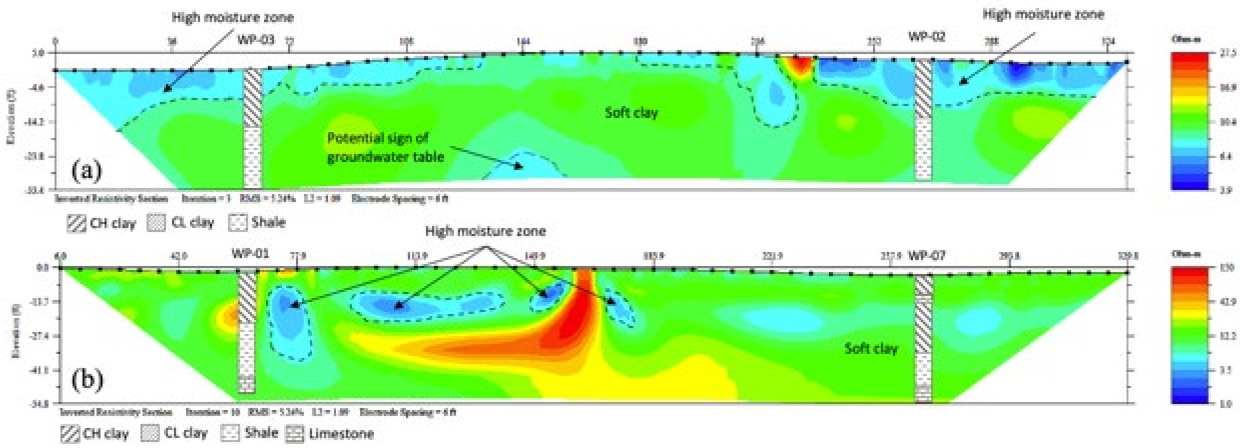


Figure 2.25. Subsurface resistivity image; (a) Line ER-1 and (b) Line ER-2

Figure 2.26 illustrates the inverted resistivity profile of Line ER-3 obtained by 4 feet electrode spacing. The resistivity profile shows low variations within the depth of the profile, ranging from 1 to 10 Ω.m, which signifies moist to saturated subsurface material. Weather data and field observations, however, do not support this conclusion. A high resistive anomaly, shown in the middle of the profile, interfered with the ERI measurements. This anomaly is possibly extended towards Line ER-2.

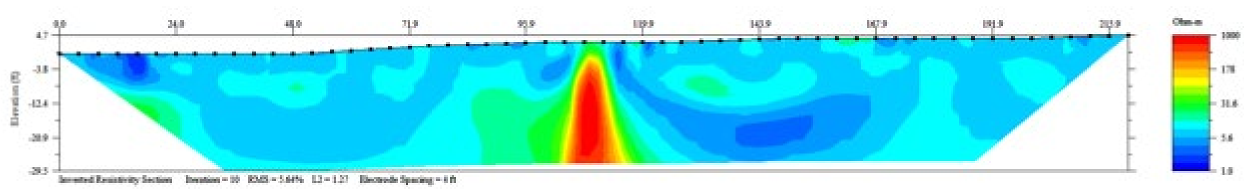


Figure 2.26. Subsurface resistivity image of Line ER-3 at a close distance to bridge piles

2.2.5 SH 170 at N Main St

The study area is located at SH 170 at N Main St in Tarrant County, Fort Worth, Texas. Figure 2.27 shows the location of the study area on the Fort Worth map.

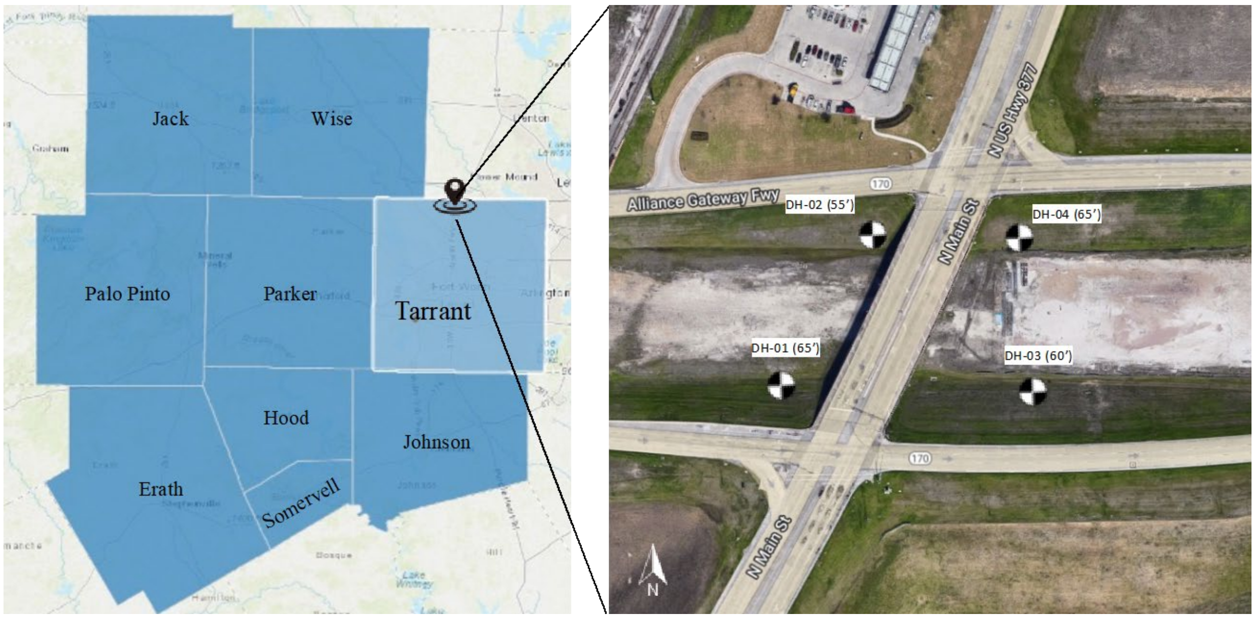
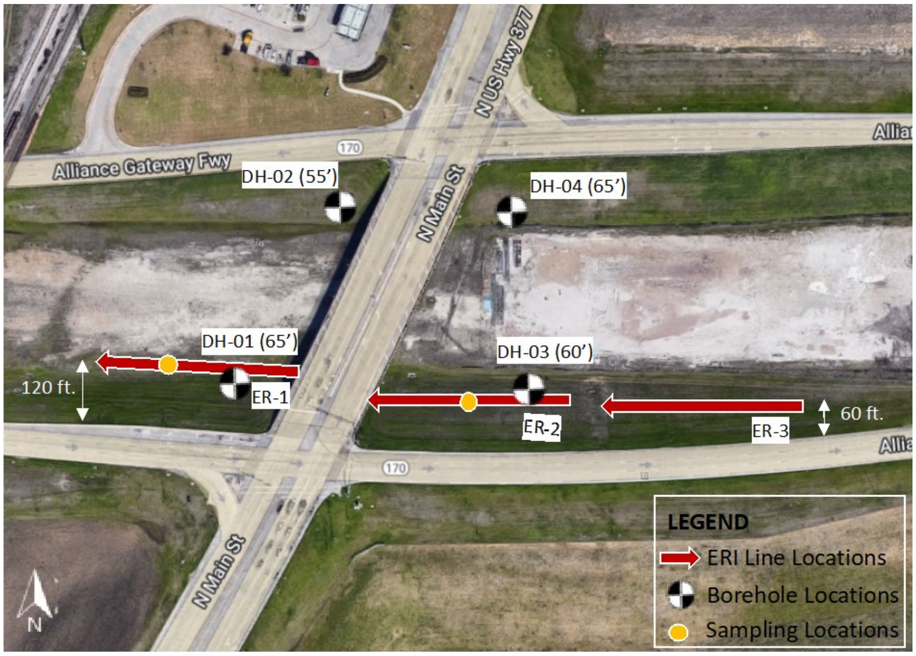


Figure 2.27. Location of SH 170 at N Main St on the Fort Worth map

The study area is situated in a region mapped with Grayson Marl and Main Street Limestone, an undivided Formation. Graystone Marl formation consists of marl and shale with a thickness of 15 to 60 feet, which forms residual clays of high plasticity. Main Street Limestone is composed of limestone with a thickness of about 10 to 20 feet. A geotechnical report for this project (documented in December 2020) shows that the subsurface materials consisted of fill materials (i.e., sand, gravel, and clays) at the top, extending to 10 feet. Fill materials are underlaid by soft to hard shale to 65 feet in depth. No groundwater was encountered in any of the soil borings during drilling. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.28 illustrates the ERI data collection plan and borehole locations for SH 170 at the N Main St project. This implementation aimed to assess the sulfate concentration levels at the study area and identify critical zones prone to sulfate-induced heaving.



Notes:
Sulfate concentration was 5,680 ppm at a depth of approximately 4 feet at borehole DH-01.
ER-1 line using 56 electrode with 6-feet spacings (330 feet long) to cover a depth of 66 feet.
ER-2 and ER-3 lines using 56 electrode with 4-feet spacings (220 feet long) to cover a depth of 44 feet.

Figure 2.28. ERI data collection plan and borehole locations for SH 170 at N Main St

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for SH 170 at N Main St on July 12th, 2022. Three ERI surveys were conducted using 56 electrodes with 4- and 6-feet spacings. Line ER-1 was implemented within the road limit; however, ER-2 and ER-3 were implemented on the slope on the south side. In addition, two soil samples were collected from two locations, as shown in Figure 2.28, to be tested in the laboratory. The borings were advanced to a maximum depth of 1 foot using an electric hand auger. Section 2.5.3 describes the laboratory electrical resistivity tests and presents sulfate testing results. Figure 2.29 shows the implementation of the ERI at SH 170 at N Main St. During 15 days before implementing the ERI surveys, no precipitation was observed at the study area (Weather Underground 2022). The average maximum temperature for a week before implementation was about 100˚F.

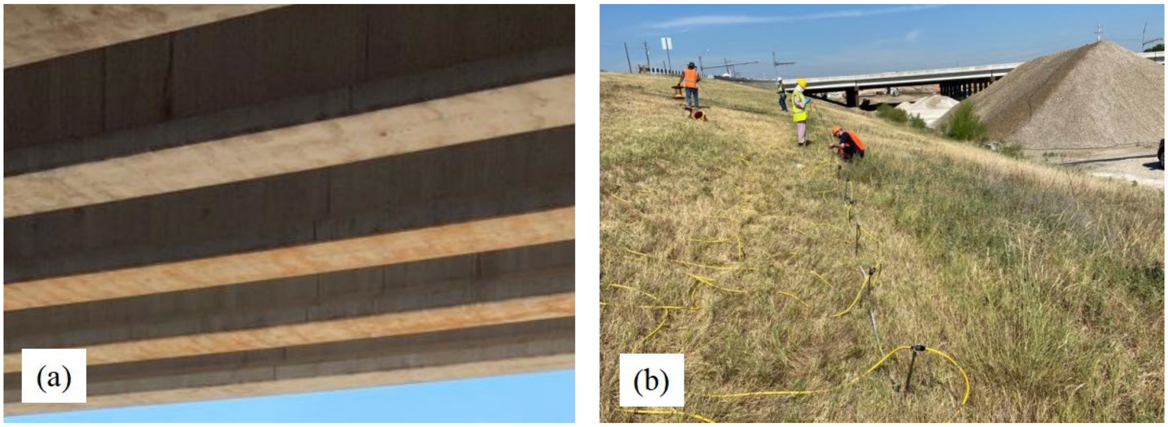


Figure 2.29. Subsurface resistivity images; (a) Line ER-1 and (b) Line ER-3

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Elevation data were also extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling. Due to the extreme weather conditions, some of the obtained data was noisy that was removed from modeling. Based on the obtained resistivity images of the subsurface, the minimum and maximum depths of investigation are 30 and 40 feet with 4 feet electrode spacing. The research team assessed the subsurface conditions, identified possible earth materials, and determined sulfate concentration levels using the obtained subsurface resistivity images, borehole results, and developed equations for the TxDOT Project 0-7008.

Figure 2.30 illustrates the inverted resistivity profiles of Line ER-1 obtained by 6 feet electrode spacing. Figure 2.30 shows resistive areas at the shallow subsurface that extends to 4 to 8 feet. These resistive areas are attributed to fill materials consisting of sand and stiff clay. No evidence of high sulfate concentration is observed through the length of the profile up to 4 to 8 feet. Laboratory tests also confirm the findings from the ERI. However, conductive areas (with electrical resistivities below 5 Ω.m) at the middle depth of the resistivity profile denote the sulfate salts accumulation beneath the top resistive layer. The sulfate salts can be transported by capillary rise and precipitate on the top layer. Intermittent zones of high electrical resistivities (>20 Ω.m) at the bottom of the resistivity profile are associated with soft to hard shale.

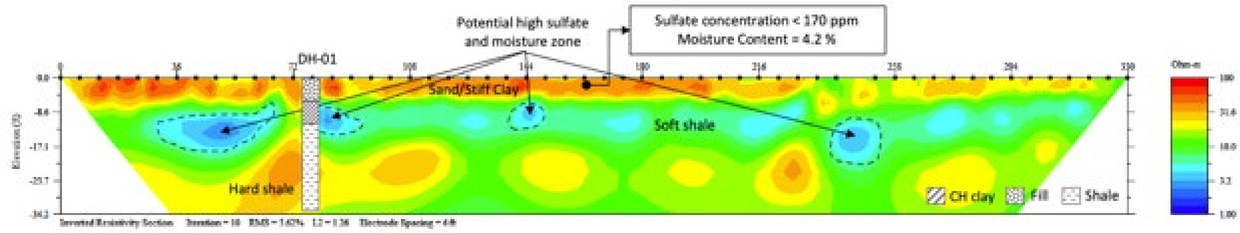


Figure 2.30. Subsurface resistivity image of Line ER-1

Figure 2.31 shows the inverted resistivity profile of Lines ER-2 and ER-3. Figure 2.31a shows high contrast in the electrical resistivities from 1 to 5000 Ω.m. A continuous resistive layer that starts from 2 feet and extends to the bottom of the profile signifies hard limestone and shale. Earth materials overlay the resistive layer with low electrical resistivities that can be attributed to soft shale and fill materials. Pockets of high moisture content in the shallow subsurface are associated with high moisture and salt concentration zones. Laboratory tests show high moisture content and low sulfate concentrations in the shallow subsurface, implying the presence of other soluble salts than sulfate. Figure 2.31b depicts a consistent subsurface condition through the depth and length of the resistivity profile; electrical resistivity varies from 10 to 100 Ω.m. Resistive zones represent soft to hard shale at the bottom and fill materials at the shallow subsurface. A zone with relatively low electrical resistivities at a 50 to 100 feet distance is attributed to a high moisture zone.

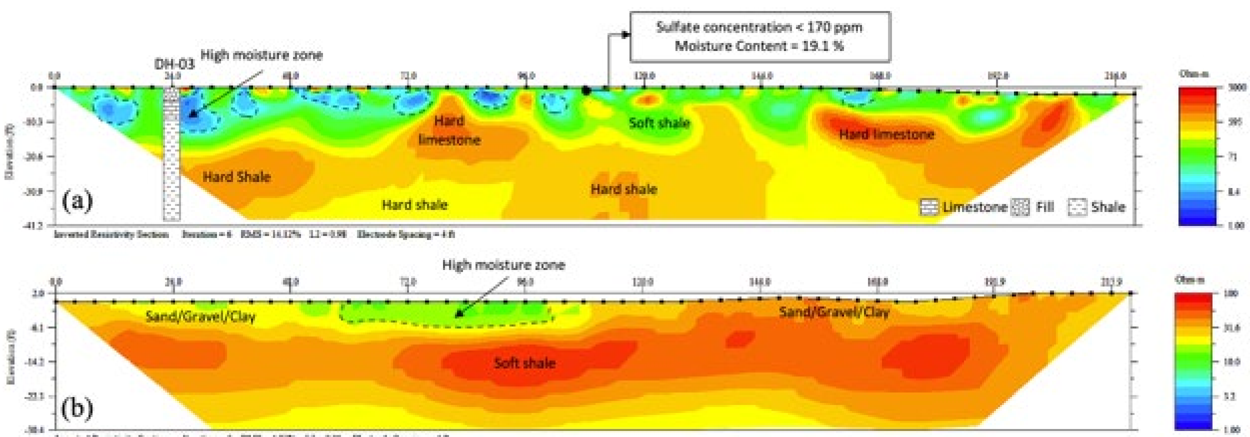


Figure 2.31. Subsurface resistivity image; (a) Line ER-2 and (b) Line ER-3

Laboratory Tests on Collected Samples from SH 170 at N Main St.

Two soil samples were collected from SH 170 at N Main St to validate the ERI findings. The research team performed a colorimetric method based on TxDOT 145-E to obtain actual sulfate concentrations of the collected soil samples. Moisture contents of the soil samples were also determined according to ASTM D2216-90. The actual sulfate concentrations and moisture contents are presented in Table 2.4.

Table 2.4. Summary of the laboratory tests of the collected samples from the SH 170 at N Main St in the Fort Worth district

Borehole No.	Soil Type	Depth (feet)	Sulfate Concentration (ppm)	Actual Moisture Content (%)
Line ER-1	Fill material	0 – 1.0	Below 170	4.2
Line ER-2	Fill material	0 – 1.0	Below 170	19.1

In addition, the research team conducted 35 laboratory electrical resistivity tests on the collected samples from SH 170 at N Main St at different moisture contents with various compaction efforts. The research team followed a Wenner four-electrode method to conduct the laboratory electrical resistivity tests (ASTM G57-20, 2020). The obtained data were used to validate the equations developed in the TxDOT Project 0-7008.

2.2.6 IH 30 at Mary's Creek

The study area is located along Mary's Creek in Tarrant County, Fort Worth, Texas. Figure 2.32 shows the location of the study area on the Fort Worth map.

Figure 2.32. Location of the IH 30 at Mary's Creek on the Fort Worth map

The study area is situated in a region mapped with the Goodland Limestone Formation with a thickness of 90 feet (USGS Texas Geology Map). A geotechnical report for this project (documented in March 2022) shows lean clays (CL up to a depth of 13 feet) at borehole B-851 and fill material (top 10 feet) at borehole B-852. The plasticity indices range from 11 to 25. Limestone and sandstone are underlaid the top materials and extend to a depth of 60 feet. Groundwater was observed at 16 feet during drilling at borehole B-851. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.33 illustrates the ERI data collection plan and borehole locations for IH 30 project at Mary's Creek. This implementation aimed to identify the water table depth along Mary's Creek (ER-1 in Figure 2.33). Moreover, the research team planned to study the application of the ERI for determining the bridge foundation depth (ER-2 in Figure 2.33).

Notes:
Groundwater depth below the existing grade was 18.0 feet in the borehole B-852.
ER-3 using 56 electrodes with 6-feet spacings (330 feet long) to cover a depth of approx. 66 feet.
ER-4 using 28 electrodes with 4-feet spacing (108 feet long) to cover a depth of approx. 22 feet.

Figure 2.33. ERI data collection plan and borehole locations for IH 30 project at Mary's Creek

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 30 project on September 16th, 2022. Three ERI surveys (ER-2 was performed in parallel and at the center of bridge piles) were conducted using 28 and 56 electrodes with 4- and 6-feet spacings. Figure 2.34 shows the implementation of the ERI along Mary's Creek. In the first week of September 2022, 2.68 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.34. Implementation of the ERI along Mary's Creek; (a) ER-1 and (b) ER-2 within a small distance from the bridge piles

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the minimum and maximum depths of investigation are 26 feet with 4 feet electrode spacing and 52 feet with 6 feet electrode spacing. The research team assessed the subsurface conditions and identified possible earth materials, water table depth, and depth of foundation piles using the obtained subsurface resistivity images, borehole results, and the developed equations for TxDOT Project 0-7008.

Figure 2.35 illustrates the inverted resistivity profile of Line ER-1. The electrical resistivity shows high contrast through the depth of the profile, ranging from 4 to 250 Ω.m. Low electrical resistivity areas (below 20 Ω.m) scattered at the shallow subsurface are attributed to high moisture zones. Resistive areas centered at a depth of about 26 feet are associated with the weathered limestone. Low electrical resistivity zones at the bottom of the profile denote possible signs of the water table.

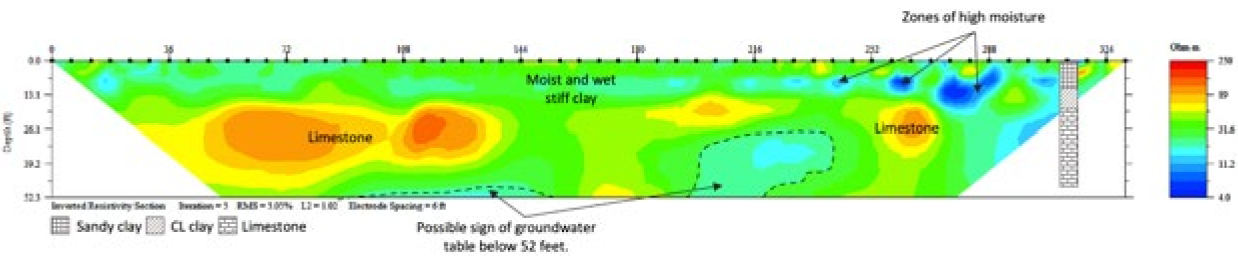


Figure 2.35. Subsurface resistivity image of Line ER-1

Figure 2.36 shows the inverted resistivity profiles of ER-2 at the center of and within a small distance from the foundation piles. Locations of the bridge piles are also shown in Figure 2.36. Both resistivity images illustrate similar subsurface conditions with minor differences. Since the electrical resistivity of reinforced concrete varies from 1 to 20 Ω.m (Wang and Hue 2015), the pile foundation depths were determined at depths in which the electrical resistivities changed abruptly from 10 to 100 Ω.m. From Figure 2.36, the depths of foundations are estimated to be at least 7 feet for pier 1 and 14 feet for pier 2. However, no conclusive result can be obtained for the depth of pier 3 as the results from the two lines are inconsistent. A resistive area at the bottom of the profile is associated with unweathered limestone or sandstone, which is the continuation of the resistive zone from Line ER-1.

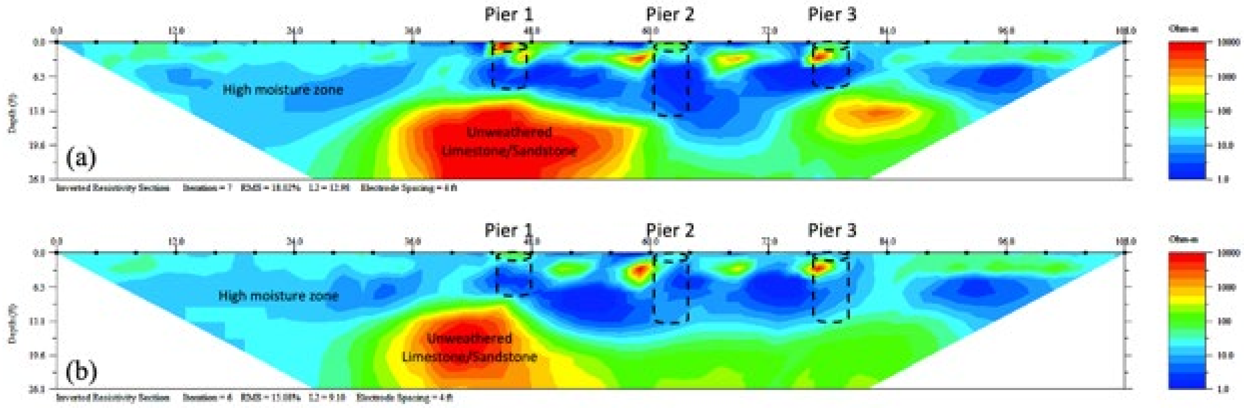


Figure 2.36. Subsurface resistivity image; (a) Line ER-2 at the center of bridge piles and (b) Line ER-2 within a small distance from the bridge piles

2.2.7 IH 30 at Chapel Creek Blvd

The study area is located along IH 30 at Chapel Creek Blvd in Tarrant County, Fort Worth, Texas. Figure 2.37 shows the location of the study area on the Fort Worth map.

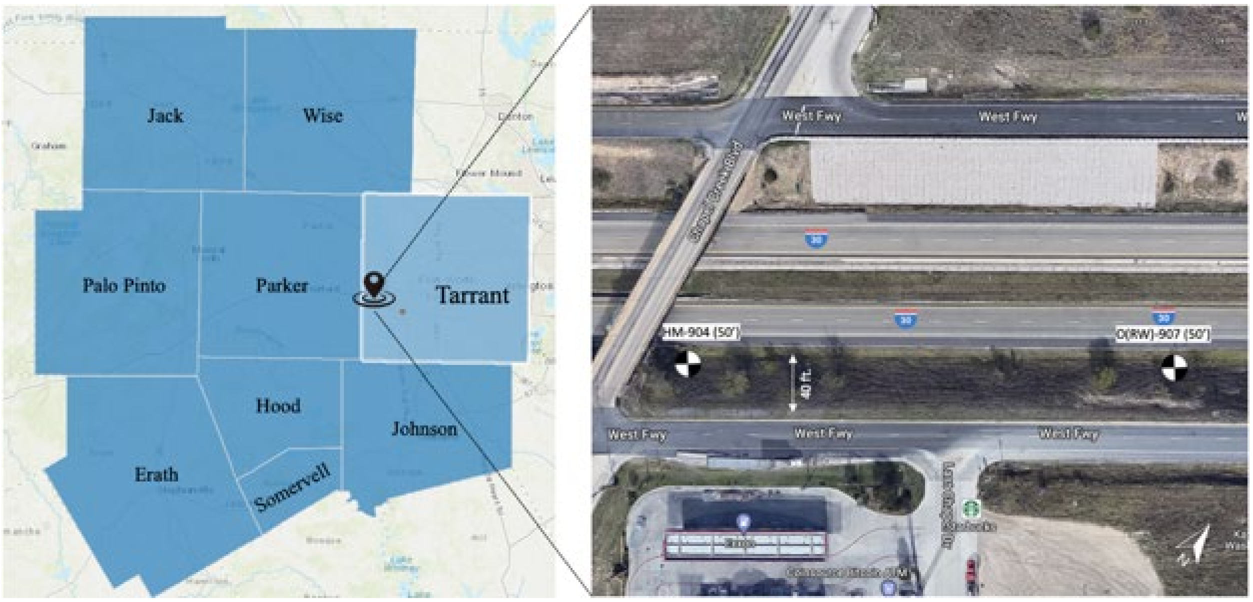


Figure 2.37. Location of the IH 30 at Chapel Creek Blvd on the Fort Worth map

The study area is situated in a region mapped with the Goodland Limestone Formation with a thickness of 90 feet (USGS Texas Geology Map). A geotechnical report for this project (documented in March 2022) identifies clayey sand (SC) and lean clay (CL) in the shallow subsurface. The plasticity indices range from 14 to 24. Limestone (moderately to highly weathered) with intermittent shale is underlaid on the top materials and extends to a depth of 50 feet. No groundwater was encountered at any soil borings during drilling. Boring logs for this project are attached in Appendix A.

Data Collection

Figure 2.38 illustrates the ERI data collection plan and borehole locations for IH 30 at Chapel Creek Blvd. This implementation aimed to identify the subsurface conditions behind the retaining wall (ER-1 in Figure 2.38) and assess the stability of the slope (ER-2 in Figure 2.38).

Notes:
Lines ER-1 and ER-2 using 28 electrodes with 6-feet spacings (165 feet long) to cover a depth of approx. 33 feet.

Figure 2.38. ERI data collection plan and borehole locations for IH 30 at Chapel Creek Blvd

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 30 at Chapel Creek Blvd on December 2nd, 2022. Two ERI surveys were conducted using 28 electrodes with 2 feet spacings. Figure 2.39 shows the implementation of the ERI along IH 30 at Chapel Creek Blvd. In a week before the implementation, 0.49 inches of precipitation were recorded at the site (Weather Underground 2022).

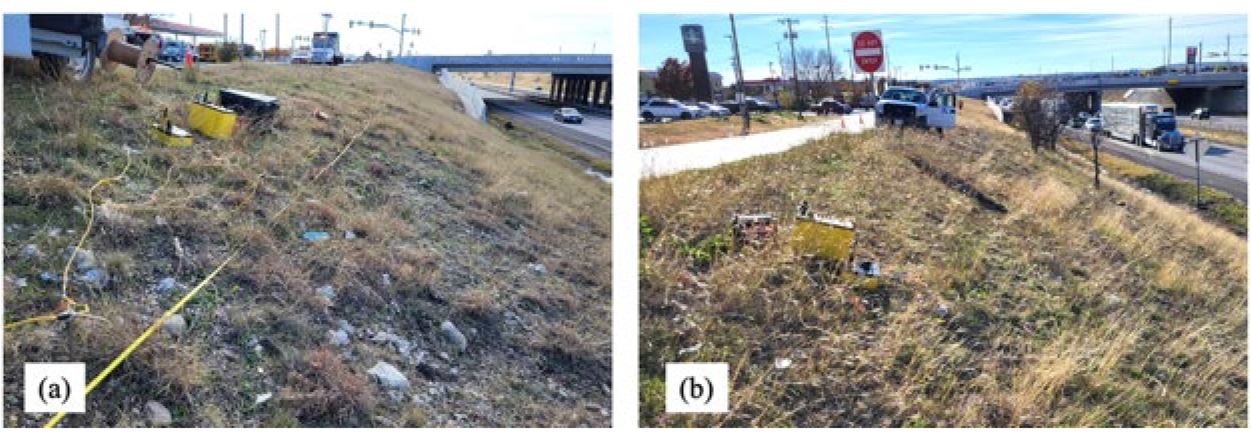


Figure 2.39. Implementation of the ERI along IH 30 at Chapel Creek Blvd; (a) Line ER-1 and (b) Line ER-2

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is 39 feet with 6 feet electrode spacing. The research team assessed the subsurface conditions behind the retaining wall and the slope stability using the obtained subsurface resistivity images and borehole results.

Figure 2.40 illustrates the inverted resistivity profile of Line ER-1 performed in parallel to the retaining wall. The electrical resistivity shows low variation through the depth of the profile, ranging from 14 to 50 Ω.m. Less resistive areas at the shallow subsurface are attributed to wet clayey sand. More resistive areas at a depth of about 20 feet with an electrical resistivity of about 50 Ω.m could be associated with highly weathered limestone based on the site's geology. As shown in Figure 2.40, the top layer retains a higher moisture content than the deep layers. No high moisture zone is observed below the top layer.

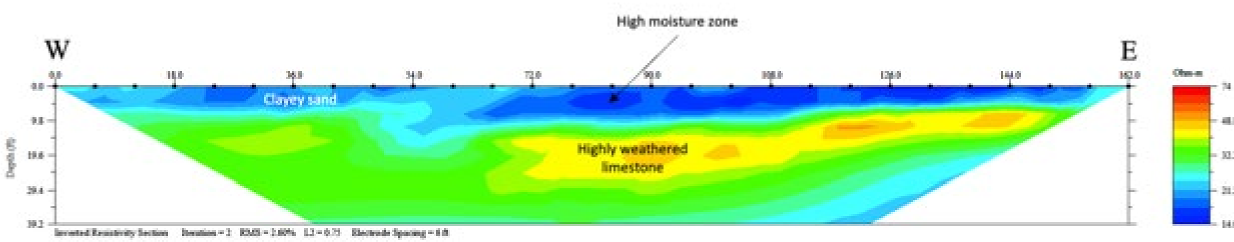


Figure 2.40. Subsurface resistivity image of Line ER-1

Figure 2.41 illustrates the inverted resistivity profile of Line ER-2. The electrical resistivity changes from 14 to 74 throughout the profile depth, representing dry to moist subsurface materials. The top resistive layer is attributed to dry to moist sandy clay based on the site's geology. The top layer is underlaid by high moisture zones at depths of 10 and 20 feet. The instability of slopes may originate from the locations of high moisture zones. At the location of the high moisture zone on the left, shallow slope failure is more concerning.

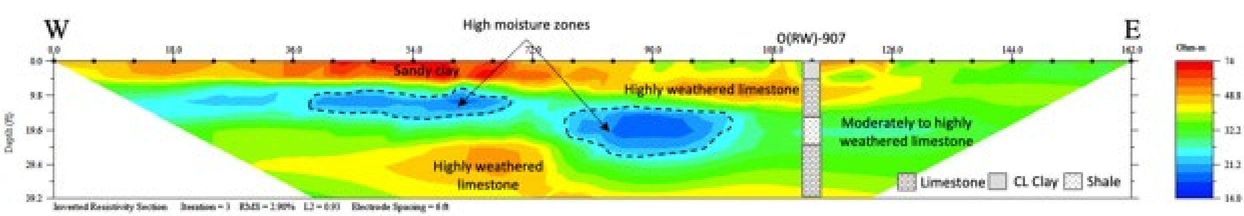


Figure 2.41. Subsurface resistivity image of Line ER-2

2.2.8 IH 30 at Walsh Ranch Pkwy

The study area is located along IH 30 at Walsh Ranch Pkwy in Parker County, Fort Worth, Texas. Figure 2.42 shows the location of the study area on the Fort Worth map.

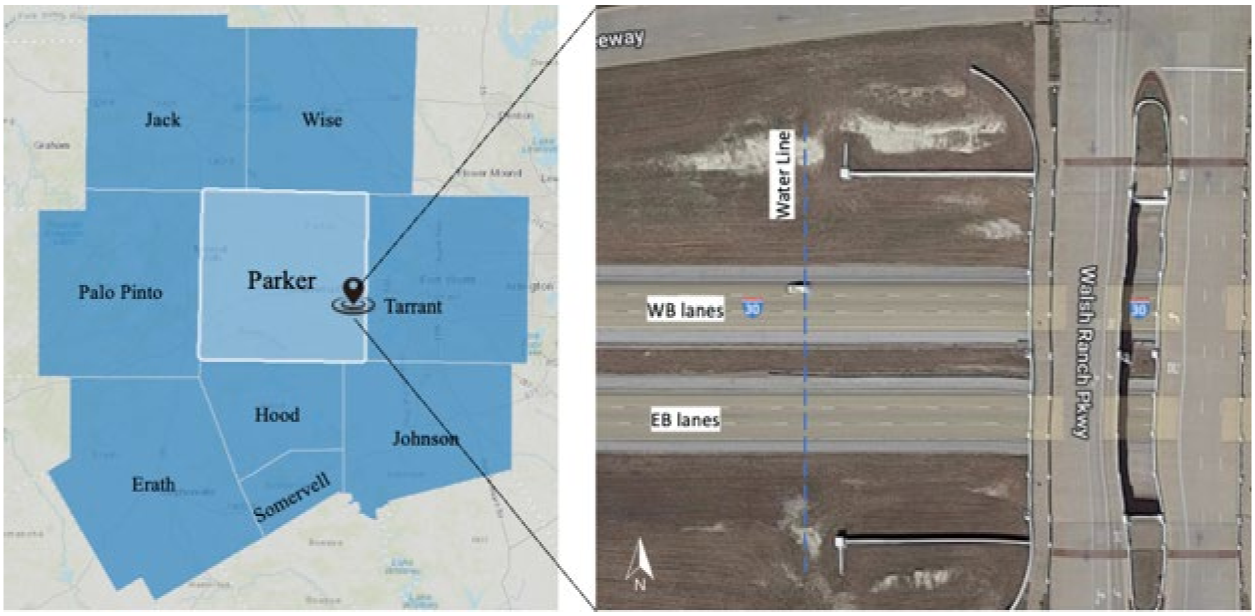
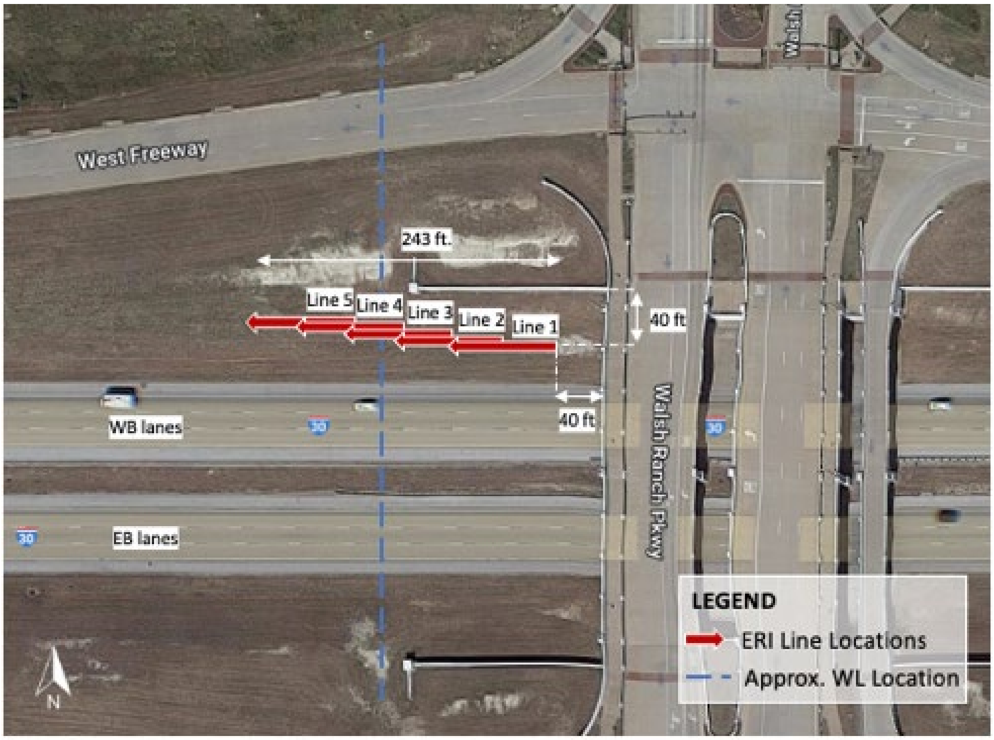


Figure 2.42. Location of the IH 30 at Walsh Ranch Pkwy on the Fort Worth map

The study area is situated in a region mapped with the Goodland Limestone Formation with a thickness of 90 feet. A utility layout for the project (see Appendix C) shows that a water line is located on the left side of the Walsh Ranch Pkwy, which crosses the IH 30 main lanes. The approximate location of the water line is shown in Figure 2.42. According to the utility layout, the water pipe is a 24-inches concrete pipe with stainless steel casing spacers.

Data Collection

Figure 2.43 illustrates the ERI data collection plan for IH 30 at Walsh Ranch Pkwy. This implementation aimed to locate an underground water pipe crossing the IH 30.



Notes:
ER Lines 1 to 5 using 28 electrode with 3-feet spacings (81 feet long) to cover a depth of approx. 16 feet.
3-feet spacing is suitable for locating 18 inches diameter pipe size and larger pipes.

Figure 2.43. ERI data collection plan for IH 30 at Walsh Ranch Pkwy

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 30 project on November 30th, 2022. Five ERI surveys were conducted using 28 electrodes with 3 feet spacing. The ERI lines were performed continuously and overlapped with one another. Overlapping lines ensure no gaps between the lines, so the water line is unlikely to be missed. Additionally, it increases the confidence level of the ERI findings since two series of data are available for each location. Figure 2.44 shows the implementation of the ERI along IH 30 at Walsh Ranch Pkwy. In a week before the implementation, 1.97 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.44. Implementation of the ERI along IH 30 at Walsh Ranch Pkwy

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous subsurface resistivity images. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is 19.6 feet with 3 feet electrode spacing. The research team assessed the subsurface conditions and attempted to locate a water line using the obtained subsurface resistivity images. The concrete pipe with steel casing spacers can be detected by areas with low electrical resistivities.

Figure 2.45 shows the inverted resistivity profiles for Lines 1 to 5. The electrical resistivity changes slightly from 10 to 30 Ω.m within 90 feet distance from the bridge abutment (50 feet from the starting point). The intermittent resistive zones centered at 63 feet for Line 3, 58 feet for Line 4, and 42 and 69 feet for Line 5 are attributed to rocky materials in the shallow subsurface based on the site information. However, the electrical resistivity of background materials varies slightly. No unique solution was found to represent the water line's location within the wet-to-saturated materials. However, according to Figure 2.45, the water line could be found at a distance of 82, 144, 167, and 195 feet from the bridge abutment (shown with dashed circles). However, based on the utility layout, it was found that Figure 2.45c shows the actual location of the water pipe; the top of the pipe is embedded at 8 feet deep (the actual depth of cover is 7 feet).

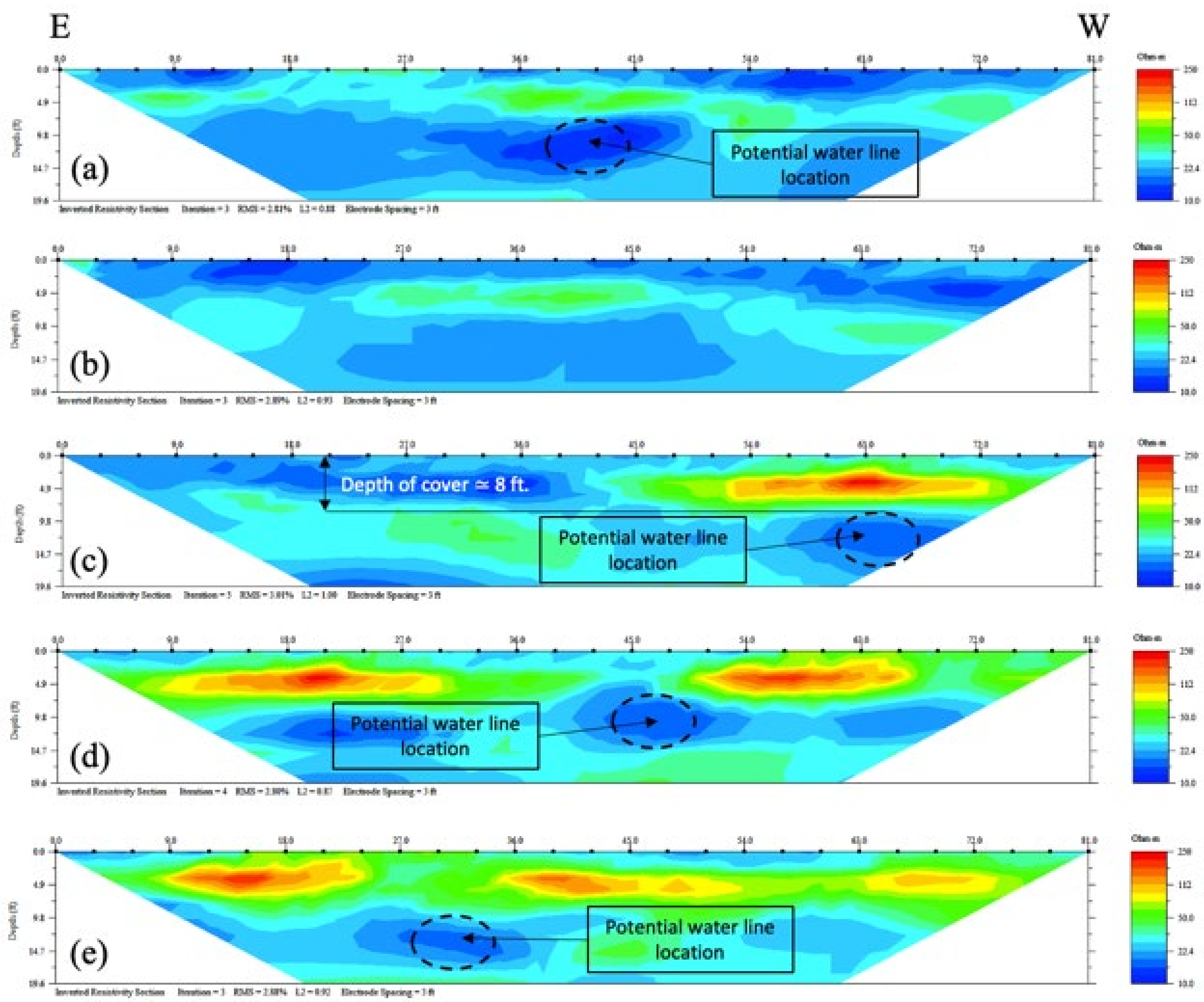


Figure 2.45. Subsurface resistivity image of (a) Line 1, (b) Line 2, (c) Line 3, (d) Line 4, and (e) Line 5

2.2.9 IH 20 East of Farmer Rd

The study area is located along IH 20 east of Farmer Rd in Parker County, Fort Worth, Texas. Figure 2.46 shows the location of the study area on the Fort Worth map.

Figure 2.46. Location of the IH 20 at the east side of Farmer Rd on the Fort Worth map

The study area is situated in a region mapped with the Duck Creek Formation with a thickness of 30 to 100 feet. A utility layout for the project (see Appendix C) shows that two water lines are located on the east side of Farmer Rd that cross the IH 20 main lanes. The approximate locations of the water lines are shown in Figure 2.46. According to the utility layout, the water pipes are 36-inch concrete pipes with steel casing spacers.

Data Collection

Figure 2.47 illustrates the ERI data collection plan for IH 20 east of Farmer Rd. This implementation aimed to locate two underground water pipes crossing the IH 20.

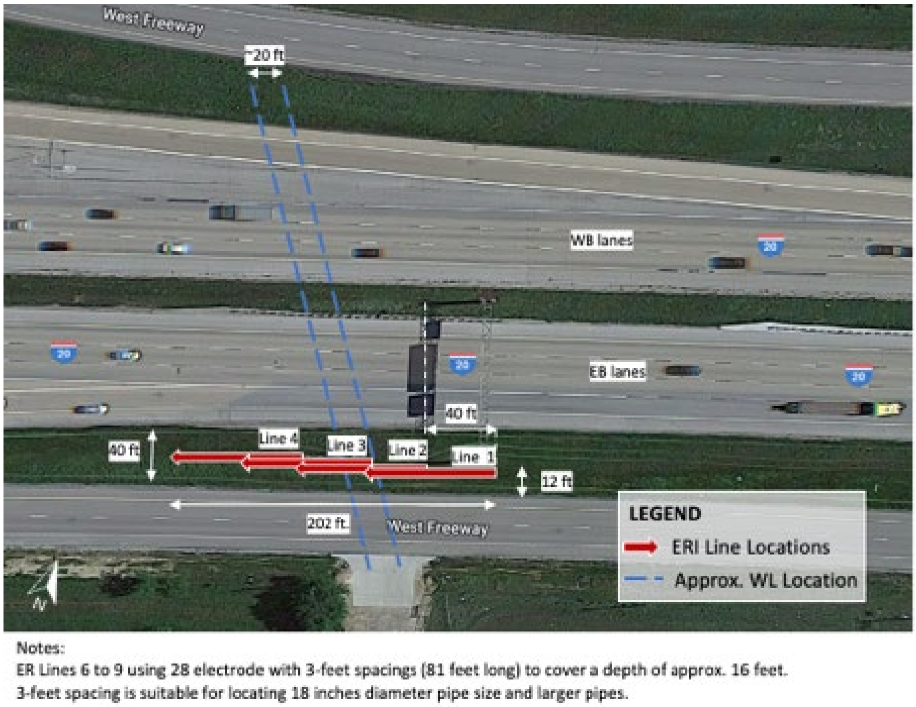


Figure 2.47. ERI data collection plan for IH 20 east of Farmer Rd

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 20 project on December 2nd, 2022. Four ERI surveys were conducted using 28 electrodes with 3 feet spacings. The ERI lines were performed continuously and overlapped with one another. Overlapping lines ensure no gaps between the lines, so the water lines are unlikely to be missed. Additionally, it increases the confidence level of the ERI findings since there are two series of data available for each location. Figure 2.48 shows the implementation of the ERI along IH 20 east of Farmer Rd. In a week before implementation, 0.49 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.48. Implementation of the ERI along IH 20 at the east side of Farmer Rd

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is 19.6 feet with 3 feet electrode spacing. The research team assessed the subsurface conditions and attempted to locate possible water lines using the obtained subsurface resistivity images.

Figure 2.49 shows the inverted resistivity profiles of Lines 1, 3, and 4. According to Figure 2.49, the subsurface earth materials consisted of three layers: a resistive layer at 6 feet depth which is bound by less resistive layers at the top and bottom. The less resistive areas with electrical resistivities of around 20 Ω.m, indicated in Figure 2.49a with dashed circles, show potential water line locations that are centered at 27 and 43 feet from the starting point (13 feet to the left and 3 feet to the right of the overhead signpost). However, according to the utility layout, the water lines are approximately located 38 and 58 feet to the right of the overhead signpost.

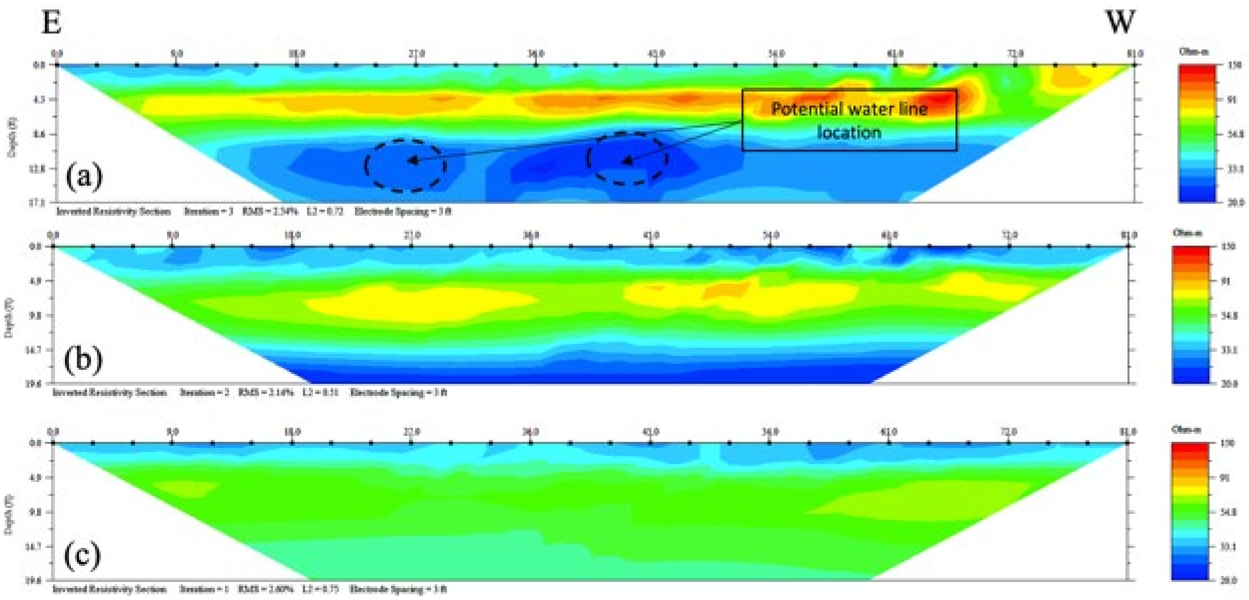


Figure 2.49. Subsurface resistivity image of (a) Line 1, (b) Line 3, and (c) Line 4

2.2.10 SH 352 at White Rock Creek

The study area is located along SH 352 at White Rock Creek in Dallas County, Dallas, Texas. Figure 2.50 shows the location of the study area on the Dallas map.

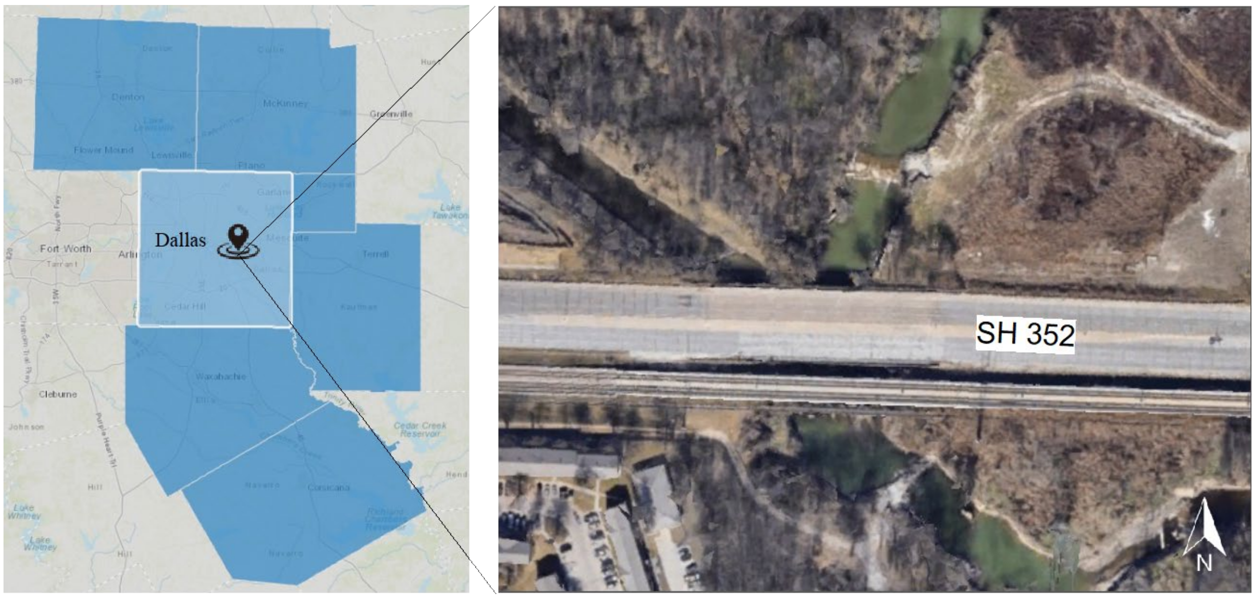


Figure 2.50. Location of SH 352 at White Rock Creek on the Dallas map

The study area is situated on Alluvium and Fluviatile terrace deposits composed of gravel, sand, silt, silty clay, and organic matter. Borehole data shows that the soil is composed of clay, clay with White Rock, and Austin Chalk at the bottom.

Data Collection

Figure 2.51 illustrates the ERI data collection plan for SH 352 project. This implementation aimed to determine the bridge pile's depth for the 2nd and 3rd bents from the west side of the bridge.

Notes:
ER Lines 1 and 2 using 28 electrode with 1.5-feet spacings (40.5 feet long) to cover a depth of approx. 8 feet.
ER Line 3 using 28 electrode with 2-feet spacings (54 feet long) to cover a depth of approx. 10 feet.

Figure 2.51. ERI data collection plan and borehole locations for SH 352 project

In coordination with the Dallas district contacts, the research team implemented the ERI plan for SH 352 project at White Rock Creek on October 7th, 2022. Three ERI surveys were conducted using 28 electrodes with 1.5- and 2-feet spacings. Figure 2.52 shows the implementation of the ERI for SH 352 at White Rock Creek. During 15 days before implementing the ERI surveys, no precipitation was observed at the study area (Weather Underground 2022).

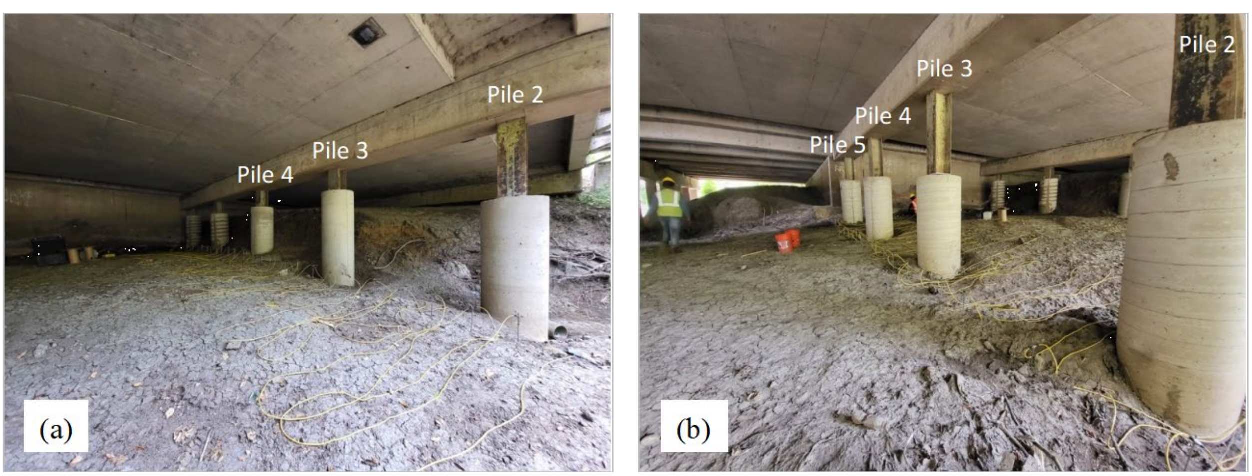


Figure 2.52. Implementation of ERI for SH 352 at White Rock Creek; (a) Line 1, (b) Line 2.

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained subsurface resistivity images, the minimum and maximum depths of investigation are 10 feet with 1.5 feet electrode spacing and 13 feet with 2 feet electrode spacing. The research team assessed the subsurface conditions and identified possible earth materials and depth of the bridge foundation using the obtained subsurface resistivity images, borehole results, and the developed equations for the TxDOT Project 0-7008.

Figure 2.53 illustrates the inverted resistivity profile of Line 1. The resistivity profile shows low variations through the profile with electrical resistivities in the range of 4 to 13.5 Ω.m, implying the presence of weak and wet earth materials. According to Figure 2.53, the relatively high electrical resistivity zones indicate the location of foundation piers (pier 2, 3, and 4). The electrical resistivity decreases to the background electrical resistivity of 8 Ω.m at a depth of approximately 5 feet. A saturated zone is observed at the bottom of the resistivity profile with electrical resistivities below 6 Ω.m.

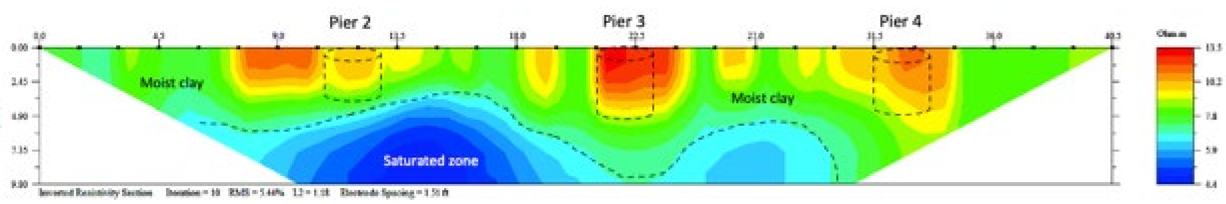


Figure 2.53. Subsurface resistivity image for Line 1

Figure 2.54 shows the extracted electrical resistivities for Line 1 under piers 2, 3, and 4. Based on Figure 2.54, the depths at which electrical resistivities drop significantly and reach background electrical resistivity were identified as the piers' depth (about 5 feet).

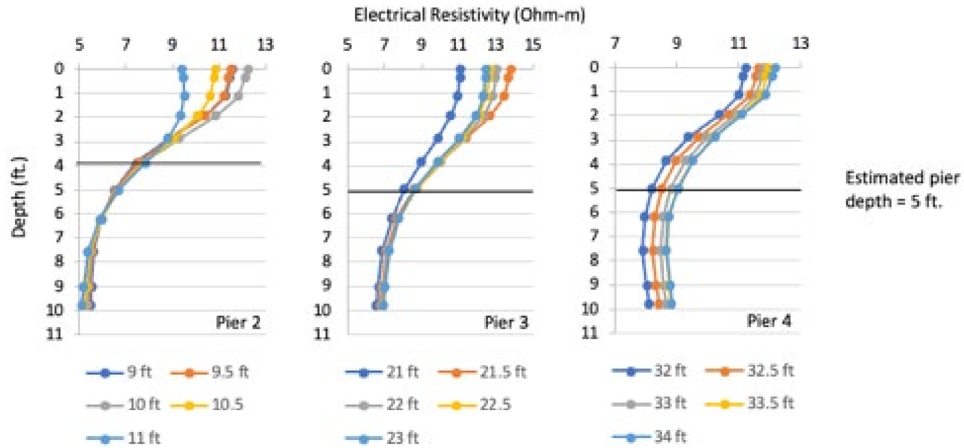


Figure 2.54. Extracted electrical resistivities for Line 1 under piers 2, 3, and 4

Figure 2.55 depicts the subsurface conditions along Line 2. The electrical resistivity varies from 3 to 21 through the depth of the profile. The resistivity image shows higher electrical resistivities (between 10 and 21 Ω.m) than the background where the foundation piers are located. At a depth of approximately 5 feet, there is a sudden drop in the electrical resistivities through the deeper depths, indicating the water table level.

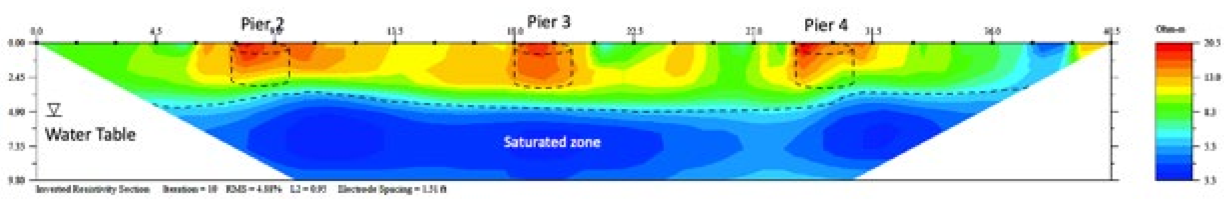


Figure 2.55. Subsurface resistivity image for Line 2

Figure 2.56 shows the extracted electrical resistivities for Line 2 under piers 2, 3, and 4. The piers' depth was determined by a sudden change in the electrical resistivities below the piers' location. According to Figure 2.56, this depth is about 4 feet.

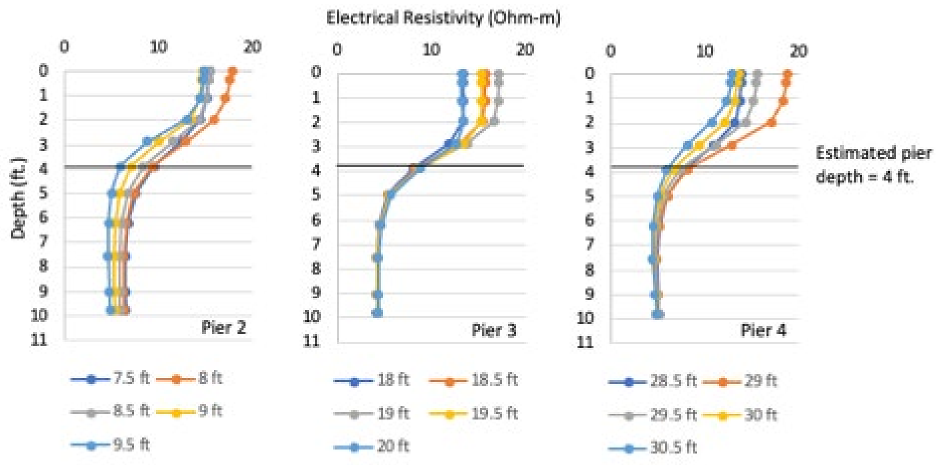


Figure 2.56. Extracted electrical resistivity for Line 2 under piers 2, 3, and 4

Figure 2.57 shows the inverted resistivity profile for Line 3. The resistivity profile shows high electrical resistivities at the location of pier 5 at Line 2 compared to the background electrical resistivity (8 Ω.m). Areas with high electrical resistivity at the top right and left corners are associated with the clays with White Rock. A saturated zone at the bottom of the profile signifies the water table, which is consistent with the findings from Line 2.

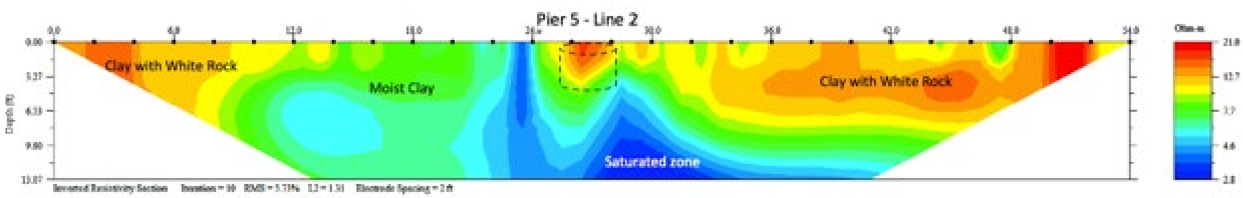


Figure 2.57. Subsurface resistivity image for Line 3

Although the resistivity images accurately illustrate the foundation piers' location, a large gap between the findings can be observed by comparing the piers' depth from ERI findings and bridge layout (see Appendix C). According to the bridge layout, the depth of foundation piers at bent 2 and 3 are about 10 feet long. The discrepancy between the results is mainly due to the high elevation of groundwater. The differentiation between the subsurface layers is challenging because the materials' electrical resistivity has slight variations in the saturated areas (Shahandashti et al., 2021; Hunt, 2005). It is interesting to repeat the tests during a wet season to compare the results and identify the optimal subsurface conditions yielding more accurate results in determining the foundation piers' depth.

2.2.11 Ronald Reagan Memorial Hwy (IH 20) – Site 1

The study area is located along Ronald Reagan Memorial Hwy in Parker County, Fort Worth, Texas. Figure 2.58 shows the location of the study area on the Fort Worth map.

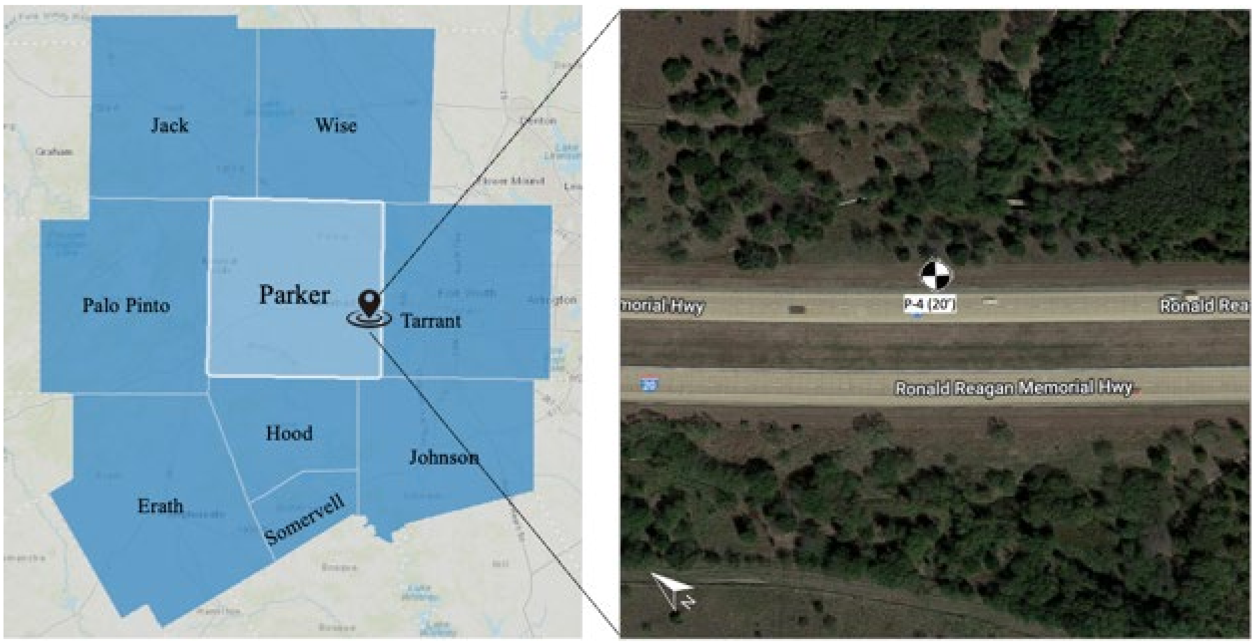


Figure 2.58. Location of Site 1 along Ronald Reagan Memorial Hwy on the Fort Worth map

The study area is situated in a region mapped with the Goodland Limestone with a thickness of about 90 feet. A geotechnical report for this project (documented in May 2022) shows lean and fat clays (CL and CH) with limestone fragments up to 20 feet. The plasticity indices range from 35 to 38. No groundwater was observed in the soil test boring at the site during drilling. Low concentrations of sulfate (up to 2,773 ppm) were reported at boreholes P-4. The boring log for this project is attached in Appendix A.

Data Collection

Figure 2.59 illustrates the ERI data collection plan and borehole location for Site 1 along Ronald Reagan Memorial Hwy. This implementation aimed to assess the sulfate concentration levels at the study area and determine critical zones prone to sulfate-induced heaving if any.

Notes:
ER Lines 1 to 3 using 28 electrode with 3-feet spacings (81 feet long) to cover a depth of approx. 20 feet.
Sulfate concentration was 2,773 ppm at a depth of approximately 4 feet at borehole P-4.

Figure 2.59. ERI data collection plan and borehole location for Site 1 along Ronald Reagan Memorial Hwy

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for Site 1 along Ronald Reagan Memorial Hwy on December 9th, 2022. Three ERI surveys were conducted using 28 electrodes with 3 feet spacings. The ERI lines were performed continuously and overlapped with one another. In addition, five soil samples were collected from multiple locations, as shown in Figure 2.60, to be tested in the laboratory. The borings were advanced to a maximum depth of 1 foot using an electric hand auger. Figure 2.60 shows the implementation of the ERI along Ronald Reagan Memorial Hwy and soil sample collection. In the first week of December 2022, 0.08 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.60. Implementation of the ERI along Ronald Reagan Memorial Hwy and soil sample collection

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is 19.6 feet with 3 feet electrode spacing. The research team assessed the subsurface conditions, identified possible earth materials, and evaluated sulfate concentration levels using the obtained subsurface resistivity images and borehole results.

Figure 2.61 shows the inverted resistivity imaging of Lines 1, 2, and 3. All resistivity images show similar subsurface conditions; a more resistive layer at the top 4 feet and a conductive layer beneath the top layer that extends to the bottom of the profile. The top resistive layer (electrical resistivities > 20 Ω.m) is associated with the moist to dry clays. The electrical resistivities around 5 Ω.m represent saturated clays. No critical sulfate concentration is indicated within 4 feet deep since the ERI and borehole results agree with each other.

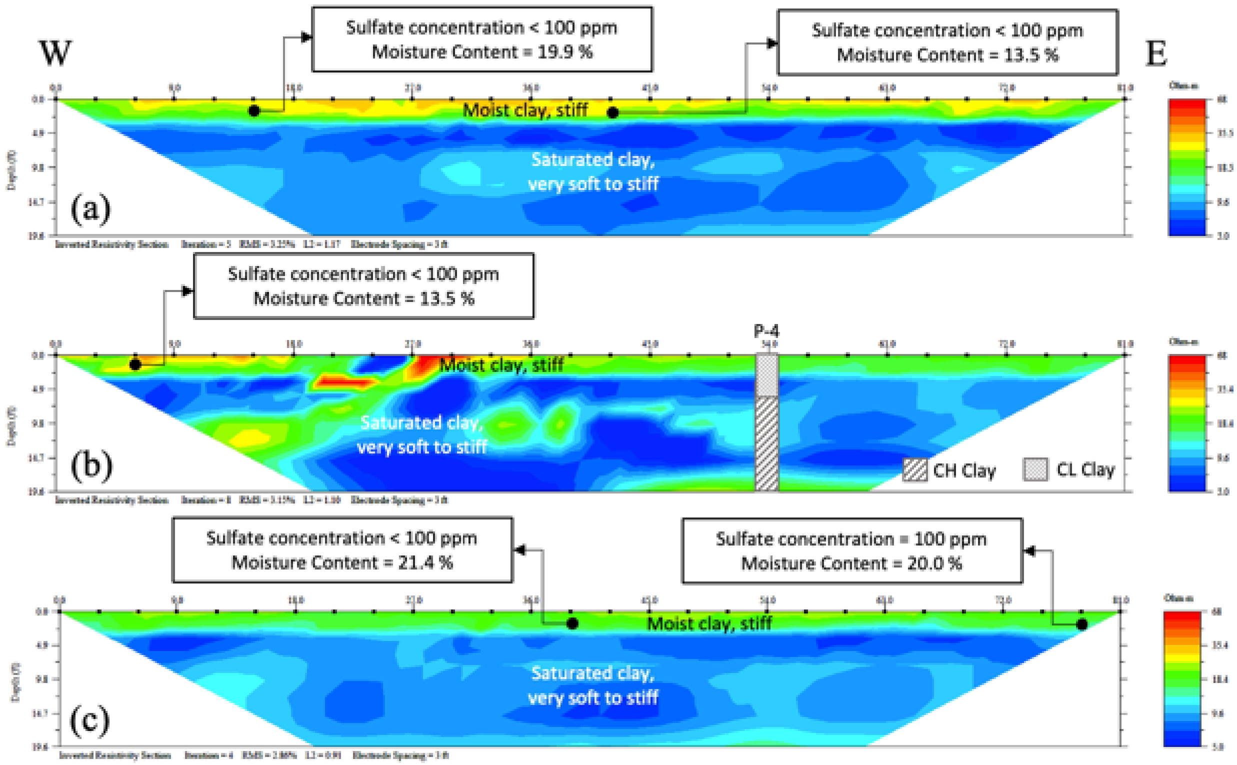


Figure 2.61. Subsurface resistivity image of (a) Line 1, (b) Line 2, and (c) Line 3

Laboratory Tests on Collected Samples from IH 20 (Site 1)

Five soil samples were collected from IH 20 (Site 1) to validate the ERI findings. The research team performed a colorimetric method based on TxDOT 145-E to obtain actual sulfate concentrations of the collected soil samples. Moisture contents of the soil samples were also determined according to ASTM D2216-90. The actual sulfate concentrations and moisture contents are presented in Table 2.5. According to Table 2.5, the measured sulfate concentrations were consistent with the ERI and borehole results.

Table 2.5. Summary of the laboratory tests of the collected samples from the IH 20 (Site 1) project in the Fort Worth district

Borehole No.	Soil Type	Depth (feet)	Sulfate Concentration (ppm)	Actual Moisture Content (%)
1	CL	1.5 – 2.5	Below 100	19.86
2	CL	1.5 – 2.5	Below 100	13.50
3	CL	1.5 – 2.5	Below 100	17.45
4	CL	1.5 – 2.5	Below 100	21.36
5	CL	1.5 – 2.5	100	20.00

2.2.12 Ronald Reagan Memorial Hwy (IH 20) – Site 2

The study area is located along Ronald Reagan Memorial Hwy in Parker County, Fort Worth, Texas. Figure 2.62 shows the location of the study area on the Fort Worth map.

Figure 2.62. Location of Site 2 along Ronald Reagan Memorial Hwy on the Fort Worth map

The study area is situated in a region mapped with Kiamichi Formation with alternating clay and limestone layers. The Kiamichi Formation's thickness is between 20 and 50 feet. A geotechnical report for this project (documented in May 2022) shows lean and fat clays (CL and CH) with limestone fragments up to 18 feet. Highly weathered shale with 2 feet thickness underlaid the CL and overlaid hard to very hard limestone. The plasticity indices range from 14 to 32. No groundwater was encountered in the soil test boring at the site during drilling. The boring log for this project is attached in Appendix A.

Data Collection

Figure 2.63 illustrates the ERI data collection plan and borehole location for Site 2 along Ronald Reagan Memorial Hwy. This implementation aimed to determine the water table depth.

Notes:
ER Line 4 using 56 electrode with 8-feet spacings (440 feet long) to cover a depth of approx. 88 feet.
Groundwater was not encountered at the boring B-1.

Figure 2.63. ERI data collection plan and borehole location for Site 2 along Ronald Reagan Memorial Hwy

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for Site 2 along Ronald Reagan Memorial Hwy on December 9th, 2022. One ERI survey was conducted using 56 electrodes with 8 feet spacing. Figure 2.64 shows the implementation of the ERI along Ronald Reagan Memorial Hwy. In the first week of December 2022, 0.08 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.64. Implementation of the ERI for Site 2 along Ronald Reagan Memorial Hwy

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is 104 feet with 8 feet electrode spacing. The research team assessed the subsurface conditions and identified a potential groundwater table using the obtained subsurface resistivity image and borehole results.

Figure 2.65 illustrates the inverted resistivity profile of Line 1. Two resistive zones are illustrated on either side of the resistivity profile, representing limestone, shale, and stiff clays. The resistive layers are bound with low electrical resistivity areas of about 5 Ω.m which are attributed to saturated earth materials at 10- and 20-feet depths. The conductive zone in the middle of the profile at 78 feet of depth indicates a possible groundwater table.

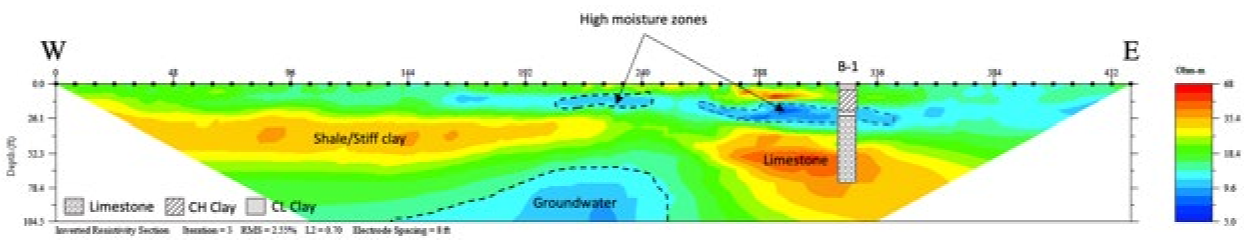


Figure 2.65. Subsurface resistivity image of Line 1

2.2.13 IH 35W at Railroad

The study area is located at IH 35W and railroad along the South freeway in Tarrant County, Fort Worth, Texas. Figure 2.66 shows the location of the study area on the Fort Worth map.

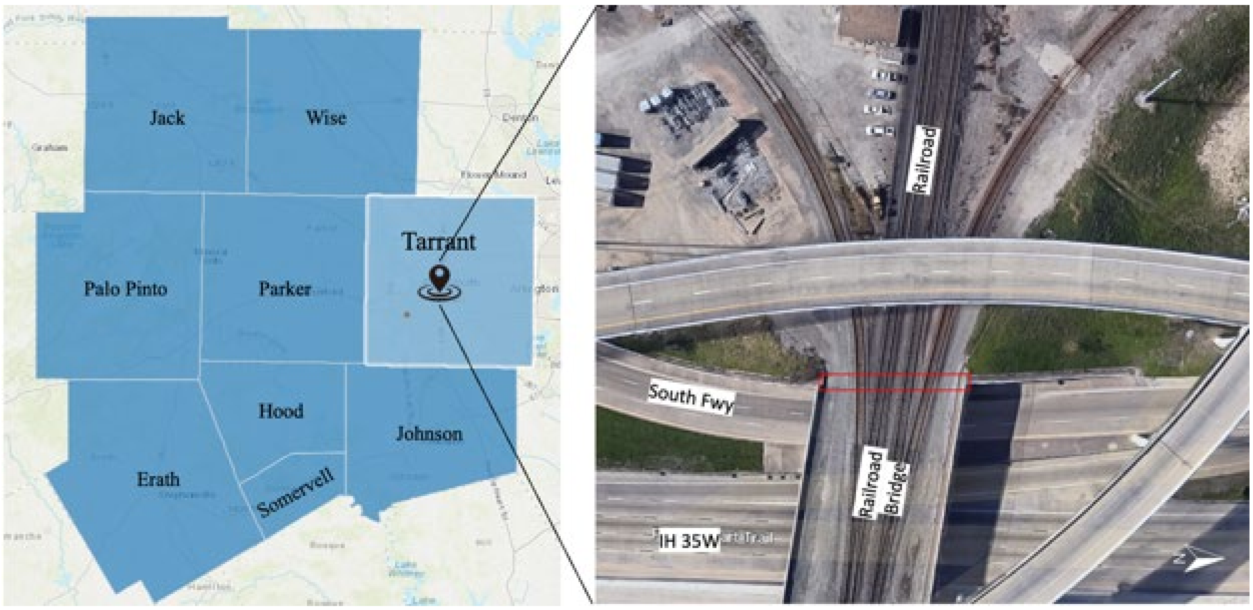


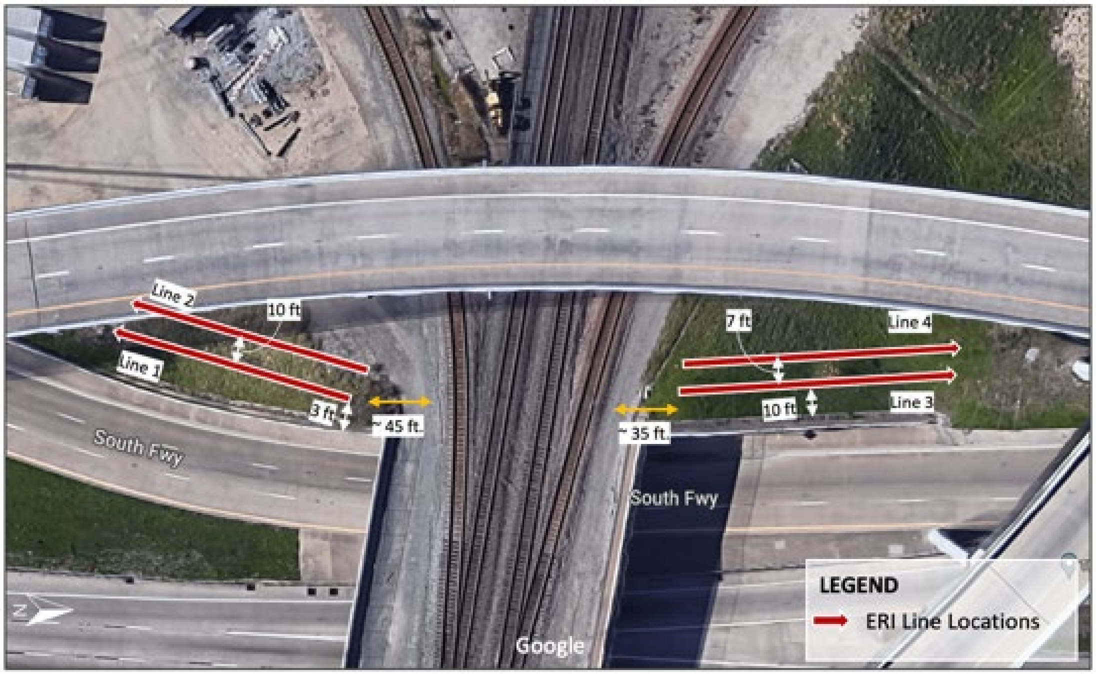
Figure 2.66. Location of the IH 35W and railroad intersection on the Fort Worth map

The study area is situated in a region mapped with Fort Worth Limestone and Duck Creek Formation with a thickness of 30 to 100 feet. Figure 2.67 shows the current conditions of the retaining wall beneath the bridge.

Figure 2.67. Current conditions of the retaining wall beneath the bridge

Data Collection

Figure 2.68 illustrates the ERI data collection plan for IH 35W at the railroad bridge. This implementation aimed to identify the subsurface conditions behind the retaining wall under the bridge and assess the source of leakage from the wall.



Notes:
ER Lines 1 to 2 using 28 electrode with 3-feet spacings (81 feet long) to cover a depth of approx. 16 feet.
ER Lines 3 to 4 using 28 electrode with 4-feet spacings (108 feet long) to cover a depth of approx. 22 feet.

Figure 2.68. ERI data collection plan at IH 35W and railroad

In coordination with the Fort Worth district contacts, the research team implemented the ERI plan for IH 35W and the railroad on February 20th, 2023. Four ERI surveys were conducted using 28 electrodes with 3- and 4-feet spacings. Figure 2.69 shows the implementation of the ERI along the South Freeway. In a week before the ERI implementation, 0.66 inches of precipitation were recorded at the site (Weather Underground 2022).

Figure 2.69. Implementation of the ERI at IH 35W and railroad; (a) Line 1 and (b) Line 3

Continuous Subsurface Resistivity Images

The research team processed the collected electrical resistivity data using EarthImager 2D software and generated continuous resistivity images of the subsurface. Due to the high difference between the starting and ending point elevations, the elevation data were extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling. Based on the obtained resistivity images of the subsurface, the maximum depth of investigation is around 30 feet with 3- and 4-feet electrode spacing. Note that the maximum depth of investigation decreases as the slope angle increases; with the same ERI line configuration, the depth of investigation is greater for a flat surface than for slopes. Using the obtained subsurface resistivity images, the research team assessed the subsurface conditions and identified problematic zones that cause leakage from the retaining wall.

Figure 2.70 illustrates the inverted resistivity profile of Lines 1 and 2 conducted on the south side of the railroad. According to the resistivity profiles, intermittent high resistive areas with electrical resistivities up to 320 Ω.m are present at the top 6 feet, indicating dry and relatively hard subsurface materials. Below that level, however, the resistivity profiles depict saturated subsurface conditions (shown with dashed lines), especially near the retaining wall on Line 1.

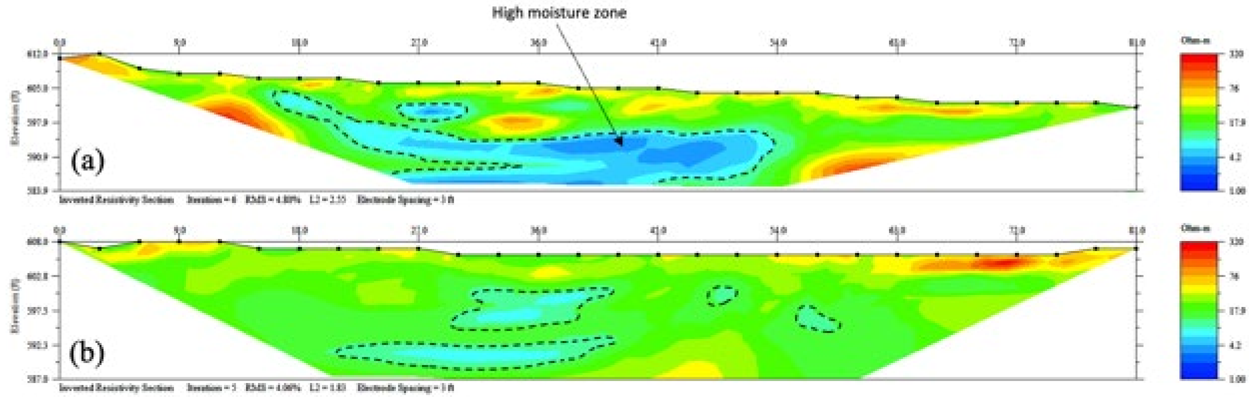


Figure 2.70. Subsurface resistivity images at the south side of the railroad (a) Line 1 and (b) Line 2

Similarly, Figure 2.71 shows high resistive areas at the top along Lines 3 and 4, representing dry and relatively hard materials. Less resistive areas with electrical resistivities below 10 Ω.m (saturated zones) are present at the depth of about 20 feet below the ground surface. Since high moisture zones are more than 10 feet deep, shallow slope failures are not a concern. In Line 3, near the retaining wall, the extent of less resistive zones is larger than in Line 4.

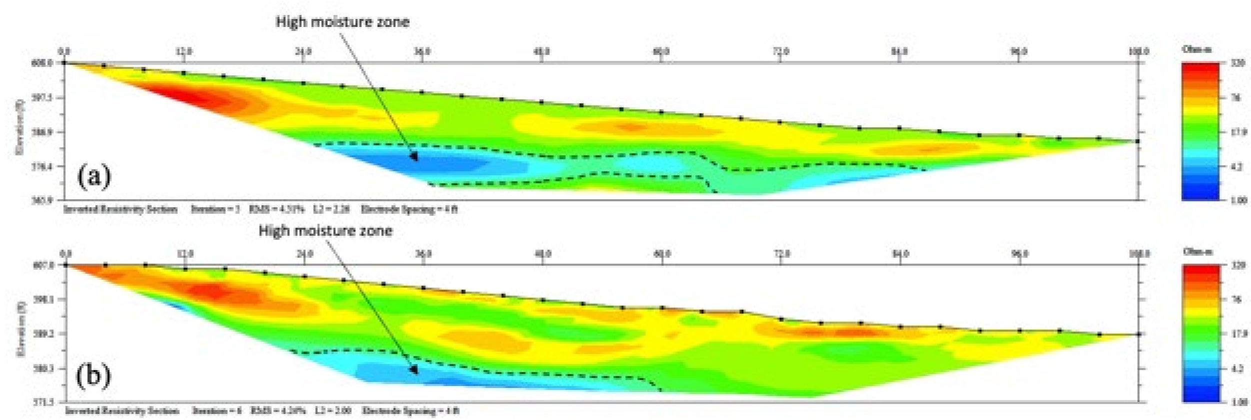


Figure 2.71. Subsurface resistivity images at the north side of the railroad (a) Line 3 and (b) Line 4

According to the resistivity profiles, the leakage from the retaining wall could be originated from the south side of the railroad due to the higher extent of less resistive zones in the south compared to the north side. Moreover, according to the depth of high moisture zones which are shallower on the south than on the north side, the water movement direction could be toward the north side.

2.3 Laboratory Experiments to Collect Data to Characterize the Relationship between Soil Sulfate Content and Electrical Resistivity Values

Based on the recommendations received during the meetings with the Fort Worth and Dallas district contacts, the research team designed a factorial experiment to assess the variability of soil electrical resistivity at different sulfate concentration levels. The impact of sulfate content on the soil electrical resistivity values was not investigated in the original research (i.e., TxDOT Project 0-7008). The research team analyzed the laboratory data and proposed an approach for characterizing sulfate concentration levels based on electrical resistivity imaging. Section 2.3.1 elaborates on the experimental design, laboratory electrical resistivity, and sulfate testing procedures. Section 2.3.2 presents the findings and results of the data analysis.

2.3.1 Design of Experiments

In practice, the potential risk of sulfate-induced heave is generally assessed based on some threshold levels of sulfate. The TxDOT has guidelines for stabilizing sulfate-rich soils and associates a low risk of sulfate-induced heave in soils with a sulfate concentration below 3000 ppm (TxDOT 2005). Conversely, the potential risk of sulfate-induced heave is high in soils with a sulfate concentration above 8000 ppm. There is a moderate risk of sulfate-induced heave in soils with a sulfate concentration between 3000 and 8000 ppm (Table 2.6).

Table 2.6. The associated risk of sulfate-induced heaving with sulfate concentration levels (TxDOT, 2005)

Sulfate concentration	Associated Risk of sulfate-induced heaving
Below 3000 ppm	Low
Between 3000 to 8000 ppm	Moderate
Above 8000 ppm	High

The research team designed a factorial experiment to measure the electrical resistivity of soil samples collected from the Fort Worth and El Paso districts for the TxDOT Project 0-7008 at different levels of sulfate concentration. The sulfate concentrations of soil samples were modified by adding calcium sulfate in 1,000 ppm increments to represent sulfate concentrations ranging from 0 to 12,000 ppm. Approximately 1.7 gm of calcium sulfate dissolved in water was added and mixed with the soil samples at each step. The soil samples were kept in an oven for 48 hours at a temperature of 140°F. The soils were then pulverized and prepared for the electrical resistivity tests. Since soil index properties such as moisture content and dry unit weight affect the soil electrical resistivity values (Shahandashti et al. 2021), the soil samples were mixed with different amounts of water (10%, 20%, 30%, and 40%) and compacted in a resistivity box with three different compaction efforts. The research team conducted 382 laboratory electrical resistivity tests at sulfate concentrations from 0 to 12,000 ppm (twelve laboratory electrical resistivity tests on each soil mixture).

Following the laboratory electrical resistivity tests, the sulfate concentrations of the soil samples were determined using a colorimetric method based on TxDOT 145-E. Figure 2.72 shows the laboratory electrical resistivity and sulfate tests.

Figure 2.72. Laboratory electrical resistivity and sulfate tests; (a) measuring 1.7 gm of calcium sulfate, (b) mixing the sulfate with water and soil samples, (c) keeping the soil samples in the oven for 48 hours, (d) performing laboratory electrical resistivity tests, (e) preparing the soil for sulfate testing, (f) measuring the sulfate concentration using colorimetric method.

2.3.2 Data Analysis and Results

Artificial Intelligence (AI) techniques have the potential to revolutionize designs, construction, and maintenance of the infrastructure systems by providing advanced analytics, automation, and predictive capabilities (Darghiasi et al. 2024; Zamanian et al. 2023a; Darghiasi et al. 2023a; Baral et al. 2022). Among the AI techniques, Random Forest (RF) is a popular supervised classifier that consistently offers the highest prediction accuracy compared to other models in the classification setting (Fernández-Delgado et al. 2014). The popularity of RF is primarily due to its capability to efficiently handle non-linear classification tasks (Zamanian et al. 2023a). RF is a collection of many classification trees. Each tree is trained using a bootstrapped sample of the training data, and at each node, the algorithm only searches across a random subset of the variables to determine a split. Results from each tree are aggregated to give a prediction for each observation. The generalization error always converges by increasing the number of trees in the model. The random forest is more robust than an individual decision tree to any changes in the input data and outliers in predictors (Breiman et al. 2017). Since each tree is an independent random experiment, the risk of overfitting is low (Youssef et al. 2016). Figure 2.73 illustrates the structure of a random forest model. There is no need to rescale, transform, or modify the resistivity data to grow a random forest and evaluate the model performance. In soil science, the random forest has been used for classifying soils with acid sulfate (Estévez 2020) and organic content (Pouladi et al. 2019), as well as determining soil classes (Gambill et al. 2016).

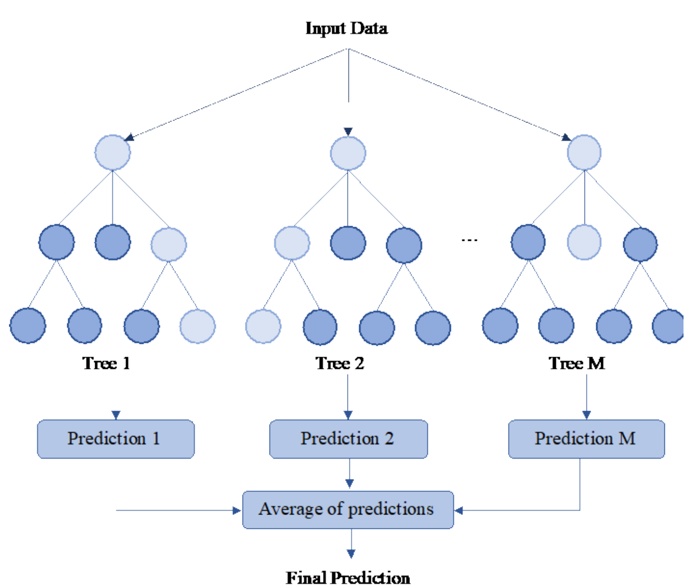


Figure 2.73. Random forest model structure

In this study, hyper-parameters of the random forest model were tuned based on a grid search. It is recommended to keep the number of trees between 64 to 128 to balance the model performance, processing time, and memory usage (Oshiro et al. 2012). The number of trees was fixed to 100 after the initial analysis. The research team used a minimum node size of one to grow the random forest (Hastie et al. 2009) for classifying sulfate concentration based on electrical resistivity and moisture content. A synthetic minority oversampling technique (SMOTE) was also used to compensate for the imbalanced class distributions (i.e., more samples of one class than others) and improve the performance of the random forest classifier while avoiding overfitting (Yao et al., 2013). The SMOTE uses an interpolation technique based on the existing observations to artificially generate new data for the minority class (Yao et al. 2013). The distribution of low and high sulfate concentrations was changed since they had lower observations in their groups compared to moderate sulfate concentration levels.

A comparison of the performance metrics (i.e., precision, recall, and F1-score) of the random forest model with balanced and imbalanced class distributions for training datasets is shown in Figure 2.74. The results show that balancing the class distributions increases the performance of the trained random forest model by 3 to 16% for different metrics, meaning that the number of positive predictions that are classified correctly from actual positive values is increased by balancing the class distributions. There is no change in the model recall on the moderate sulfate concentration level since the class distribution of moderate sulfate concentration remains the same after SMOTE. Overall, the accuracy of the random forest with balanced class distributions increased from 59.2 to 68.8%, indicating the significance of a balanced dataset in the model prediction performance.

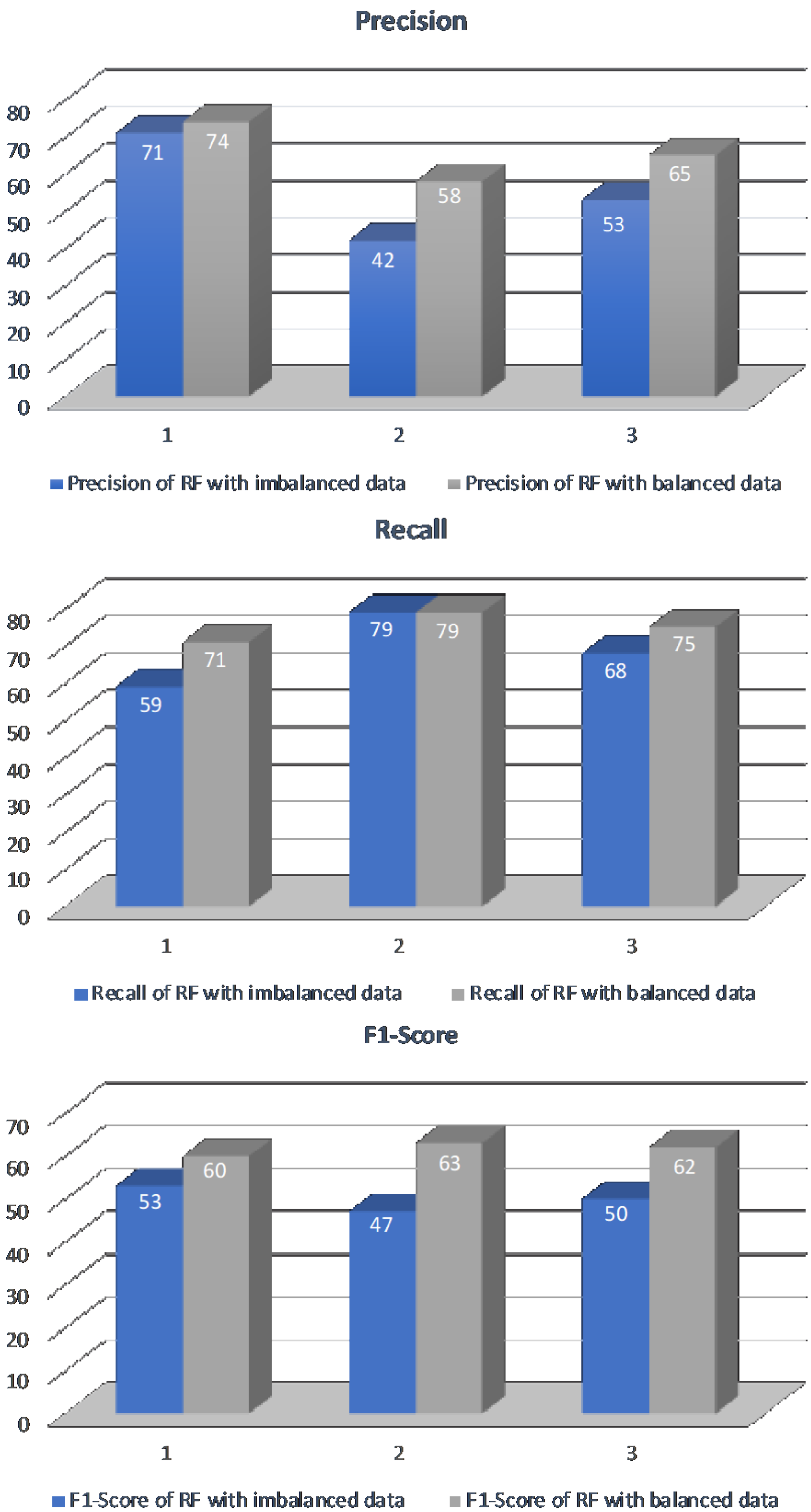


Figure 2.74. Comparison of performance metrics of random forest model with balanced and imbalanced class distributions of training datasets

CHAPTER 3 LESSONS LEARNED AND IMPLEMENTATION CHALLENGES

3.1 Introduction

This chapter provides recommendations and best practices for implementing the ERI in the field sites. The following sections elaborate on lessons learned from the implementation of the ERI manual on 13 projects in the Fort Worth and Dallas districts, as well as the implementation challenges and remedies to alleviate them.

3.2 Lessons Learned

This section summarizes lessons learned from the implementation of the ERI manual on 13 projects in the Fort Worth and Dallas districts. These findings are based on extensive testing to examine various applications (e.g., pavement, bridge, maintenance), geotechnical conditions, and operational environments to ensure a successful implementation of the ERI.

3.2.1 Lesson 1: Define Surveying Objectives and Review Project Information to Plan Properly

Overall understanding subsurface conditions before the survey helps in better planning to achieve surveying objectives. One of the most important lessons learned in this project is to review project information (e.g., geotechnical reports and layouts) and obtain general information before planning regarding groundwater table, buried manmade structures, and stratigraphy.

Understanding the groundwater table is essential in evaluating feasibility studies for identifying the depth of piles or critical sulfate concentration zones using the ERI. As reinforced concrete and steel structures have electrical resistivities close to saturated earth materials (Wang and Hue 2015; Kermani 2014), the identification of these structures within saturated soils, especially in saturated clays, is challenging and may lead to misleading interpretations. For example, Figure 3.1 shows an attempt to determine the bridge foundation piles within a saturated medium. Although the research team could delineate the piles' location in the shallow subsurface based on the resistivity contrast, they could not accurately identify the piles' depth due to the high groundwater table. Based on the information provided by the receiving agency, it was found that the embedded depths of the bridge foundation piles are about 10 feet which is inconsistent with the ERI findings.

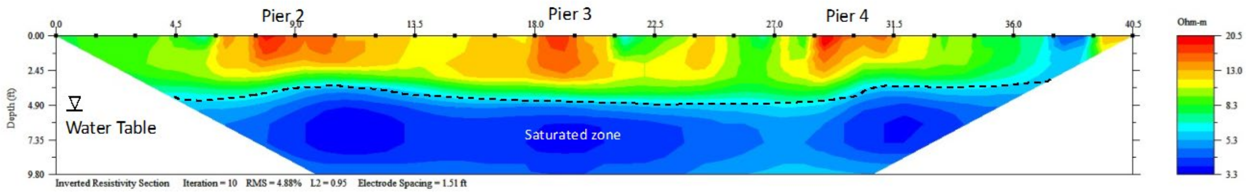


Figure 3.1. High groundwater table and determining the depth of the bridge foundation pile – SH 352 at White Rock Creek

Furthermore, understanding buried manmade structures or utilities in the vicinity of the study area allows the planner to design the ERI lines away from these structures to ensure a successful implementation of the ERI. It also allows the interpreter to make more reliable conclusions about the subsurface conditions in case the buried structures do not interfere with the readings. For example, Figure 3.2 shows an example of a potential buried object along a line at SH 170 at Westport Pkwy. As shown in Figure 3.2, the resistivity data are missing in the middle section of the ERI line which could be caused by an unknown object buried in the ground, leading to unreliable results.

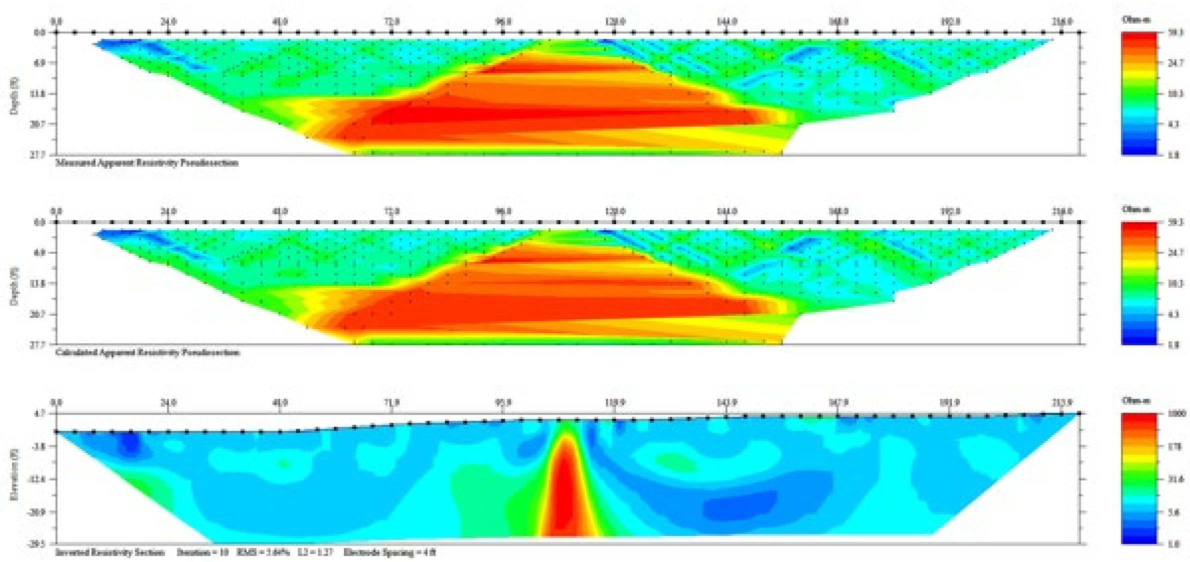


Figure 3.2. An unknown buried structure interfered with the data collection – SH 170 at Westport Pkwy

Moreover, understanding the subsurface layers results in more practical and feasible plans. For example, a highly resistive layer at the shallow subsurface (e.g., stony layer) could impede the transmission of the current through the depth, prohibiting a successful implementation of the ERI.

In conclusion, the research team recommends reviewing the project information before planning and surveying. If the project information is not available, it is always worthwhile to perform a preliminary test before actual surveying to obtain an overall insight into subsurface conditions. It is better to schedule the ERI tests near creeks, rivers, and lakes during dry seasons when the groundwater table is low, especially if planning to investigate buried reinforced concrete and steel structures.

3.2.2 Lesson 2: Monitor Weather Conditions before Surveying

Another important lesson learned from this project is to monitor weather conditions for a period of at least a week before implementing the ERI. It was found that the ERI technology cannot be used to effectively resolve anomalous subsurface conditions when performed right after heavy rains or persistent drought conditions.

Monitoring precipitations before implementing the ERI may lead to misleading interpretation, especially when performed to investigate low resistive anomalies such as critical sulfate concentration zones, buried reinforced concrete or steel structures, etc. For example, according to Figure 3.3, the research team differentiated two conductive areas to represent the potential water pipe locations at IH 20 East Farmers Rd. However, by comparing the project information with the ERI results (the approximate location of the water pipe is shown in Figure 3.3), it was found that the ERI results do not coincide with the actual locations of water pipes and these conductive areas perhaps are zones of high moisture. Therefore, any inferences solely based on the resistivity profiles regarding less resistive anomalies within a saturated medium could be misleading; the ERI results should be used along with additional project information.

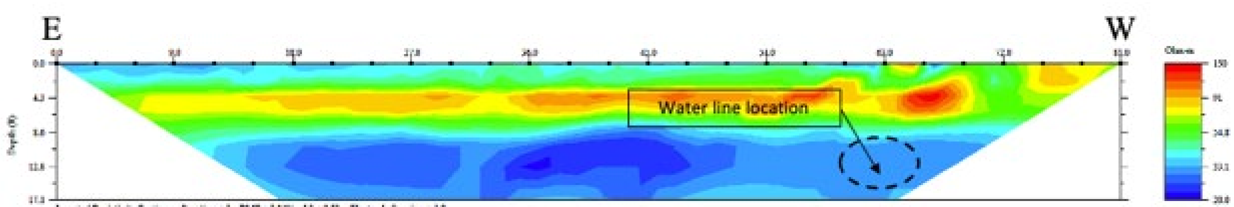


Figure 3.3. Saturated medium and investigating water line location – IH 20 East Farmers Rd.

On the other hand, surveying after persistent extreme heat (i.e., above 90˚F) and drought leads to noisy readings, resulting in inconsistent results with the field observations and subsurface conditions. For example, the background resistivity in Figure 3.4 shows slight variations with less resistive areas at the shallow subsurface which could represent high moisture zones. However, according to the historical weather data, no precipitation was recorded a month before surveys; the average temperature was 90˚F (the average maximum temperature was 99˚F) within a month before surveying. Besides, due to the extreme heat and dry conditions observed in the field site, the soil around the electrodes was wet to keep the electrode's contact resistance below the recommended threshold and perform the tests. Thus, the ERI results represent unrealistic subsurface conditions in the study area according to the weather data and visual observations, and any inferences about them should be used with caution.

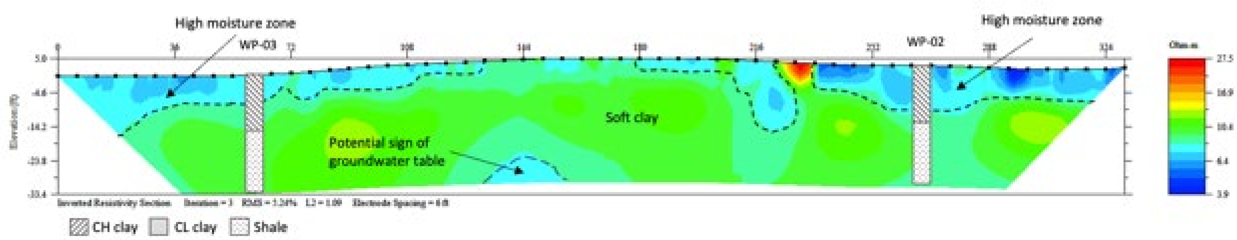


Figure 3.4. Inconsistency between resistivity profiles with field observations and subsurface conditions – SH 170 at Westport Pkwy

In conclusion, the research team recommends that the ERI tests be conducted at least a week after heavy rains, and after the first rain following persistent extreme heat. However, if there are time constraints, the results should be used with caution along with additional project information; the tests should be repeated later to validate the findings.

3.2.3 Lesson 3: Visit Proposed Field Sites before Planning

The purpose of an ERI survey and site conditions are critical factors in selecting a survey approach, electrode configuration, and needed operators – feasibility of ERI tests. Field sites, especially those under construction, should be pre-visited to allow planners to design proper ERI lines with respect to surveying objectives and eliminate surveyor confusion in implementing the plans. Although a preliminary assessment of site conditions using widely available tools such as Google Earth could be helpful, a comprehensive assessment of site conditions may not be achieved due to continuous construction activities. For example, the research team evaluated and planned for the ERI tests for two different field sites using Google Earth which led to changes in the plans due to unexpected conditions in the field sites, as shown in Figure 3.5. In some cases, surveying objectives may not be met due to significant changes in ERI plans, such as surveys conducted on SH 170 at N Main St. (Figure 3.5a). However, if the lines could be oriented differently, failure to implement the ERI lines as planned may not affect the survey results significantly, such as surveying for IH 35W at the railroad (Figure 3.5b).

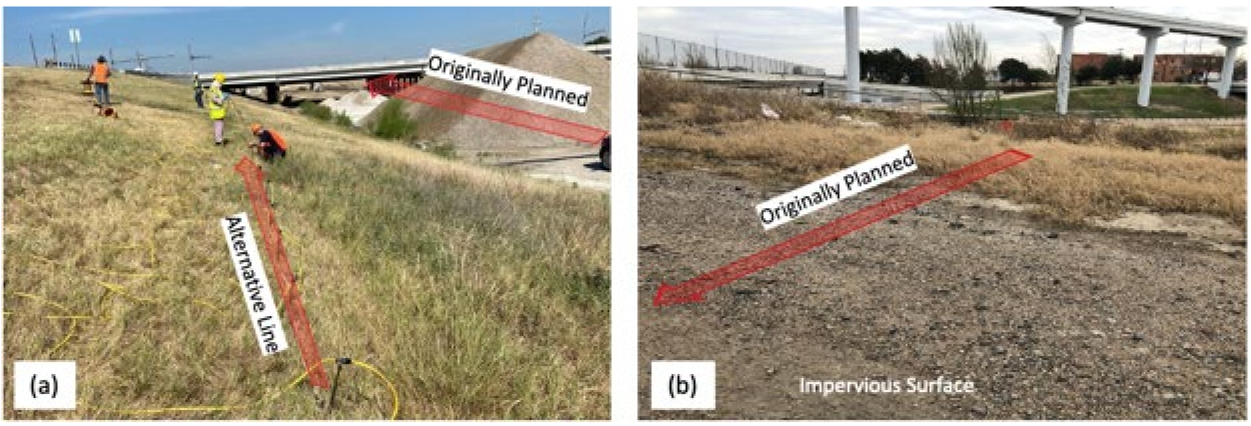


Figure 3.5. Failure to implement the ERI lines as planned; (a) SH 170 at N Main St. and (b) IH 35W at the railroad

3.2.4 Lesson 4: Coordinate Plans and be Flexible as Plans Change Due to Site's Constraints

An efficient and successful ERI survey depends on proper project management and coordination. The ERI planners must coordinate the purpose of surveying, their plans, and specific site conditions with surveyors. One of the important lessons learned from this project is that a lack of proper communication between the actors can lead to confusion, undesirable results, or even postponement of the scheduled surveys. The planner must prepare a detailed ERI plan considering the site's conditions and discuss it with the surveyors before the actual survey. The accessibility of the field sites should also be evaluated by the planner and communicated carefully with the surveyors. For example, the research team visited the study area at SH 352 at White Rock multiple times before the actual site visit to ensure the feasibility of the plan and assess safe access to reach the area. In addition, when a traffic control plan is required, the surveyor and traffic controller must work closely and coordinate their plans with each other to avoid delays in fieldwork.

Planning should be flexible to the site's constraints and surveyor needs when a preliminary evaluation of a field site is not feasible unless it harms the surveying objectives. The research team adjusted several plans (e.g., electrode configurations were changed and ERI lines were relocated) based on unexpected site conditions and time constraints.

3.2.5 Lesson 5: Link Geotechnical Reports, Layouts, and Visual Observations with ERI Results

The ERI technology, like all other geophysical methods, provides non-unique results and the findings from surveys are specific to the geology and site conditions. Therefore, a complete assessment of subsurface conditions can be accomplished when information from previous studies (e.g., stratigraphy, geological and hydrological models of the site, and site topography) are combined and assessed alongside electrical resistivity data. This information helps validate the ERI results and obtain additional reliable information between the boreholes.

For example, geotechnical reports enable interpreters to identify subsurface layers and anomalies between the boreholes more accurately. Since many factors affect the electrical resistivities of earth materials, the subsurface conditions cannot be assessed properly if relying solely on the ERI data. Figure 3.6 shows how borehole information helps to resolve the high resistive area on the left side of the profile for IH 30 at Mary's Creek.

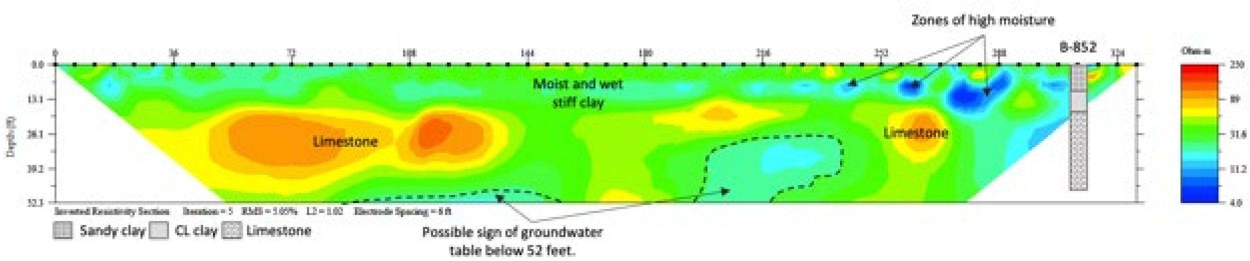


Figure 3.6. Borehole information is used as a guide to obtain additional information – IH 30 at Mary's Creek

If the previous studies are insufficient, sampling and testing might be needed at a few locations for specific applications (i.e., in determining the sulfate concentration levels) to validate the ERI results and avoid misleading interpretations. For example, critical sulfate concentrations were reported in Cedar Hill State Park at some locations from the previous studies. However, there was no additional information on the area where the ERI test was performed (Figure 3.7). Although the resistivity image shows low resistive zones in the shallow subsurface that could represent high sulfate concentration zones, the laboratory testing results indicated that these low electrical resistivities are associated with the presence of other soluble salts than sulfate.

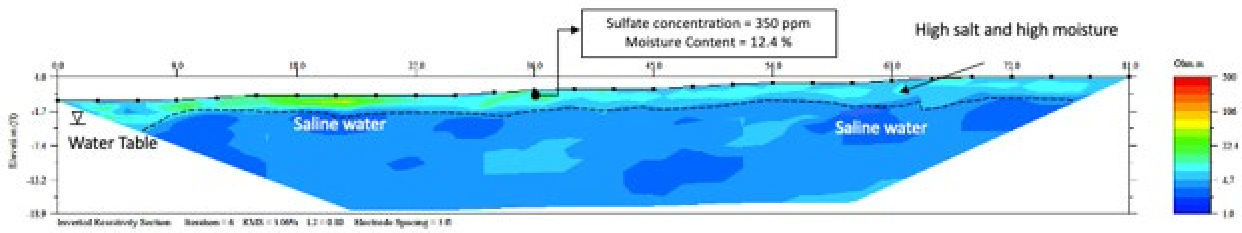


Figure 3.7. Necessity of ground truth information – Cedar Hill State Park

Hence, the research team recommends that the ERI results be assessed and interpreted along with previous studies to make reliable information about the site conditions. Samplings and testing may be required to validate the ERI findings in the absence of previous studies and if the surveying objective requires it.

3.2.6 Lesson 6: Account for Surface Unevenness in Data Processing

Ground surface unevenness should be considered in the data processing, especially for locations with high elevation differences between the starting and ending points such as slopes. The elevation data could be extracted from Google Earth at the approximate locations of the ERI lines and be imported to the EarthImager as a terrain file to generate resistivity images that are most representative of the subsurface conditions. For example, Figure 3.8 depicts differences between two resistivity images for a line at IH 35W at the railroad with and without elevation data. Although both profiles show similar patterns, consideration of slope geometry provides more reliable and accurate information about the extent of subsurface anomalies.

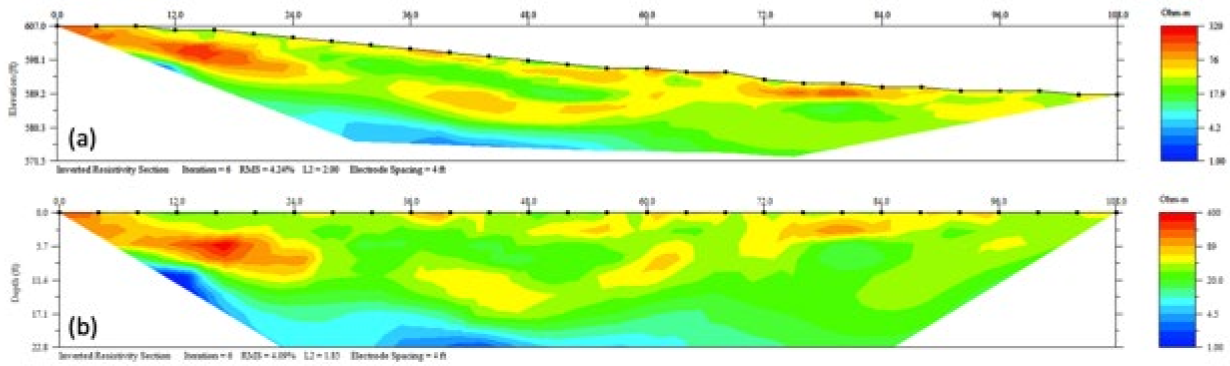


Figure 3.8. Importance of creating terrain files for slopes; (a) using elevation data and (b) without elevation data

Terrain files are created using simple text editors that represent ground elevations at the corresponding electrode locations. An example of a terrain file used for the EarthImager software program is shown in Figure 3.9.

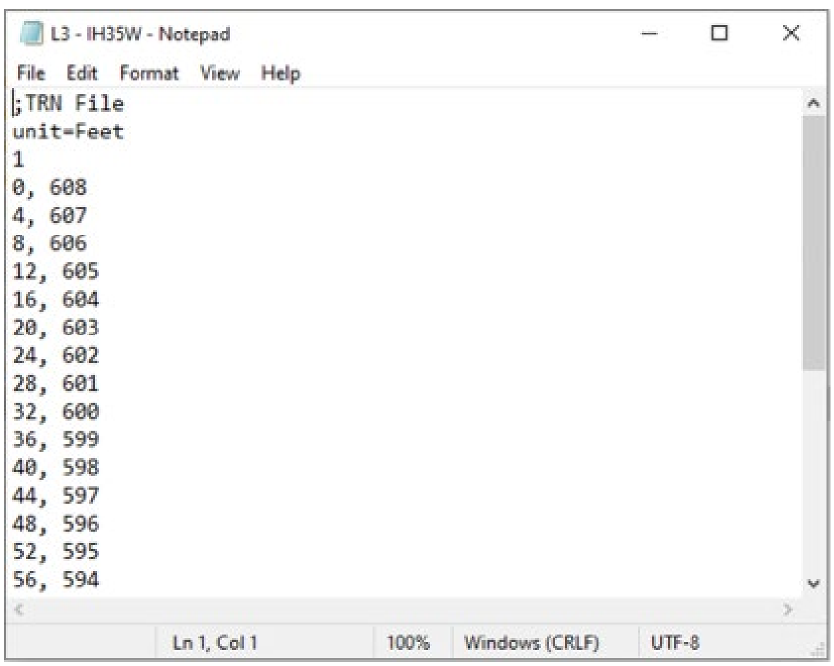


Figure 3.9. Example of a terrain file readable by EarthImager program

3.3 ERI Implementation Challenges

Table 3.1 summarizes the implementation challenges resulting from adverse geotechnical conditions and operational environments. It also presents remedies to alleviate such challenges for the receiving agency derived from the gained experience and lessons learned from implementing the ERI on real projects.

Table 3.1. ERI implementation challenges, possible causes, and remedies

Challenges/Problems	Possible Cause(s)	Remedies
High contact resistance	- Inadequate electrical contact to transfer the current into the ground.	- Fixing the electrode-cable connections. - Pushing the loosely placed electrodes further into the ground. - Using water, bentonite, and water-saturated sponges around the electrodes in dry, permeable, and rocky surfaces. - Using two or more electrodes in parallel with the electrodes with high contact resistance.
Electrode's placement	- Stiff surfaces such as concrete, asphalt, etc. - Dry surface materials. - Muddy and saturated surface materials.	- Drilling the surface at the electrode's location before surveying. - Waiting for a few days to allow the surface moisture to evaporate.
Short-circuiting of the measured current	- Proximity to cultural interferences such as buried utilities or buried metal objects. - Effects of natural noises such as natural earth currents.	- Improving signal-to-noise ratio by increasing the magnitude of the current or using a proper electrode configuration for noisy areas. - Using smaller electrode spacings with shorter cables.
Polarization	- Heterogeneity in electrical properties of earth materials.	- Experimenting with different electrode configurations,

		modifying line location, or magnitude of current to improve the signal-to-raise ratio.
Malfunctioning of equipment	- Uncalibrated equipment. - Extreme weather conditions.	- Conducting routine equipment inspection, maintenance, and calibration as needed. - Avoiding surveying in extreme heat/cold weather.
Site accessibility constraints	- Limited/Isolated areas. - Permits required.	- Performing feasibility studies and assessing the study areas before planning and actual surveying to finding safe access. - Coordinating and obtaining required permits to access the site before surveying.
Unexpected delays	- Specific site conditions. - Lack of expertise and knowledge of actors. - Lack of a clear plan. - Miscommunication between different actors.	- Visiting the study areas before actual surveying. - Assigning specific tasks to different actors and defining their responsibilities. - Using qualified and trained actors for different tasks. - Reviewing plans with different actors before actual surveying.

Addressing these challenges often requires a combination of technical knowledge, experience, and careful planning. Chapter 5 describes proper project planning and management that are imperative to ensure a successful implementation of the ERI manual.

CHAPTER 4 CASE STUDIES

4.1 Introduction

This chapter presents five case studies to illustrate the successful implementation of ERI for different types of projects in the TxDOT Fort Worth and Dallas districts. The final case studies for distribution among the potential TxDOT districts are presented in the following section.

4.2 Developed Case Studies

Out of the 13 projects in the Fort Worth and Dallas districts, the research team chose five to develop case studies for illustrating the successful implementation of the ERI manual for different applications. These case studies were distributed among potential TxDOT districts through targeted emails to related personnel to introduce the ERI technology and disseminate the knowledge for technology deployment (refer to Appendix D).

4.2.1 ERI for Mapping Sulfate Concentration Zones

This implementation aimed to map sulfate concentration levels at the study area and determine the critical zones prone to sulfate-induced heaving.

Location

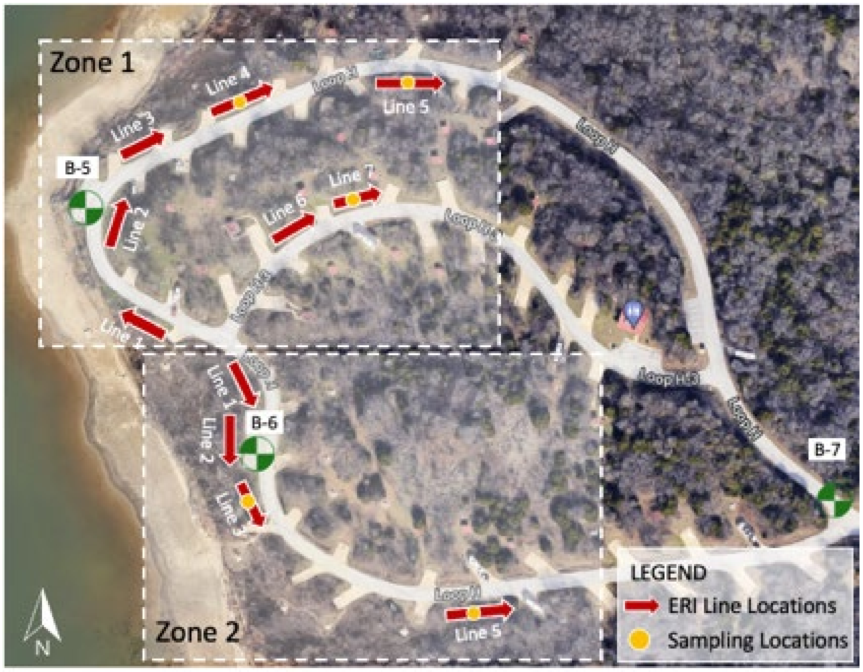
The study area is located along Eagle Ford and Shady Ridge loops in Dallas County, Dallas, Texas.

General Site Information

The study area is situated in a region mapped with the Eagle Ford formation and is bound by Joe Pool Lake to the west. The Eagle Ford formation consists of shale, siltstone, and limestone and has an estimated thickness of 300 to 400 feet in north Texas. The existing asphalt pavement consists of a layer of dense crushed limestone (<1.5 feet depth) at the shallow surface. This layer is underlaid by stiff to hard, fat (CH) and lean (CL) clays extended to a depth of 20 feet. The plasticity index ranges from 14 to 45. Sulfate concentration is up to 22,080 ppm at boreholes B-5 and B-6. No groundwater was encountered. No precipitation was observed within 15 days before implementing the ERI surveys at the study area.

ERI Line Configurations

Eleven ERI surveys were conducted using 28 electrodes with 2- and 3-feet spacings. Figure 4.1 illustrates the ERI data collection plan and borehole locations for Cedar Hill State Park. In addition, six soil samples were collected from multiple locations, as shown in Figure 4.1, to be tested in the laboratory.



Notes:
Three ERI lines (Line Z1-L4, Z1-L5, and Z2-L5), using 28 electrode with 3-feet spacings (81 feet long) to a depth of 15 feet.
Other ERI lines, using 28 electrode with 2-feet spacings (54 feet long) to a depth of 10 feet.

Figure 4.1. ERI data collection plan and borehole locations for Cedar Hill State Park

Figure 4.2 shows the implementation of the electrical resistivity imaging at Cedar Hill State Park and soil sample collection.

Figure 4.2. Implementation of ERI for Cedar Hill State Park; (a) Line 1 in Zone 1, (b) Line 2 in Zone 2, (c) Line 2 in Zone 2, and (d) soil sampling.

The Results

Figures 4.3 and 4.4 show examples of inverted resistivity profiles (Lines 2 and 7 in Zone 1 in Figure 4.1) generated by EarthImager.

Figure 4.3 illustrates the inverted resistivity profile of Line 2 in Zone 1. The borehole profile is also shown in the approximate borehole location on the resistivity image. Borehole B-5 at a 14 feet distance shows a layer of crushed limestone at the top, which is underlaid by stiff to very stiff clays up to a depth of 20 feet. On the other hand, the resistivity image shows low variations in the electrical resistivity between 1 and 50 Ω.m through the length and depth of the profile, indicating the existence of similar earth materials. The inconsistencies between the observations imply that high moisture and sulfate concentration levels exist in the shallow subsurface; note that the typical values of electrical resistivity for crushed limestone are larger than 50 Ω.m. It is worth mentioning that soluble sulfate in soils can significantly decrease the resistance of earth materials to a flow of electric currents. In other words, the electrical resistivity decreases as the soluble sulfate in the soil increases. The borehole result also shows a sulfate concentration of 22,080 ppm at a depth of 1.2 feet. A zone with relatively higher electrical resistivities (between 30 and 50 Ω.m) at the top left corner of the profile can be attributed to the soils with sulfate concentrations below 8000 ppm. The electrical resistivities below 3 Ω.m are attributed to saline water (water with high soluble salts).

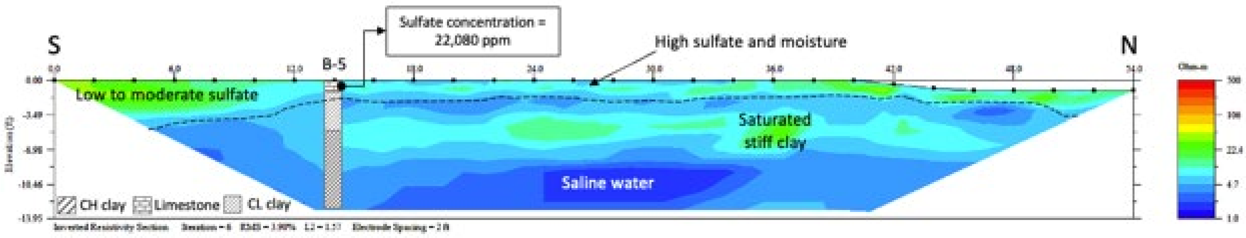


Figure 4.3. Subsurface resistivity image of Line 2 in Zone 1

Figure 4.4 illustrates the inverted resistivity profiles for Line 7 along Loop H-3 in Zone 1. Figure 4.4 shows three layers in the subsurface: a resistive layer at the top with electrical resistivities >60 Ω.m (crushed limestone), a transition layer with electrical resistivities of about 30 Ω.m, and a conductive layer with electrical resistivities <9 Ω.m. A sharp drop in the electrical resistivities through the depth indicates the water table level at approximately 8 feet below the ground surface. The low electrical resistivities (below 3 Ω.m) are associated with saline water (water with high soluble salts). No evidence of high sulfate concentration is observed through the length of the profile up to a depth of 3 feet However, there is a potential risk of the movement of salts from the underlying water-saturated layer to the top layer due to capillary rise during the dry season. The results of laboratory tests confirm that the subsurface earth materials contain low water and sulfate concentrations at a 24 feet distance.

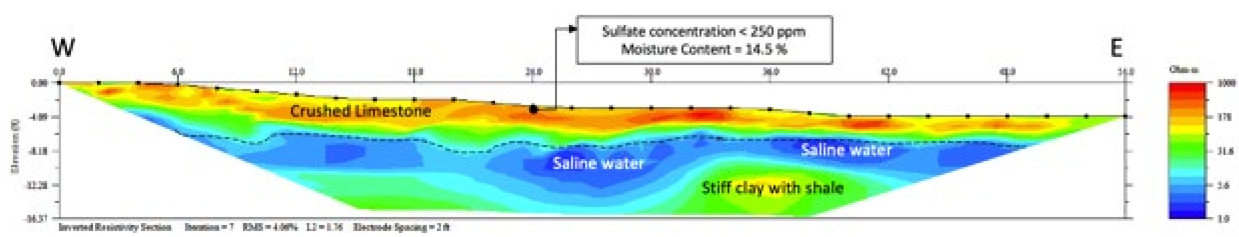


Figure 4.4. Subsurface resistivity image of Line 7 in Zone 1

Lessons Learned

As shown in Figure 4.5, a map of sulfate concentration can be generated by continuous measurement and analyzing the resistivity images to identify potential zones with a risk of sulfate-induced heaving. As indicated in Figure 4.5, the extent of critical sulfate concentration zones along Loop H goes beyond zone 1 and 2 limits. However, there is a low risk of sulfate-induced heaving towards Loop H-3.

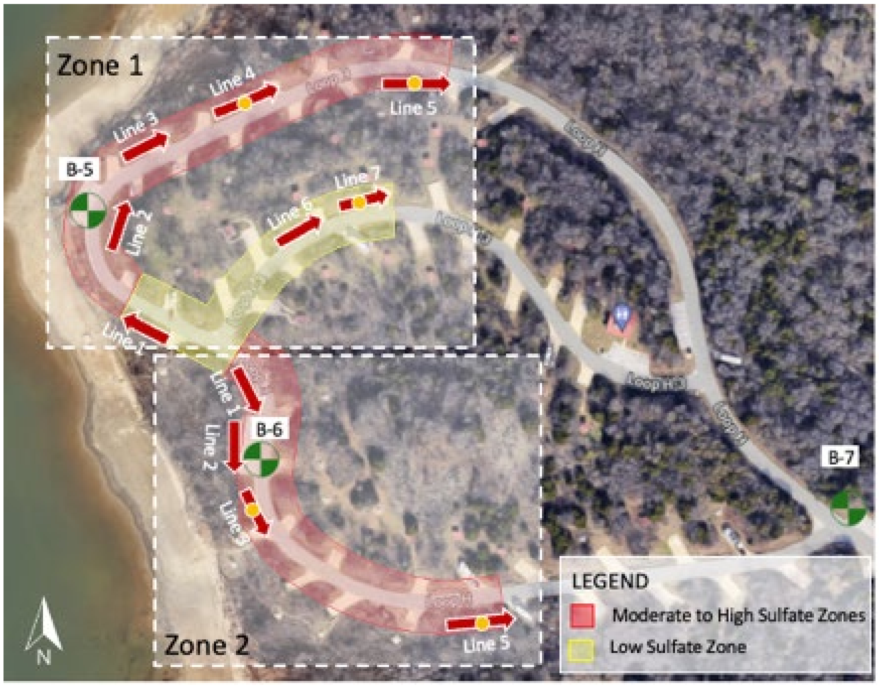


Figure 4.5. Overview of the extent of critical zones with the risk of sulfate-induced heaving

It is expected that the findings from the ERI will help TxDOT in decision-making by providing a comprehensive evaluation of sulfate concentration levels. The sulfate concentration maps assist in determining roadway segments that are unlikely to suffer from sulfate-induced heaving to eliminate unnecessary site investigations that are costly and time-consuming. The sulfate concentration maps also help in diagnosing areas that may contain critical sulfate concentrations to mitigate pavement failures due to inadequate site information (Zamanian et al. 2023).

4.2.2 ERI for Delineating Groundwater Table

This implementation aimed to delineate the groundwater table at the study area and identify the recharge zones.

Location

The study area is located along Ronald Reagan Memorial Hwy in Parker County, Fort Worth, Texas.

General Site Information

The study area is situated in a region mapped with Kiamichi Formation with alternating clay and limestone layers. The Kiamichi Formation's thickness is between 20 and 50 feet. The subsurface is composed of lean and fat clays (CL and CH) with limestone fragments up to 18 feet. Highly weathered shale with 2 feet thickness underlaid the CL and overlaid hard to very hard limestone. The plasticity index ranges from 14 to 32. No groundwater was encountered in the soil test boring at the site during drilling. In the first week of December 2022, 0.08 inches of precipitation were recorded at the site.

ERI Line Configurations

One ERI survey was conducted using 56 electrodes with 8-feet spacings to penetrate to a depth of 88 feet. Figure 4.6 illustrates the ERI data collection plan and borehole location along Ronald Reagan Memorial Hwy.

Notes:
ER Line 1 using 56 electrode with 8-feet spacings (440 feet long) to cover a depth of approx. 88 feet.
Groundwater was not encountered at the boring B-1.

Figure 4.6. ERI data collection plan and borehole location along Ronald Reagan Memorial Hwy

Figure 4.7 shows the implementation of the electrical resistivity imaging along Ronald Reagan Memorial Hwy.

Figure 4.7. Implementation of the ERI along Ronald Reagan Memorial Hwy

The Results

Figure 4.8 illustrates the inverted resistivity profile of Line 1. Two resistive zones are illustrated on either side of the resistivity profile, representing limestone, shale, and stiff clays. The resistive layers are bound with less resistive areas with electrical resistivities of about 5 Ω.m. These zones are associated with the saturated earth materials and indicate the presence of potential recharge zones (where water infiltrates the subsurface and replenishes groundwater resources) centered at 10 and 20 feet depths. The conductive zone in the middle of the profile at 78 feet depth indicates a potential groundwater table.

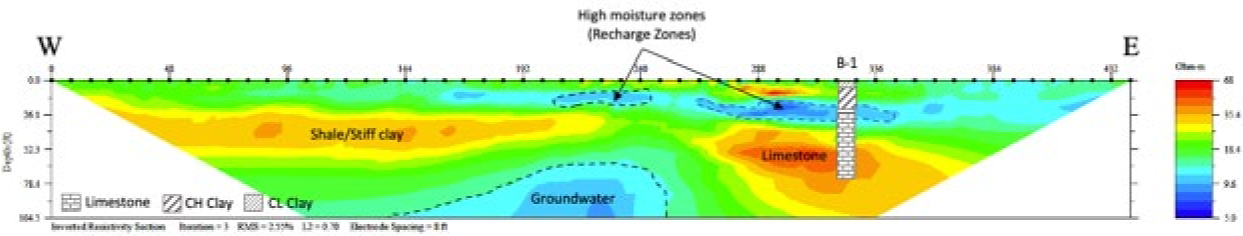


Figure 4.8. Subsurface resistivity image of Line 1

Lessons Learned

The ERI provides a continuous image of the subsurface using which distribution of high moisture content zones can be comprehended; the potential groundwater table can be identified by less resistive areas (electrical resistivities of below 10 Ω.m) that extend down to the bottom of the resistivity images. It is expected that the ERI will enable TxDOT to identify potential groundwater table levels and recharge zones between boreholes and incorporate the ERI findings into design considerations by continuously assessing site characteristics.

4.2.3 ERI for Inspecting Retaining Walls

This implementation aimed to assess the subsurface conditions behind the retaining wall at the study area and identify the study area drainage condition.

Location

The study area is located at IH 35W and railroad along the South freeway in Tarrant County, Fort Worth, Texas.

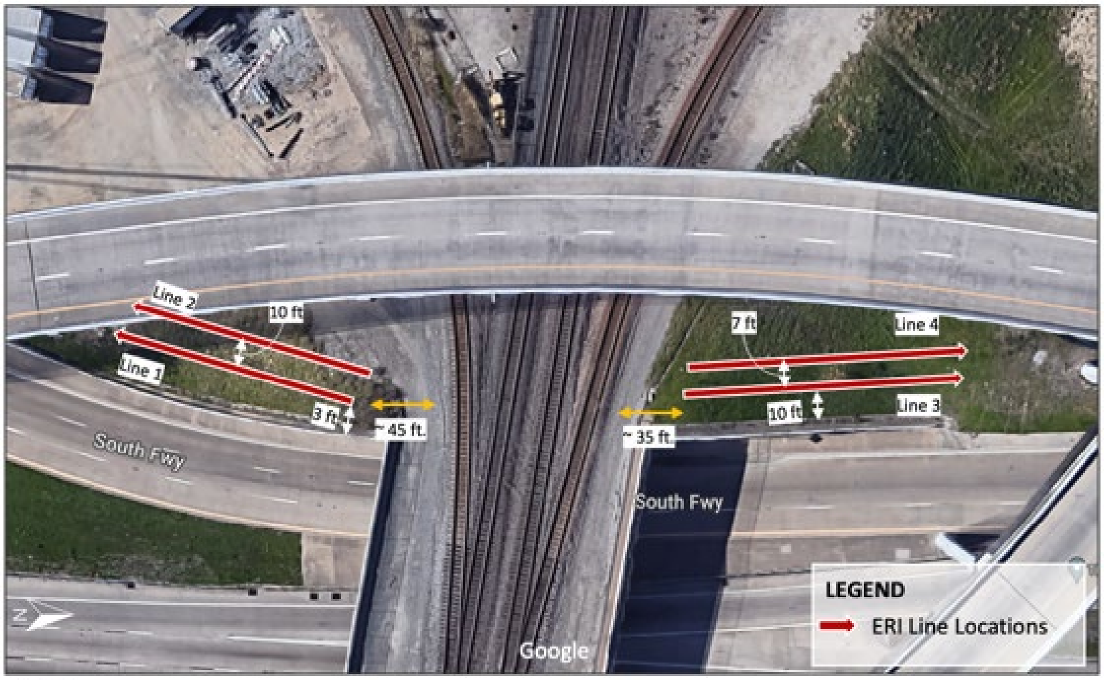
General Site Information

The study area is situated in a region mapped with Fort Worth Limestone and Duck Creek Formation with a thickness of 30 to 100 feet. Figure 4.9 shows the current conditions of the retaining wall beneath the railroad bridge. In a week before the ERI implementation, 0.66 inches of precipitation were recorded at the study area.

Figure 4.9. Conditions of the retaining wall beneath the bridge at the time of surveying

ERI Line Configurations

Four ERI surveys were conducted using 28 electrodes with 3- and 4-feet spacings. Figure 4.10 illustrates the ERI data collection plan for IH 35W at the railroad bridge.



Notes:
ER Lines 1 to 2 using 28 electrode with 3-feet spacings (81 feet long) to cover a depth of approx. 16 feet.
ER Lines 3 to 4 using 28 electrode with 4-feet spacings (108 feet long) to cover a depth of approx. 22 feet.

Figure 4.10. ERI data collection plan at IH 35W and railroad

Figure 4.11 shows the implementation of the electrical resistivity imaging along the South Freeway at the railroad.

Figure 4.11. Implementation of the ERI at IH 35W and railroad; (a) Line 1 and (b) Line 3

The Results

Figures 4.12 and 4.13 show examples of inverted resistivity profiles (Lines 1 and 2) generated by EarthImager. Due to the high difference between the starting and ending point elevations, the elevation data were extracted from Google Earth and imported into the software as a terrain file to consider the ground surface's unevenness in the modeling.

According to Figure 4.12, intermittent high resistive areas with electrical resistivities up to 320 Ω.m are present at the top 6 feet, indicating dry and relatively hard earth materials. Below that level, however, the resistivity profiles depict saturated subsurface conditions (shown with dashed lines) in the middle of the resistivity image close to the retaining wall. The high moisture zone may be the potential area with drainage problems at the study area.

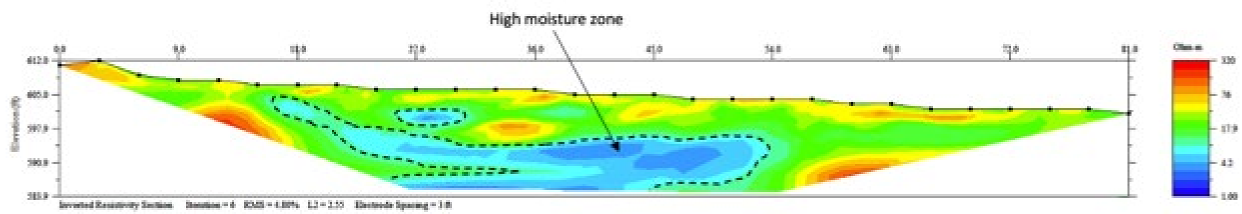


Figure 4.12. Subsurface resistivity image of Line 1

Similarly, intermittent high resistive areas are observed in Figure 4.13 at the shallow subsurface, indicating dry and relatively hard earth materials. In general, the resistivity image of Line 2 shows consistent subsurface conditions with relatively low variations in the electrical resistivities. Line 2, which is located at a greater distance from the wall than Line 1, exhibits a reduced presence of saturated zones in comparison to Line 1.

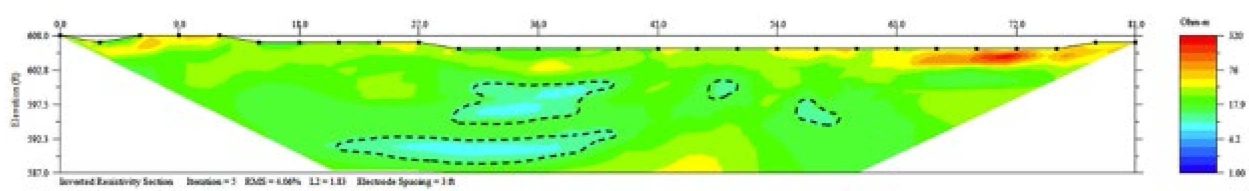


Figure 4.13. Subsurface resistivity image of Line 2

Lessons Learned

According to the resistivity profiles, the leakage from the retaining wall could be originated from the south side of the railroad due to the higher extent of less resistive zones in the south compared to the north side. The high moisture zones in the resistivity images can be indicators of potential locations with drainage problems. Without additional site information, it is expected that the ERI will help TxDOT to gain insights into the distribution of high moisture zones to conduct hydrological site assessments and mitigate drainage issues.

4.2.4 ERI for Assessing Slope Stability

This implementation aimed to characterize subsurface conditions at the study area and assess the slope stability.

Location

The study area is located along IH 30 at Chapel Creek Blvd in Tarrant County, Fort Worth, Texas.

General Site Information

The study area is situated in a region mapped with the Goodland Limestone Formation with a thickness of 90 feet (USGS Texas Geology Map). The subsurface earth materials are composed of clayey sand (SC) and lean clay (CL) in the shallow subsurface up to 6 feet. The plasticity index ranges from 14 to 24. Limestone (moderately to highly weathered) with intermittent shale is underlaid on the top materials and extends to a depth of 50 feet. No groundwater was encountered at any soil borings during drilling. In a week before the implementation, 0.49 inches of precipitation were recorded at the site.

ERI Line Configurations

Two ERI surveys were conducted using 28 electrodes with 6-feet spacings to penetrate to a depth of 33 feet. Figure 4.14 illustrates the ERI data collection plan and borehole locations for IH 30 at Chapel Creek Blvd.

Notes:
Lines ER-1 and ER-2 using 28 electrodes with 6-feet spacings (165 feet long) to cover a depth of approx. 33 feet.

Figure 4.14. ERI data collection plan and borehole locations for IH 30 at Chapel Creek Blvd

Figure 4.15 shows the implementation of the electrical resistivity imaging along IH 30 at Chapel Creek Blvd.

Figure 4.15. Implementation of the ERI along IH 30 at Chapel Creek Blvd; (a) Line ER-1 and (b) Line ER-2

The Results

Figure 4.16 shows low variation through the depth of the profile, ranging from 14 to 50 Ω.m. Less resistive areas at the shallow subsurface are attributed to wet clayey sand. More resistive areas at a depth of about 20 feet with an electrical resistivity of about 50 Ω.m could be associated with highly weathered limestone based on the site's geology. As shown in Figure 4.16, the top layer (top 5 to 10 feet) retains a higher moisture content than the deep layers which may be concerning in terms of shallow slope failure.

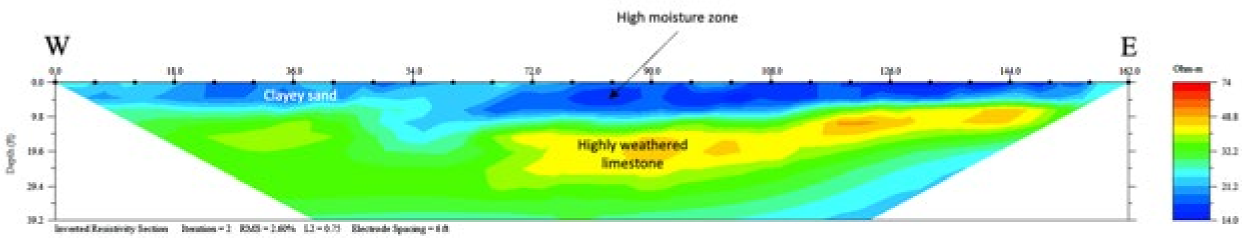


Figure 4.16. Subsurface resistivity image of Line 1

Figure 4.17 illustrates the inverted resistivity profile of Line 2. The electrical resistivity changes from 14 to 74 throughout the profile depth, representing dry to moist subsurface earth materials. The top resistive layer is attributed to dry to moist sandy clay based on the site's geology. The top layer is underlaid by high moisture zones at depths of 10 and 20 feet. Shallow slope failure seems to be a greater concern in the vicinity of the high moisture zone on the left side of the resistivity image.

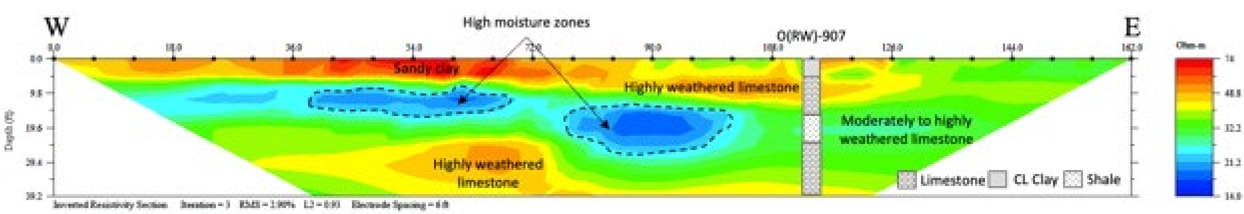


Figure 4.17. Subsurface resistivity image of Line 2

Lessons Learned

The high moisture zones or the less resistive zones in resistivity images are the potential locations that initiate slope instability. It is expected that the ERI will help TxDOT by providing an overview of subsurface conditions to locate areas characterized by weak shear strength and evaluate the slope susceptibility to shallow failures. This will be particularly valuable between the boreholes or at locations where the subsurface information is limited.

4.2.5 ERI for Identifying Critical Sulfate Concentration Zones

This implementation aimed to identify the extent of critical sulfate concentration zones at the study area and confirm the findings.

Location

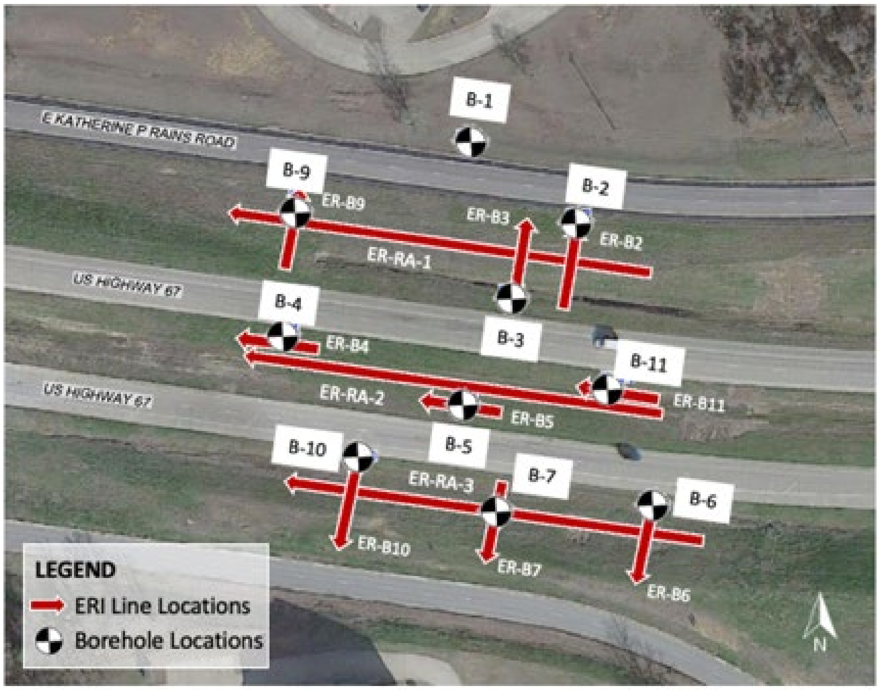
The study area is located along Highway US 67 in Johnson County, Fort Worth, Texas.

General Site Information

The study area is situated in a region mapped with Woodbine formation. Woodbine formation consists primarily of sandstone and shale with a thickness of about 320 feet. Lean and fat clayey soils (CL and CH) are dominant in the study area. The plasticity index ranges from 14 to 67. Clayey sandy (SC) soil overlays CL and CH soils at some locations; the depth of the SC layer varies from one to 9 feet. In some areas, borings reached a dense layer (shale) at least 9 feet below the ground surface. A trace of water was observed at four soil borings (B-2, B-3, B-4, and B-5) at a minimum depth of 10 feet. High concentrations of sulfate (>16,000 ppm) were reported at boreholes B-5, B-6, B-7, and B-11. Two days before conducting the ERI surveys, 0.33 inches of precipitation were recorded at the study area.

ERI Line Configurations

Twelve ERI surveys were conducted using 28 and 56 electrodes with 3-, 6-, and 8-feet spacings. Figure 4.18 illustrates the ERI data collection plan and borehole locations for US 67. In addition, six soil samples were collected from locations of high sulfate concentrations to be tested in the laboratory.



Notes:
Line ER-RA-1 and ER-RA-3: 56 electrodes with 6 ft. spacing
Line ER-RA-2 : 56 electrodes with 8 ft. spacing
Other: 28 electrodes with 3 ft. spacing

Figure 4.18. ERI data collection plan and borehole locations for US 67

Figure 4.19 shows the implementation of electrical resistivity imaging along Highway US 67 and soil sample collection.

Figure 4.19. Implementation of ERI along Highway US 67 and soil sample collection

The Results

Figures 4.20 and 4.21 show examples of inverted resistivity profiles (Lines 1 and 2) generated by EarthImager. Borehole results are also shown in the approximate borehole locations on each resistivity image.

Figure 4.20 shows slight variations in the electrical resistivity values, ranging from 3 to 18 Ω.m, through the depth and length of the profiles. The top layer illustrates a relatively resistive area, indicating the presence of low to moderate sulfate concentrations. However, areas with electrical resistivity values below 10 Ω.m indicate the zones of high moisture and high sulfate concentrations (shown with dashed lines in Figure 4.20). The borehole results show a sulfate concentration of 21,000 ppm at a depth of 2 feet at 40 feet distance.

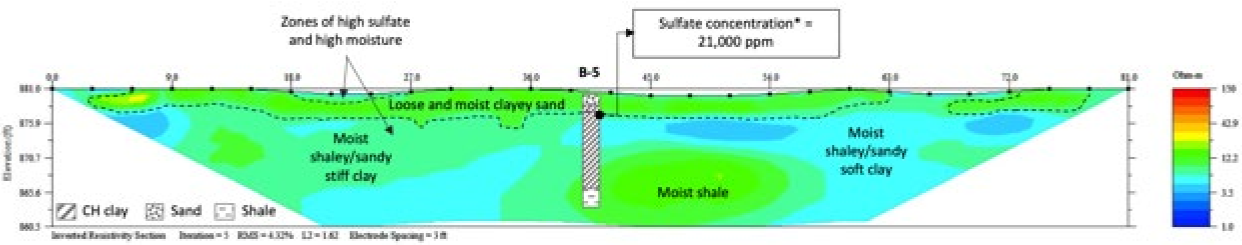


Figure 4.20. Subsurface resistivity image Line B-5

Figure 4.21 illustrates a similar pattern to the resistivity image of Line B-5. However, the resistivity image of Line B-11 shows less resistive zones with a larger extent than Line B-5, indicating a considerable amount of sulfate minerals in the vicinity of the borehole. The borehole results show a sulfate concentration of 40,000 ppm at a depth of 4 feet at 40 feet distance.

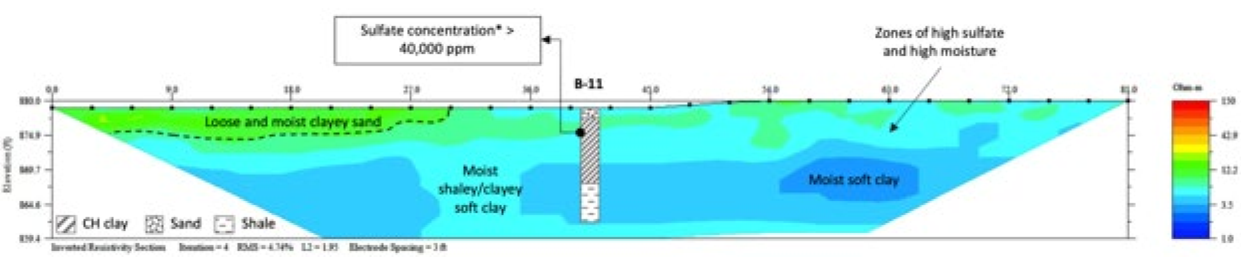


Figure 4.21. Subsurface resistivity image Line B-11

Lessons Learned

Since the sulfate concentration in soils varies widely over time and space, the ERI can be used to determine and monitor the extent of critical sulfate concentration zones that cannot be understood from the borehole data. It is expected that the findings from the ERI will help TxDOT in identifying critical sulfate concentration zones and potential locations where alternative materials and pavement designs are needed.

CHAPTER 5 SUCCESSFUL PROJECT PLANNING AND MANAGEMENT PRACTICES

5.1 Introduction

This chapter offers successful project planning and management practices based on the extensive implementation of the ERI in different geotechnical conditions and operational environments to facilitate the adoption of the ERI manual by the receiving agency. It also proposes a process for initiating the ERI in a TxDOT district.

5.2 Proposed Project Management and Planning

The following subsections present key considerations for effective project management and planning to ensure a successful ERI implementation for the intended applications.

5.2.1 Define Surveying Objectives and Expected Results

Successful planning for implementing the ERI highly depends on defining clear surveying objectives to ensure expected results. The ERI technology can be used to locate boring and sampling intervals or provide fill-in information about subsurface heterogeneity to overcome the inherent limitations (e.g., point-specific data) and problems (e.g., limited accessibility of drill rigs) of the conventional geotechnical site investigation methods (Shahandashti et al. 2021). The ERI technology has a broad range of applications including but not limited to:

- Identifying and mapping critical sulfate concentration zones (Zamanian et al. 2023),
- Delineating groundwater table depth (Shahandashti et al. 2021),
- Assessing slope stability (Ismail et al. 2019),
- Mapping topography and bedrock depth (Akingboye et al. 2020),
- Estimating clay content and other geotechnical parameters (Ademila 2021),
- Identifying voids and sinkholes (Montgomery et al. 2020),
- Locating aquifers (Riwayat et al. 2018),
- Identifying buried pipes (Hassan et al. 2018),
- Conducting forensic assessment (Ademila 2021), and
- Inspecting retaining walls.

Therefore, it is necessary to determine the surveying objective as it determines the required penetration depth and level of details needed for interpreting the ERI results. For example, a higher resolution at a shallower depth is required in the case of identifying sulfate concentration zones compared to determining the depth of groundwater table or bedrock. As another example, multiple overlapping lines or parallel lines with different orientations may be required to locate buried pipes or identify the extent of subsurface voids. Therefore, these considerations shall be addressed while planning for the ERI surveys.

5.2.2 Conduct a Feasibility Study to Confirm the Expected Results

Gaining insights into the general site information such as site accessibility, surface conditions (e.g., dirt or paved), resistivity contrast (i.e., stratigraphy), recent precipitation levels in the area, potential interference sources (e.g., underground utilities), and safety considerations allow for better survey planning and ensure the expected results. Additionally, it is important to keep in mind the limitations associated with the ERI technology, which have been outlined in the TxDOT RTI Final Report Project #0-7008. In cases where the existing information is inadequate, it is necessary to perform a preliminary test before conducting the actual survey. The preliminary test aims to provide a general understanding of the subsurface conditions. To ensure optimal results when investigating deep-buried reinforced concrete and steel structures, it is advisable to perform the ERI tests in proximity to creeks, rivers, and lakes during dry seasons when the groundwater table is low. Furthermore, understanding potential interference sources in the vicinity of the study area allows the planner to design the ERI lines away from these structures to ensure a successful implementation of the ERI. It also allows the interpreter to make more reliable conclusions about the subsurface conditions even if the buried structures do not interfere with the readings. Field sites, especially those under construction, should be pre-visited to allow planners to design proper ERI lines according to surveying objectives and eliminate confusion in implementing the plans.

5.2.3 Design Survey and Specifications

The planner must develop a detailed survey design based on the surveying objectives and general site information to optimize the survey approach, electrode configuration, electrode spacing, and resources required (i.e., personnel and equipment) to achieve the desired resolution and accuracy. To ensure clarity and effective communication, it is essential to use visual aids and figures to define and present the plans explicitly. This enhances collaboration and minimizes misunderstandings, leading to successful ERI implementation.

5.2.4 Develop Project Timeline

A specific timeline should be defined considering factors such as site accessibility, weather conditions, surface conditions, and availability of required equipment and personnel. For example, it is recommended to schedule the surveys at least a week after heavy rains, and after the first rain following persistent extreme heat. As another example, if the survey site is covered with resistive materials (i.e., concrete or asphalt), it is necessary to allocate time for drilling the surface at the electrode locations.

Furthermore, in situations where a traffic control plan is necessary, the surveyor and traffic controller need to collaborate closely and coordinate their respective plans to prevent any disruptions or delays during the fieldwork.

5.2.5 Assemble Qualified Team

Successful implementation of the ERI relies on the competence and proficiency of the workforce assigned to carry out various tasks involved. Roles and responsibilities of the team members including surveyors, data analysts, and project managers shall be clearly defined. The actors need to acquire knowledge about the fundamental principles of the method, field procedures, techniques for interpreting resistivity data, and general site information to effectively perform their tasks.

5.2.6 Procure Necessary Equipment and Resources

According to the scope of work and site conditions, necessary equipment and resources for the survey shall be determined and procured which include resistivity meters, electrodes, cables, power supplies, switching boxes, software for data analysis, and the needed workforce. Regular monitoring and inspection of the equipment are also essential to ensure that they are in good condition and function properly.

5.2.7 Obtain Required Permissions

Depending on the specific location of a study area, some permissions might be required from the relevant authority owning the property. This may involve obtaining permits, licenses, or approvals to access the site, perform ERI surveys, and potentially disturb the ground surface. It is important to consult with the appropriate authorities and adhere to any legal requirements or protocols in place before conducting ERI surveys.

5.2.8 Collect and Ensure Data Quality

The surveyors should set up the survey lines at the predetermined locations according to the plans and perform the tests. The quality control checks shall be performed during data collection to identify and resolve any issues such as high contact resistance, incorrect order of attached cable sections, and deeply buried electrodes to ensure the successful implementation of the ERI surveys. Any inconsistencies with the plans shall be noted by the surveyors and communicated with the data analysts.

Besides, to account for surface unevenness, the elevation data could be extracted from Google Earth at the approximate locations of the electrodes in line and used in the data processing along with the ERI data.

5.2.9 Process and Interpret Data

The collected resistivity and elevation data shall be processed using appropriate software and algorithms to generate resistivity images that best represent the subsurface conditions. Effective communication and collaboration among the ERI interpreters, engineers, and surveyors are essential to extract meaningful insights and interpretations from the data, thereby improving geotechnical analysis.

The research team created a data collection sheet for surveying with the ERI, as shown in Figure 5.1 It is intended to assist operators in the field sites in documenting critical factors that may affect data quality, as well as to aid in the data processing and interpretation.

Electrical Resistivity Imaging Data Collection Sheet

Texas Department of Transportation

Project Name/No.:____________________ County: ____________________

Station No.: ____________________ Date: ____________________

Operator(s): ____

Ambient Temp.: __________ Start Time: _____:_____ End Time: _____:_____

Equipment and Survey Specifications

Command File Name: ____________________

Data File Name: ____________________

Array Configuration: ____________________

# of Electrodes: ____________________

Electrode Spacing: ____________________

Line Direction: ____________________

Reciprocal data? ☐ Yes ☐ No

Max Error: ____________________

Max Current: ____________________ mA

Max Voltage: ____________________ V

Measure mode: ☐ RES ☐ RES/IP

Power Supply: ☐ Internal

☐ 12V External

☐ Other (specify): __________

Site Conditions (Write down observations that may affect the data quality)

Weather Conditions Comments (If there could be an effect on observations)

Did you use water to mitigate contact resistance due to dry condition? ☐ Yes ☐ No

Additional Concerns or Comments (e.g., interferences, rocky surface, battery failures)

Site Layout (Plan-View)

Additional Information

Nearby Borehole #:__________

Associated Electrode # to Nearby Borehole :__________

Groundwater Level: __________

Elevation Data Needed?

☐ Yes ☐ No

Figure 5.1. ERI Data Collection Sheet

5.2.10 Prepare Comprehensive Report to Communicate the Findings

A comprehensive report is needed to effectively communicate the findings from implementing the ERI to the engineers and decision-makers involved in a project. This report shall document the survey approach, instrumentation, and results of data analysis. Anomalous conditions, stratigraphy, and potential weak zones shall be highlighted within the resistivity images to facilitate the understanding based on the images. The report may also include some recommendations to prevent or mitigate associated problems based on the provided data by the ERI technology to help decision-makers in their assessments. These recommendations could include suggestions for further drilling or testing in certain locations, as well as adjustments to design parameters based on subsurface conditions. By carefully considering the ERI results and recommendations, the TxDOT will benefit from the ERI technology to enhance the safety and reliability of transportation assets.

5.3 Proposed Implementation Plan

Figure 5.2 proposes a process for initiating the ERI in TxDOT districts. This plan is proposed based on the gained experiences in implementing the ERI, and it could be adjusted in any way to best serve the TxDOT needs in the future.

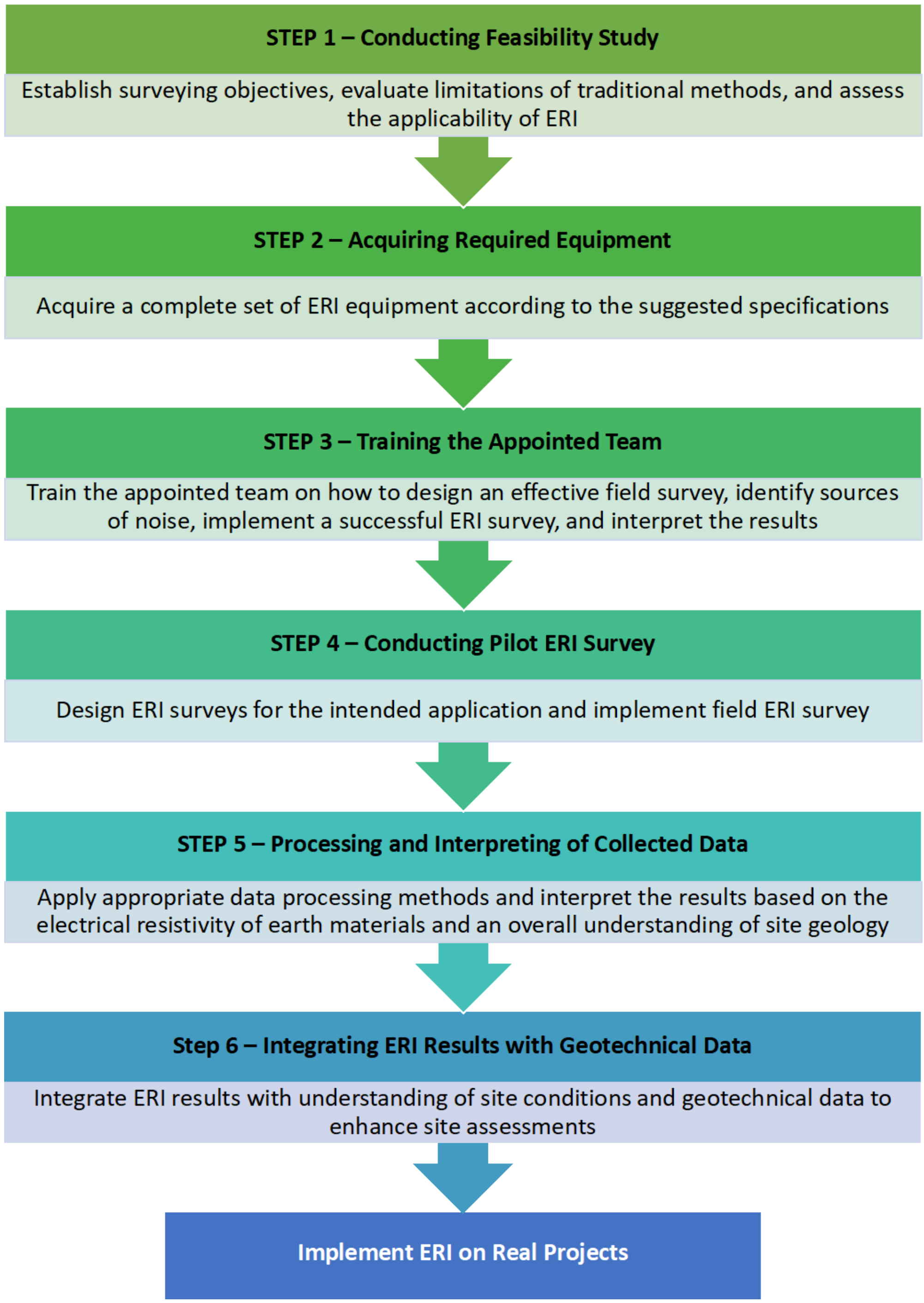


Figure 5.2. A proposed process for initiating the ERI in TxDOT districts

CHAPTER 6 COST ANALYSIS FOR IMPLEMENTING THE ELECTRICAL RESISTIVITY IMAGING MANUAL

6.1 Introduction

This chapter proposes an approach to estimate detailed costs for implementing the ERI manual in the TxDOT districts which can be used to establish the annual budget required for manual implementation in each district.

6.2 ERI Implementation Costs

The ERI manual implementation costs include the capital costs associated with acquiring the required equipment and labor costs associated with operational tasks for planning, implementing the ERI surveys, and processing and interpreting the collected data. The following subsections elaborate on each category.

6.2.1 Capital Cost

The capital costs of the ERI implementation include the one-time costs of acquiring the required equipment. The required equipment for the ERI surveying and data processing are (1) data acquisition equipment to collect electrical resistivity data from the field sites and (2) software licensing to process the collected data and generate the electrical resistivity images for obtaining additional information about subsurface conditions.

Data Acquisition Equipment

The data acquisition equipment required for ERI surveys includes a resistivity meter, stainless steel electrodes, multi-electrode cables, a switching box, and a rechargeable power supply shown in Figure 6.1. Additional equipment is also required to form a complete system, such as a tape measure and hammer.

Figure 6.1. Required data acquisition equipment for the ERI implementation

Table 6.1 shows the cost breakdown of the data acquisition equipment based on the suggested specifications for each piece of equipment. The total cost of data acquisition equipment would be approximately $60,000 for each district.

Table 6.1. The capital cost of data acquisition equipment for the ERI implementation in each district

Description	Specifications	Cost
Resistivity meter with a tablet controller, electrodes, necessary cables, switching box, and jumper wires	Eight input channels, 56 stainless steel electrodes, and four cables of 14 electrodes with 6 or 10 m takeout spacing	~$59,000
Rechargeable power supply	12v deep cycle marine battery	~$140
Additional equipment	300 ft. fiberglass tape and two polyurethane-covered hammers	~$180
Total capital costs		~$59,320

Software Licensing

Several software programs for processing the ERI data, such as RES2DINV and EarthImager, are available from various companies. These programs utilize forward and inversion modeling techniques to generate 2D inverted resistivity profiles of the subsurface and roughly yield similar results (Shahandashti et al., 2021). Most software programs require a one-time payment for licensing. The cost of licensing for ERI data processing software programs such as EathImager is shown in Table 6.2.

Table 6.2. The capital cost of licensing for ERI data processing software programs

Description	Cost
Cost of software licenses for processing of ERI data	$3,000

6.2.2 Labor Cost

The labor cost associated with implementing the ERI manual includes the wage of personnel responsible for various tasks such as planning, implementing the ERI surveys, data processing, and interpreting the collected data.

Qualified Workforce Wage

The competence of the team is critical for the successful implementation of the ERI. A TxDOT engineer who has knowledge about the field site's geology, site characterization challenges, and ERI technology could plan for the ERI tests, process the data, and obtain useful information from the ERI results to help improve geotechnical analysis. In addition, three engineering specialists are needed to perform the operational tasks in the field sites and collect the ERI data from the field. The educational text and video training materials developed for TxDOT projects #0-7008 and #5-7008 could be valuable resources for training the appointed workforce, providing them with a comprehensive knowledge of the ERI technology, field testing procedures, data processing, and interpretation techniques to ensure a successful implementation of ERI technology.

An engineer, with an average hourly wage of $52.08/hr, needs 8 hours to review project information, define the surveying objectives, conduct site visits (if needed), and finally plan for ERI tests for a line for about 100 feet distance (i.e., an ERI line with 28 electrodes and 4 ft spacing). They also need 8 hours to process the data, interpret the ERI results, and prepare a report to communicate the findings with managers and other engineers involved in a project. The engineering specialists also need to spend a minimum of 4 hours commuting to a field site and conducting an ERI test for about 100 feet distance. Assuming an hourly wage of $28.75 for an engineering specialist, the wage of a crew of four individuals would be approximately $1,200 per 100 feet distance, as shown in Table 6.3. Note that the hourly wages are based on the median salaries reported in The Texas Tribune (The Texas Tribune Website, n.d.).

Table 6.3. Qualified workforce wage for a crew of four individuals (based on median salaries from The Texas Tribune in 2023)

Crew	**Quantity**	**Cost per hour**	**No. of hours required per labor-100 ft**	**Total cost per hour-100 ft**
Engineer	1	~$52.08	16	~$833.28
Engineering Specialist	3	~$28.75	4	~345.00
Total labor costs per crew-100 ft				~$1,178.28 per crew-100 ft

Moreover, it is imperative to develop a traffic control plan at locations within the public right of way to ensure the safety of operators and the driving public during field operations. The traffic control plan must be specifically developed for a work zone location, where tests are being conducted, based on the project complexity, traffic volume, and roadway geometrics (City of Escondido, n.d.). In general, traffic control costs comprise a relatively small portion of the overall project expenses. For highway construction projects, for example, the traffic control costs typically range from 5 to 15% of the total project costs (Alaska DOT and Public Facilities, n.d.). Overall, in addition to the wages of a qualified workforce, the costs associated with the traffic control plan must also be included in the ERI implementation cost analysis.

6.3 Implementation Cost of ERI for One Sample Project

Assuming that a TxDOT district is willing to employ ERI technology on a highway segment of approximately 1800 feet in length to gain an overall view of the subsurface conditions and locate potential critical sulfate concentration zones (e.g., US 67 Project in the Fort Worth district presented in Task 2). Table 4 shows the total cost summary of ERI implementation on one sample project in a TxDOT district in addition to the capital cost.

Table 6.4. Cost summary for the ERI implementation for one sample project

Description		Total cost of the ERI implementation for one sample project
Labor Costs	Qualified workforce ($1,178.28 per crew-100 ft)	~$21,209.04

CHAPTER 7 OUTREACH ACTIVITY REPORT

7.1 Introduction

This chapter elaborates on outreach activities performed in potential TxDOT districts to disseminate knowledge about ERI technology and present the implementation results to facilitate the manual adoption.

7.2 Outreach Activities in Potential TxDOT Districts

One of the primary objectives of this project is to transfer the knowledge, case studies, and lessons learned from extensive research and implementation of the ERI manual to the receiving agency. Therefore, to achieve this objective, the research team organized several meetings and workshops among TxDOT districts to promote the implementation of the ERI manual in potential districts. The following subsections present the details about the outreach activities, a summary of the topics covered, and participants' feedback.

7.2.1 Outreach Details

The research team, in communication with the receiving agency's district contacts, coordinated several meetings with pavement and bridge sections in the TxDOT Fort Worth and Dallas districts to introduce the ERI technology and its potential applications for different project types. In bridge projects, for example, the main interest was determining the depth and type of unknown foundations. As another example, identifying zones of high sulfate concentrations was the primary concern in pavement projects. In addition to disseminating knowledge among TxDOT Dallas and Fort Worth districts, the research team organized and conducted five workshops for the TxDOT maintenance division and maintenance sections in Abilene, El Paso, Houston, and Paris districts to present the ERI manual and implementation results. Overall, the research team disseminated knowledge about the ERI technology and project findings with seven teams in TxDOT to assist in promoting and adopting the ERI manual. Table 7.1 presents outreach details for each activity.

Table 7.1. Outreach details

District/Division	Workshop Scheduled Date	No. of Participants	Duration (hour)
Maintenance Division	June 21, 2023	10	1:30
Abilene	April 10, 2023	3	1:00
Dallas	October 14, 2021	9	2:00
El Paso	June 30, 2023	12	1:00
Fort Worth	October 21, 2021	5	1:30
Houston	January 11, 2022	6	1:00
Paris	April 14, 2023	9	1:00

7.2.2 Outreach Summary

During the presentations and workshops, the performing agency offered a comprehensive 40-minute presentation and demonstrated a 10-minute video to cover the key topics outlined below:

- Importance of subsurface investigations in infrastructure projects
- Benefits and value of ERI technology in subsurface characterization
- Deterrents of using the ERI technology and practices to overcome those deterrents
- Introduction to the ERI research manual developed for TxDOT in RTI Project #0-7008 and its application on real projects
- Interpretation of continuous subsurface resistivity images along with the borehole findings
- Demonstration of a training video explaining the field data collection procedure and processing the field data using a software
- Potential applications of the ERI technology (e.g., pavement design, maintenance) with practical examples

- Statistical analysis and machine learning techniques for determining relationships between the geotechnical and geophysical parameters based on extensive data collection (from 5 different TxDOT districts)
- Results and findings from the successful implementation of the ERI manual in the TxDOT Fort Worth and Dallas Districts (RTI Project #5-7008)

The outreach summary is included in Appendix E. Following the presentations, question and answer sessions were performed to address any additional queries or suggestions raised by the participants.

7.2.3 Participants' Feedback

The participants expressed their satisfaction with the comprehensive content and informative training video illustrated during the ERI technology workshops. They valued the opportunity for knowledge sharing among the diverse group of participants among TxDOT districts. The participants found the developed case studies intriguing and acknowledged the benefits of the ERI technology in improving geotechnical analysis in their districts. Some participants asked about the ERI implementation challenges and results accuracy. The presenters provided an in-depth discussion about challenges encountered on real projects and offered practical recommendations to overcome them. There were also questions about the associated costs and the time required for implementing the ERI for a project in the districts. The performing agency stated that an approach will be developed to determine the detailed cost of ERI implementation in the TxDOT districts to help them identify the required annual budget, and the results will be distributed to them. Future collaborations regarding ERI implementation in districts other than Fort Worth and Dallas were also discussed during the workshops.

Overall, the feedback from participants highlighted the workshop's strengths in terms of content delivery and facilitation, while also identifying areas for improvement for future workshops. The workshop outcomes have the potential to promote knowledge sharing and collaboration, which positively impacts the TxDOT's existing site investigation practices.

CHAPTER 8 VALUE OF RESEARCH

8.1 Introduction

This chapter explains Value of Research (VoR) on implementation of ERI manual by determining the qualitative and economic benefits of ERI for geotechnical analysis.

8.2 Value of Research on Implementation of ERI Manual

Evaluating the value of transportation research projects plays a crucial role in promoting high value research projects and ensuring the appropriate allocation of research funds (Ashuri et al. 2014). Table 8.1 presents a summary of associated qualitative and quantitative (economic) benefits related to this project. Qualitative benefits of transportation research are those benefits that are not directly quantifiable, such as safety (Shahandashti et al. 2017). On the other hand, the quantitative benefits are those that can be quantified as savings after implementation, such as reduction in construction operations and maintenance costs (Shahandashti et al. 2017).

Table 8.1. Value of Research (VoR) Form

Benefit Area	*Qual.*	*Econ.*	*Both*	*TxDOT*	*State*	*Both*
Reduced Construction Operations and Maintenance Cost		×		×		
Environmental Sustainability	×					×
Level of Knowledge	×			×		
Safety	×					×
Infrastructure Condition	×					×
Material and Pavements	×			×		
System Reliability	×			×		
Increase Service Life		×		×		
Management and Policy	×			×		
Reduced Administrative Costs		×		×		
Traffic and Congestion Reduction	×					×
Customer Satisfaction	×					×

Notes: “Qual.” denotes Qualitative; “Econ.” denotes Economic; “State” denotes State of Texas.

The following subsections discusses the qualitative and economic benefits of this research across various areas.

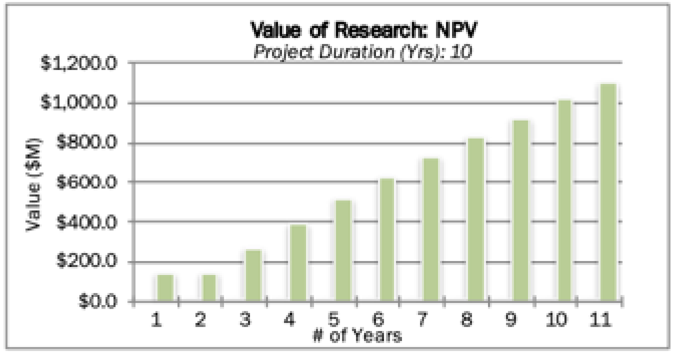
8.2.1 Reduced Construction Operations and Maintenance Costs

This project offers value by providing a comprehensive record of the benefits and limitations of the ERI technology to enable TxDOT effectively implement this technology on upcoming projects to reduce geotechnical-related cost overruns and delays due to inadequate subsurface information. Although there are certain costs associated with ERI implementation, it is proved that a slight increase in site investigation expenditure can potentially result in cost savings of up to four times the initial expenses (Goldsworthy et al. 2004).

This project illustrated the benefits of the ERI technology in identifying critical sulfate concentration zones. Detecting potential problem areas before soil treatment is the only way to prevent sulfate-induced heaving which results in high maintenance costs in the order of million dollars (TxDOT 2005). In 2021, TxDOT spent over $2,000 million for maintaining and rehabilitating 80,905 centerline miles under its jurisdiction (TxDOT, 2021 & 2022). Considering approximately 30% of the lane miles are constructed on sulfate-rich soils (TxDOT 2005), the maintenance and rehabilitation costs of pavements built on such soils would be about $600 million each year. Therefore, if TxDOT only incorporates the ERI for approximately 10% of these zones (e.g., Cedar Hill State Park Project in Chapter 2) to mitigate maintenance costs by 50%, the cost savings could amount to $1.34 billion in a 10-year horizon with a benefit-cost ratio of 4016:1. Figure 8.1 shows a result summary of VoR assessment. In this analysis, the capital cost and labor cost were calculated based on the proposed approach in Chapter 6. The cost of this project (with $274,474 capital cost) and the capital cost of procurement of ERI equipment is deducted from the expected value of year zero.

Texas Department of Transportation	Project #	5-7008-01			
	Project Name:	Implementation of Electrical Resistivity Imaging			
	Agency:	UTA	Project Budget:	$	274,474
	Project Duration (Yrs):	2.0	Exp. Value (per Yr):	$	149,008,603
	Expected Value Duration (Yrs):	10	Discount Rate:		5%
Economic Value					
Total Savings:	$ 1,340,802,953		Net Present Value (NPV):	$	1,102,251,227
Payback Period (Yrs):	0.001842		Cost Benefit Ratio (CBR, $1 : $___):	$	4,016

Years	Expected Value
0	$148,671,809
1	$0
2	$149,008,603
3	$149,008,603
4	$149,008,603
5	$149,008,603
6	$149,008,603
7	$149,008,603
8	$149,008,603
9	$149,008,603
10	$149,008,603



Notes:

Amounts on Value of Research are estimates.
Project cost should be expensed at a rate of no more than the expected value per year.
This electronic form contains formulas that may be corrupted when adding or deleting rows, by variables within the spreadsheet, or by conversion of the spreadsheet. The university is responsible for the accuracy of the Value of Research submitted.

Figure 8.1. Summary of VoR assessment

8.2.2 Environmental Sustainability

This project offers value by benefiting from non-invasive geophysical methods in site investigations. Unlike conventional geotechnical site investigation methods, the ERI technology has minimal, if any, impact on the environment. This is crucial when operating in environmentally sensitive areas, contaminated grounds, or private properties.

8.2.3 Level of Knowledge

This project offers a comprehensive record of the benefits and limitations of the ERI technology by implementing the ERI on different geotechnical conditions and operational environments that can serve as a valuable resource for TxDOT. By benefiting from these findings, TxDOT can effectively implement this technology on upcoming projects to mitigate geotechnical-related cost overruns and delays due to inadequate subsurface information. This project provides value by conducting outreach activities in about one-third of TxDOT districts to present the ERI manual and disseminate implementation results.

8.2.4 Safety

This project contributes to road safety and ride quality by offering a comprehensive record of the benefits and limitations of the ERI technology to eliminate uncertainties and minimize pavement failures and distresses (Jihanny et al. 2022). It also offers value by enhancing geotechnical analysis to reduce maintenance and rehabilitation and consequently reduce work zones. TxDOT reported more than 22,000 traffic crashes with 186 fatalities in work zones (TxDOT, 2021).

8.2.5 Infrastructure Condition

This project facilitates the adoption of the ERI technology by TxDOT to enhance its geotechnical analysis by obtaining a continuous assessment of subsurface conditions. The ERI is a cost-effective and rapid approach that can be used on various projects to improve transportation assets' service life and lower maintenance/rehabilitation costs by impacting the performance and structural stability of the infrastructure systems.

8.2.6 Material and Pavements

This project enhances geotechnical analysis for transportation systems by providing the implementation challenges and best practices for ERI implementation. This research offers value by assisting in decision-making to identify where alternative materials and pavement designs are needed to mitigate maintenance and rehabilitation costs.

8.2.7 System Reliability and Increase Service Life

This research offers value by providing implementation challenges and best practices as well as statewide outreach activities to facilitate the adoption of the ERI manual by TxDOT. By benefiting from the results of this project, TxDOT could incorporate this technology alongside the conventional geotechnical site investigation methods to enhance its geotechnical analysis and decision-making. This information helps prevent inadequate/conservative designs and mitigate geotechnical-related risks and uncertainties.

8.2.8 Management and Policy

This project provides value by offering case studies to highlight the benefits of this technology in exploring various site investigation challenges. The implementation of this manual helps reduce geotechnical-related risk and uncertainty, prevent inadequate/conservative designs, and increase accuracy in bids.

8.2.9 Reduced Administrative Costs

Maintenance and rehabilitation of transportation system failures require certain administrative tasks, such as project management and paperwork. Reducing the occurrence of these failures directly correlates to decreased costs associated with these administrative tasks. This research provides value with respect to this benefit area by providing implementation challenges and best practices for a rapid and continuous assessment of subsurface conditions to mitigate transportation system failures. Furthermore, this project creates value by offering outreach activities and freely available text materials. TxDOT is projected to allocate $1.5 million for role-based training programs during fiscal years 2022 and 2023 (TxDOT, 2020). By providing workshops and accessible text materials, this research offers the potential to reduce annual educational expenditures.

8.2.10 Traffic and Congestion Reduction

The outcomes of this project contribute to a reduction in traffic congestion by mitigating transportation system failures arising from inadequate subsurface information. As a result, this could eliminate work zone delays, which incur approximately $16 billion in costs, leading to improved traffic flow and efficiency (Schrank et al., 2015).

8.2.11 Customer Satisfaction

Due to limited capacity, maintenance and rehabilitation activities often require lane closures and disrupt traffic operations (Du et al., 2016). This research project contributes to reduced congestion, which is one of the significant factors affecting transportation customer satisfaction (Ye et al., 2013), by providing means and methods to mitigate transportation systems' failures due to insufficient subsurface information.

CHAPTER 9 SUMMARY AND CONCLUSION

This project aimed to apply the knowledge gained in the initial research (TxDOT Project #0-7008) on different geotechnical conditions and operational environments to capture challenges and best practices for the successful implementation of the ERI technology.

The research team conducted the ERI technology on 13 different projects across the Fort Worth and Dallas districts to gain more insights into the subsurface conditions in those locations, especially between the boreholes. As a result of conducting 60 ERI tests in the selected field sites and laboratory testing, this project highlighted the benefits of the ERI technology in exploring various site investigation challenges. This project demonstrated that the ERI technology can effectively identify the critical sulfate concentration zones, assess the stability of slopes, determine the groundwater table, and inspect the drainage conditions behind the retaining walls. The applicability of the ERI technology extends even to locations where borehole data is unavailable. Five case studies were developed to showcase the successful implementation of the ERI manual with various applications. The project also documented the lessons learned and recommendations to improve the future implementation of the ERI manual in different operational environments. This project offered successful project planning and management practices for implementing the ERI manual according to the gained experience and lessons learned to facilitate the adoption of the manual by TxDOT. Furthermore, an approach was presented to estimate the detailed costs for implementing the ERI manual in TxDOT districts to help them establish the annual budget required for manual implementation. This project also proposed a methodology based on machine learning approaches to classify sulfate concentration levels into three levels low (below 3,000 ppm), moderate (between 3,000 and 8,000 ppm), and high (above 8,000 ppm) using soil electrical resistivity and water content.

This project offered statewide outreach activities for different teams in around one-third of the TxDOT districts (maintenance division and different teams in Abilene, Dallas, El Paso, Fort Worth, Houston, and Paris districts) to present the ERI manual and disseminate the implementation results to potential teams to facilitate the manual adoption. By benefiting from the results of this project, TxDOT could effectively incorporate this technology alongside the conventional geotechnical site investigation methods to enhance the existing subsurface investigations and mitigate geotechnical-related cost overruns and delays due to inadequate subsurface information.

Well-informed decisions can prolong transportation assets' service life and lower maintenance/rehabilitation costs.

REFERENCES

Ademila, O. (2021). *Combined geophysical and geotechnical investigation of pavement failure for sustainable construction of Owo-Ikare highway, Southwestern Nigeria*. NRIAG Journal of Astronomy and Geophysics, 10(1), 183-201.

Akingboye, A. S., Osazuwa, I. B., & Mohammed, M. Z. (2020). *Electrical resistivity tomography for geo-engineering investigation of subsurface defects: a case study of Etioro-Akoko highway, Ondo State, southwestern Nigeria.* Studia Quaternaria, 101-107.

Alaska Department of Transportation & Public Facilities. (n.d.). Preconstruction Manual: Preconstruction Highway. Retrieved from https://dot.alaska.gov/stwddes/dcsprecon/assets/pdf/preconhwy/preconstruction_all.pdf, on July 25, 2023.

Ashuri, B., Shahandashti, M., & Tavakolan, M. (2014). *STC synthesis of best practices for determining value of research results* (No. LTRC Project No. 12-3PF). Louisiana Transportation Research Center.

ASTM G57-20 (2020). Standard Test Method for Measurement of Soil Resistivity Using the Wenner Four-Electrode Method. ASTM International, West Conshohocken, PA, <www.astm.org>.

Baral, A., Sadegh Nasr, M., Darghiasi, P., Abediniangerabi, B., & Shahandashti, M. (2022). Detection and Classification of Vegetation for Roadside Vegetation Inspection and Rehabilitation Using Deep Learning Techniques. In International Conference on Transportation and Development 2022 (pp. 143-152).

Baynes, F.J. (2010). Sources of geotechnical risk, Quarterly Journal of Engineering Geology and Hydrogeology, 43, 321–331.

Boeckmann, A. Z., & Loehr, J. E. (2016). Influence of Geotechnical Investigation and Subsurface Conditions on Claims, Change Orders, and Overruns (No. Project 20-05, Topic 46-04).

Breiman, L., Friedman, J. H., Olshen, R. A., and Stone, C. J. (2017). *Classification and regression trees*. Routledge.

City of Escondido (n.d.). Traffic Control Plan Checklist. Retrieved from https://www.escondido.org/Data/Sites/1/media/PDFs/trafficengineering/TCPChecklist.pdf, on July 24, 2023.

Darghiasi, P., Baral, A., & Shahandashti, M. (2023a). Developing a Cost-Effective Mobile-Based System for Collecting On-Demand Road Condition Images for Snowplow Operations Management. In International Conference on Transportation and Development 2023 (pp. 127-137).

Darghiasi, P., Baral, A., Abediniangerabi, B., & Shahandashti, M. (2022). A Multi-Purpose All-in-One Mobile Data Collection System for Snowplow Operation Management. In International Conference on Transportation and Development 2022 (pp. 39-50).

Darghiasi, P., Baral, A., Mattingly, S., & Shahandashti, M. (2023b). Estimation of Road Surface Temperature Using NOAA Gridded Forecast Weather Data for Snowplow Operations Management. Journal of Cold Regions Engineering. https://doi.org/10.1061/JCRGEI/CRENG-691.

Darghiasi, P., Zamanian, M., & Shahandashti, M. (2024). Enhancing Winter Maintenance Decision Making through Deep Learning-Based Road Surface Temperature Estimation. In Construction Research Congress 2024 (*Forthcoming*).

Du, B., Chien, S., Lee, J., & Spasovic, L. (2017). Predicting freeway work zone delays and costs with a hybrid machine-learning model. Journal of Advanced Transportation, 2017.

Estévez, V. (2020). *Machine Learning methods for classification of Acid Sulfate soils in Virolahti*.

Fernández-Avilés Calderón, G. (2009). Spatial regression analysis vs. kriging methods for spatial estimation. International Advances in Economic Research, 15, 44-58.

Gambill, D. R., Wall, W. A., Fulton, A. J., and Howard, H. R. (2016). Predicting USCS soil classification from soil property variables using Random Forest. *Journal of Terramechanics*, 65, 85-92.

Goldsworthy, J. S., Jaksa, M. B., Kaggwa, W. S., Fenton, G. A., Griffiths, D. V., & Poulos, H. G. (2004, August). Cost of foundation failures due to limited site investigations. In *The International Conference on Structural and Foundation Failures* (pp. 2-4).

Hassan, A. A., AL-Awsi, M. D., & Al-Obaidi, M. M. (2018). *Application of 2D electrical resistivity imaging technique for engineering site investigation.* Journal of University of Babylon for Pure and Applied Sciences, 26(5), 74-85.

Hunt, R. E. (2005). Geotechnical engineering investigation handbook. CRC Press.

Ismail, N. E. H., Taib, S. H., & Abas, F. A. M. (2019). *Slope monitoring: an application of time-lapse electrical resistivity imaging method in Bukit Antarabangsa, Kuala Lumpur*. Environmental Earth Sciences, 78(1), 1-15.

Jihanny, J., Ayuningtyas, K. N. S., David, A., Salsabila, F. Z., Kamajaya, M., & Salmadhia, D. (2022, July). The Impact of Pavement Distress to Vehicle Maneuver in Bandung City. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1065, No. 1, p. 012060). IOP Publishing.

Kermani, B., Coe, J. T., Nyquist, J. E., Sybrandy, L., Berg, P. H., & McInnes, S. E. (2014, March). Application of electrical resistivity imaging to evaluate the geometry of unknown bridge foundations. In 27th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) (pp. cp-400). European Association of Geoscientists & Engineers.

Montgomery, J., Jackson, D., Kiernan, M., & Anderson, J. B. (2020). *Use of geophysical methods for sinkhole exploration* (No. 930-945). Auburn University. Highway Research Center.

Pouladi, N., Møller, A. B., Tabatabai, S., and Greve, M. H. (2019). Mapping soil organic matter contents at field level with Cubist, Random Forest and kriging. *Geoderma*, 342, 85-92.

Prezzi, M., McCullouch, B., & Mohan, V. K. D. (2011). Analysis of change orders in geotechnical engineering work at INDOT (No. FHWA/IN/JTRP-2011/10).

Riwayat, A. I., Nazri, M. A. A., & Abidin, M. H. Z. (2018, April). *Detection of Potential Shallow Aquifer Using Electrical Resistivity Imaging (ERI) at UTHM Campus, Johor Malaysia*. In Journal of Physics: Conference Series (Vol. 995, No. 1, p. 012103). IOP Publishing.

Rosenblad, B. L., & Boeckmann, A. Z. (2020). Advancements in Use of Geophysical Methods for Transportation Projects (No. Project 20-05, Topic 50-01).

Schrank, D., Eisele, B., Lomax, T., & Bak, J. (2015). 2015 urban mobility scorecard. U.S. Department of transportation. (2017). Facts and Statistics – Work Zone Mobility. Retrieved from the Federal Highway Administration website: https://ops.fhwa.dot.gov/wz/resources/facts_stats/mobility.html

Shahandashti, M., Ashuri, B., & Tavakolan, M. (2017). Synthesis of Methods and Measures for Determining Value of Transportation Research. *Journal for the Advancement of Performance Information and Value*, *9*(1).

Shahandashti, M., Hossain, S., Baral, A., Adhikari, I., Pourmand, P., & Abediniangerabi, B. (2022a). *Slope repair and maintenance management system* (No. FHWA/TX-20/5-6957-01-1). Texas Department of Transportation.

Shahandashti, M., Hossain, S., Khankarli, G., Zahedzahedani, S. E., Abediniangerabi, B., & Nabaei, M. (2019). *Synthesis on rapid repair methods for embankment slope failure* (No. FHWA/TX-18/0-6957-1). University of Texas at Arlington.

Shahandashti, M., Hossain, S., Zamanian, M., & Akhtar, M. A. (2021). *Advanced Geophysical Tools for Geotechnical Analysis* (No. FHWA/TX-20/0-7008-1).

Shahandashti, M., Mattingly, S., Darghiasi, P., Baral, A., & Abediniangerabi, B. (2022b). *Snowplow Operations Management System* (No. FHWA/TX-22/5-6996-01-1). Texas Department of Transportation. Research and Technology Implementation Office.

Shrestha, P. P., & Neupane, K. P. (2020). Identification of geotechnical-related problems impacting cost, schedule, and claims on bridge construction projects. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 12(2), 04520005.

Texas Department of Transportation (TxDOT), (2005). Guidelines for Treatment of Sulfate-Rich Soils and Bases in Pavement Structures. Accessed March 29, 2022. https://ftp.dot.state.tx.us/pub/txdot-info/cmd/tech/sulfates.pdf

Texas Department of Transportation (TxDOT), (2020). Agency Strategic Plan for Fiscal Years 2021-2025. Retrieved from https://ftp.txdot.gov/pub/txdot/commission/2020/0528/9.pdf, on July 27, 2023.

Texas Department of Transportation (TxDOT), (2021). Conditions of Texas Pavements. Accessed July 26, 2023. https://ftp.txdot.gov/pub/txdot/mtd/pmis-annual-report.pdf

Texas Department of Transportation (TxDOT), (2021). Pocket Facts FY2022. Accessed July 27, 2023. https://www.txdot.gov/content/dam/docs/news/txdot-pocket-facts.pdf

Texas Department of Transportation (TxDOT), (2021). Work Zones. Retrieved from https://www.txdot.gov/inside-txdot/media-center/psas/distracted-driving/work-zones.html, on July 27, 2023.

The Texas Tribune (n.d.). Retrieved Accessed from < salaries.texastribune.org>, on July 10, 2023.

Wang, H., & Hu, C. H. (2015). Identification on unknown bridge foundations using geophysical inspecting methods. The e-Journal of Nondestructive Testing, 20(11), 905-912.

Weather Underground. (2022). Weather Underground. www.wunderground.com. Accessed July 14, 2022.

Ye, L., Hui, Y., & Yang, D. (2013). Road traffic congestion measurement considering impacts on travelers. Journal of Modern Transportation, 21(1), 28-39.

Zamanian, M., & Shahandashti, M. (2022). Investigation of Relationship between Geotechnical Parameters and Electrical Resistivity of Sandy Soils. In Construction Research Congress 2022 (pp. 686-695).

Zamanian, M., Asfaw, N., Chavda, P., & Shahandashti, M. (2023a). Classifying Soil Sulfate Concentration Using Electrical Resistivity Imaging and Random Forest Algorithm. In Airfield and Highway Pavements 2023 (pp. 204-213).

Zamanian, M., Darghiasi, P., Shahandashti, M. (2024). Empirical Study of the Correlation Between Geoelectrical and Soil-Index Properties of Clayey Soils. In Construction Research Congress 2024 (*Forthcoming*).

Zamanian, M., Thorat, Y. A., Asfaw, N., Chavda, P., & Shahandashti, M. (2023b). *Electrical Resistivity Imaging for Identifying Critical Sulfate Concentration Zones Along Highways.* Transportation Research Record, 0(0). https://doi.org/10.1177/03611981231167162.

APPENDIX A – BORING LOGS

US 67

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-2	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/13/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	-10.00 ft

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, stiff, dry, reddish brown, sandy (CL)			7	30	14		PP=4.5+; SS=173ppm
						13			132	PP=4.5+; SS=171ppm
-5.	5		CLAY, soft, moist, reddish brown and gray, slickensided, few to some sand partings and gypsum lenses (CH)			17	62	45		PP=2.0
				0	25	28			115	PP=1.75
	10					31	85	57		water bearing sand partings at 10' & 13' PP=1.5; #4(%)-99; #40(%)-90
						31			118	PP=2.0
-13.			CLAY, stiff to hard, moist, reddish brown and gray, shaley, slickensided, few to some sand partings and gypsum lenses (CH)			30				PP=4.5+
	15					33	88	62	115	PP=4.5+; #4(%)-100; #40(%)-97
										PP=4.5+
-20.	20					29				PP=4.5+
	25									

Remarks: Seepage observed at 10' during drilling. Dry at completion. Water at 16' after 40 hours. GPS coordinates were obtained using the WGS-84 coordinate system. SS=soluble sulfate Latitude: 32.38477 Longitude: -97.33446

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore	County	Johnson	Hole	B-3	District	Fort Worth
Version 3.3	Highway	US 67	Structure	Pavement	Date	10/14/2020
	CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
			Offset		GW Elev.	-17.00 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SAND, loose to slightly compact, dry to moist, reddish tan and light gray, clayey, few to some silty sand partings and clay lenses (SC)			10	37	24		#4(%)-99; #40(%)-97 PP=4.5+; SS=82ppm
						15			138	PP=4.5+
5						14	33	20		PP=3.5
						15				PP=3.75
-9. 10			CLAY, soft to hard, moist, light brown and gray, shaley, slickensided, trace to some silty sand partings and gypsum lenses (CH)			33				PP=2.0
						33	91	64		PP=2.75
										PP=4.5
15						28	84	60		PP=4.5+
										PP=4.5+
-20. 20						23				PP=4.5+
25										

Remarks: Trace water observed at 17' during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=soluble sulfate Latitude: 32.38458 Longitude: -97.33466

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-4	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/14/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	-10.00 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
-1.			SAND, loose, dry, reddish tan, silty (ML)			26				PP=0.5
			SAND, loose to slightly compact, moist, reddish tan and light gray, clayey, interbedded fat clay layers (SC)			13				PP=4.5+; SS=780ppm
										fat clay layers at 2.5-3.5', and 4.5-5.5'
						20	40	26		PP=4.5+; SS=300ppm; #40(%)-100
5										
-6.						30				PP=2.0
			CLAY, soft to hard, moist, brown and gray, shaley, slickensided, trace to some silty sand partings and gypsum lenses (CH)			31	87	63		PP=2.25; #4(%)-100; #40(%)-94
										water bearing sand partings at 10'
10						30			117	PP=2.0
										PP=4.5+
						30	87	61		PP=4.5+
15										PP=4.5+
										PP=4.5+
-20. 20						27	81	54		PP=4.5+
25										

Remarks: Trace water observed at 10' during drilling. Dry at completion. Water observed at 13.5' after 24 hours. GPS coordinates were obtained using the WGS-84 coordinate system. SS=soluble sulfate Latitude: 32.38449 Longitude: -97.33533

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-5	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/14/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	-14.00 ft

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		SAND, loose, moist, reddish tan, clayey (SC)							
-1.		CLAY, soft to hard, moist, brown and gray, shaley, slickensided, trace to few silty sand partings and gypsum lenses (CH)			31				PP=2.0; SS=667ppm
					32	82	54		#4(%)-100#; 40(%)-94 PP=4.5; SS=21,378ppm
5			0	29	34			118	PP=4.5+
					29	76	47		PP=4.5+
10					26				PP=4.5+
					30	68	46		PP=4.5+
-14.		SHALE, soft, moist, gray, fissile, trace calcareous deposits and sand partings							water bearing sand partings at 14' PP=4.5+
15									
-16.	50 (3) 50 (3)				24	80	53		PP=4.5+
20									
25									

Remarks: Trace water observed at 14' during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system.
SS=soluble sulfate Latitude: 32.38433 Longitude: -97.3348

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-6	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/15/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
		SAND, loose, moist to dry, reddish tan, clayey, fine grained, few silty sand partings (SC)			10	0	0		#4(%)-100; #40(%)-98 PP=2.0; SS=662ppm
-3.		CLAY, stiff to hard, moist, gray, shaley, slickensided, trace gypsum lenses and silty sand partings (CH)			27				PP=4.5+; SS>40,000ppm
5					28	77	49		PP=4.5+; #4(%)-98; #40(%)-87
					24			126	PP=4.5+
-10. 10					25	62	38		PP=4.5+
		SHALE, soft, moist, gray, fissile, trace calcareous deposits and sand partings			24	70	41		PP=4.5+
					21				SPT=41/12in.
-14.	49 (6) 50 (5)								
15									
20									
25									

Remarks: No seepage observed during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=solu sulfate Latitude: 32.38405 Longitude: -97.33425

The ground water elevation was not determined during the course of this boring.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-7	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/13/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, soft to hard, moist, gray and brown, shaley, slickensided, few to some sand partings and gypsum lenses (CL)			17	47	30		SPT=17/12in.
				0	31	32			112	PP=4.5+; SS=16,956ppm
-4.			CLAY, stiff to hard, moist, gray and brown, shaley, slickensided, few to some sand partings and gypsum lenses (CH)			24	77	45		PP=4.5+; #4(%)-100; #40(%)-85
5						19			124	PP=4.5+
						24	66	36		PP=4.5+
-9.			SHALE, soft, moist, dark gray, fissile, trace calcareous deposits and sand partings			23				SPT=48/12in.
10						22	79	53		SPT=60/12in.
										SPT=47/12in.
-15. 15		50 (3) 50 (2.5)								
20										
25										

Remarks: No seepage observed during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=solu sulfate Latitude: 32.38403 Longitude: -97.33472

The ground water elevation was not determined during the course of this boring.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore	County	Johnson	Hole	B-9	District	Fort Worth
Version 3.3	Highway	US 67	Structure	Pavement	Date	10/15/2020
	CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
			Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, soft to hard, moist, light brown and gray, shaley, slickensided, trace to few gypsum lenses (CH)			9	55	38		PP=4.25; #4(%)-95; #40(%)-88
				0	52	24			125	PP=4.5+; SS=516ppm
5						27	92	67		PP=4.5+
				0	64	27			122	PP=4.5+
10						27	75	48		trace silty sand partings below 10' PP=4.5+; #4(%)-100; #40(%)-99
										PP=4.5+
										PP=4.5+
-15. 15						25	74	49		PP=4.5+
20										
25										

Remarks: No seepage observed during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=soluble sulfate Latitude: 32.38486 Longitude: -97.3353

The ground water elevation was not determined during the course of this boring.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-10	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/15/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
-1.		FILL, SAND, loose, moist, reddish tan, clayey, fine grained (SC)							
		CLAY, soft to hard, moist, light brown and gray, shaley, slickensided, trace to few gypsum lenses and silty sand partings (CH)			27				PP=4.5+; SS=1,520ppm
					29	71	39		#4(%)-98; #40(%)-93 PP=4.5+; SS=1,909ppm
5					30	76	46		PP=4.5+
					31			118	PP=4.5+
10					29	77	45		PP=4.5+
-12.					24			120	PP=4.5+
		SHALE, soft, moist, gray, fissile, trace calcareous deposits and sand partings			24	73	45		PP=4.5+
15 / -15.5									SPT=58/12in.
20									
25									

Remarks: No seepage observed during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=soluble sulfate Latitude: 32.38417 Longitude: -97.33513

The ground water elevation was not determined during the course of this boring.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

DRILLING LOG

WinCore
Version 3.3

County	Johnson	Hole	B-11	District	Fort Worth
Highway	US 67	Structure	Pavement	Date	10/15/2020
CSJ	0259-06-011	Station		Grnd. Elev.	0.00 ft
		Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
-1.			FILL, SAND, loose, dry, reddish tan, clayey, fine grained (SC)							
			CLAY, soft to hard, moist, light brown and gray, shaley, slickensided, trace to few gypsum lenses and silty sand partings (CH)			32				PP=4.5+; SS=19,200ppm
						32	73	43		#4(%)-100; #40(%)-98 PP=4.5+; SS>40,000ppm
5						32			118	PP=4.5+
						32				PP=4.5+
10						30	73	43		PP=4.5+
-12.						26				PP=4.5+
			SHALE, soft, moist, gray, fissile, trace calcareous deposits and sand partings			25	70	41	115	PP=4.5+
15 / -15.5						23				SPT=52/12in.
20										
25										

Remarks: No seepage observed during drilling. Dry at completion. GPS coordinates were obtained using the WGS-84 coordinate system. SS=solub sulfate Latitude: 32.38436 Longitude: -97.33436

The ground water elevation was not determined during the course of this boring.

Driller: Scott Campbell Logger: Bradford Weddell Organization: Terracon Consultants, Inc.

IH 20 at Clear Fort Trinity

DRILLING LOG

WinCore	County	Tarrant	Hole	B-3	District	Fort Worth
Version 3.1	Highway	I20@820	Structure	Bridge	Date	6/8/17
	CSJ	0008-16-042	Station		Grnd. Elev.	609.26 ft
			Offset		GW Elev.	585.76 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, lean, with sand, soft to very stiff, dry, brown, trace organics at top 2 feet (CL)							
						7.8	29	17		
5		8 (6) 10 (6)								
						10.0				%Pass #200 Sieve:75.7
10		14 (6) 18 (6)								
				0	30.3	12.8	28	16	128	
15		5 (6) 6 (6)								
589.8			GRAVEL, clayey, with sand							
20		5 (6) 7 (6)								
						14.2				%Pass #4 Sieve:55.5 %Pass #200 Sieve:22.2
585.3			LIMESTONE, interbedded with shale layers, very hard, light gray, dark gray							
25		50 (0.5) 50 (0.25)								
				0	1681.8	4.9			148.7	
30		50 (0.25) 50 (0.125)								REC=98%, RQD=90%

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was encountered at 23.5 feet during drilling. Northing: 6934121.542, Easting: 2299299.333

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-3	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	6/8/17
CSJ	0008-16-042	Station		Grnd. Elev.	609.26 ft
		Offset		GW Elev.	585.76 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, interbedded with shale layers, very hard, light gray, dark gray	0	4114.7	1.6			161.6	
35		50 (0.25) 50 (0.25)								REC=82%, RQD=82%
				0	271.1	6.7			145.9	
40		50 (0.125) 50 (0.125)								REC=97%, RQD=97%
568.8										
45										
50										
55										
60										

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was encountered at 23.5 feet during drilling. Northing: 6934121.542, Easting: 2299299.333

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-4	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	6/29/17
CSJ	0008-16-042	Station		Grnd. Elev.	612.02 ft
		Offset		GW Elev.	589.02 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, lean, sandy, stiff to very stiff, dry, brown, with calcareous nodules (CL)							PP:4.5+
						12.1	26	15		PP:4.5
				0	92.2	13.0				PP:4.5+ %Pass #200 Sieve:53.5
5		19 (6) 22 (6)								
										PP:4.5+
						15.6	22	12		
10		14 (6) 25 (6)								
600.			SAND, clayey, with gravel, compact, dry to wet, tan (SC)							
						9.9				%Pass #4 Sieve:80.1 %Pass #200 Sieve:23.5
15		24 (6) 25 (6)								
20		32 (6) 29 (6)								
						17.9				%Pass #4 Sieve:68.5 %Pass #200 Sieve:22.7
588.			LIMESTONE, very hard, tan, light gray, weathered							
25		50 (0.25) 50 (0.25)								
586.			LIMESTONE, very hard, light gray, interbedded dark gray shale							
				0	4372.1	8.5			150.5	
30		50 (0.125) 50 (0.125)								REC=97%, RQD=90%

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was encountered at 23 feet during drilling. Northing: 6934284.559, Easting: 2299341.347

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Coretest **Logger: PK** **Organization: HVJ Associates®**

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-4	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	6/29/17
CSJ	0008-16-042	Station		Grnd. Elev.	612.02 ft
		Offset		GW Elev.	589.02 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	Properties MC	Properties LL	Properties PI	Properties Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, light gray, interbedded dark gray shale							
				0	1495.9	8.3			147.7	
35		50 (0.25) 50 (0.125)								REC=98%, RQD=98%
				0	1099.7	8.3			144.7	
										REC=95%, RQD=95%
40		50 (0.25) 50 (0.25)								
571.5										
45										
50										
55										
60										

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was encountered at 23 feet during drilling. Northing: 6934284.559, Easting: 2299341.347

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driler: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-5	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	6/15/17
CSJ	0008-16-042	Station		Grnd. Elev.	612.43 ft
		Offset		GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		PAVEMENT, 10 inches of Asphalt and 2 inches of Base							PP:4.5+
611.4		CLAY, lean, sandy, stiff to very stiff, moist, dark brown to brown, trace calcareous nodules (CL)							%Pass #200 Sieve:52.4
			0	45.3	11.7			130.6	PP:4.5+
5	9 (6) 12 (6)				12.0	30	19		PP:4.5+
									PP:4.5+
605.4		SAND, clayey, with gravel, dense, dry, tan			5.7				%Pass #4 Sieve:71.9 %Pass #200 Sieve:23.6
10	41 (6) 50 (3.5)								
598.4		LIMESTONE, very hard, tan, weathered			8.9				
15	50 (0.25) 50 (0.125)								
593.4		LIMESTONE, very hard, light gray, dark gray, with interbedded shale layers							
20	50 (0.5) 50 (0.5)								
25	50 (0.5) 50 (0.25)		0	1941.1	6.9			148	REC=97%, RQD=97%
			0	2431.4	6.1			147.6	
30	50 (0.25) 50 (0.25)								REC=100%, RQD=100%

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Elevation was assumed. Northing: 6934126.543, Easting: 2299104.576

The ground water elevation was not determined during the course of this boring.

Driler: Coretest **Logger: PK** **Organization: HVJ Associates®**

DRILLING LOG

WinCore	County	Tarrant	Hole	B-5	District	Fort Worth
Version 3.1	Highway	I20@820	Structure	Bridge	Date	6/15/17
	CSJ	0008-16-042	Station		Grnd. Elev.	612.43 ft
			Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, light gray, dark gray, with interbedded shale layers							
				0	1246.9	7.7			146	
35		50 (0.25) 50 (0.125)								REC=97%, RQD=97%
				0	300.7	8.5			142.2	
										REC=100%, RQD=100%
40		50 (1) 50 (0.125)								
571.9										
45										
50										
55										
60										

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Elevation was assumed. Northing: 6934126.543, Easting: 2299104.576

The ground water elevation was not determined during the course of this boring.

Driler: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore Version 3.1	County: Tarrant	Hole: B-6	District: Fort Worth		
	Highway: I20@820	Structure: Bridge	Date: 5/31/17		
	CSJ: 0008-16-042	Station:	Grnd. Elev.: 611.61 ft		
		Offset:	GW Elev.: N/A		

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		CLAY, lean, very stiff, moist, brown (CL)							PP:4.5+
					5.7	43	28		PP:4.5+
			0	24.6	5.9			131.1	PP:4.5+
607.1 / 5	24 (6) 42 (6)	SAND, clayey, with gravel, compact, dry, tan to brown (SC)							
					5.6				%Pass #4 Sieve:63.4 %Pass #200 Sieve:26.5
603.6		CLAY, lean, with sand, soft, moist, brown (CL)							
10	4 (6) 9 (6)				5.2	38	25		PP:1.5 %Pass #200 Sieve:82.7
598.6		LIMESTONE, weathered, very hard, tan							
15	50 (0.25) 50 (0.125)								
594.6		LIMESTONE, very hard, light gray, with frequent shale seams, 8 inch shale layer at 30.4 feet							
20	50 (0.25) 50 (0.25)								
25	50 (0.5) 50 (0.5)		0	2129.7	6.0			152	REC=100%, RQD=100%
			0	5685	4.3			158	
30	50 (0.25) 50 (0.125)								REC=100%, RQD=100%

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Northing: 6934194.735, Easting: 2299053.645

The ground water elevation was not determined during the course of this boring.

Driller: Coretest **Logger:** PK **Organization:** HVJ Associates®

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-6	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	5/31/17
CSJ	0008-16-042	Station		Grnd. Elev.	611.61 ft
		Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, light gray, with frequent shale seams, 8 inch shale layer at 30.4 feet							
				0	4317.9	4.9			156.1	
35		50 (0.5) 50 (0.5)								REC=96%, RQD=96%
				0	1102.9	7.2			149.8	
40		50 (0.5) 50 (0.5)								REC=94%, RQD=94%
571.1										
45										
50										
55										
60										

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Northing: 6934194.735, Easting: 2299053.645

The ground water elevation was not determined during the course of this boring.

Driller: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-7	District	Fort Worth
Highway	I20@820	Structure	Bridge	Date	6/15/17
CSJ	0008-16-042	Station		Grnd. Elev.	610.18 ft
		Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			PAVEMENT, 2 inches of Asphalt and 6 inches Base							
609.2			CLAY, lean, with sand, soft, moist, brown (CL)							PP:4.5+
						15.2	35	21		PP:4.5+
						17.3				PP:4.5+ %Pass #200 Sieve:73.1 3 inch boulder at 5 feet
5		6 (6) 6 (6)								
604.2			CLAY, lean, sandy, stiff to very stiff, moist, brown (CL)	0	32.7	11.4	31	21	138	PP:4.5+
						13.7				PP:4.5+ %Pass #200 Sieve:56.2
10		8 (6) 50 (4)								
598.2			LIMESTONE, very hard, tan, weathered							
15		50 (0.125) 50 (0.125)								
594.2			LIMESTONE, very hard, light gray, interbedded with shale layers							
20		50 (0.25) 50 (0.25)								
25		50 (0.25) 50 (0.25)								REC=87%, RQD=87%
				0	2854.9	7.5			128.6	
30		50 (0.25) 50 (0.25)								

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Northing: 6934278.156, Easting: 2298993.529

The ground water elevation was not determined during the course of this boring.

Driler: Coretest Logger: PK Organization: HVJ Associates®

DRILLING LOG

WinCore	County	Tarrant	Hole	B-7	District	Fort Worth
Version 3.1	Highway	I20@820	Structure	Bridge	Date	6/15/17
	CSJ	0008-16-042	Station		Grnd. Elev.	610.18 ft
			Offset		GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, light gray, interbedded with shale layers							REC=90%, RQD=90%
				0	2564.7	6.3			150.6	
35		50 (0.5) 50 (0.25)								REC=92%, RQD=92%
				0	3101.1	5.8			150.2	REC=92%, RQD=92%
40		50 (0.125) 50 (0.125)								
569.7										
45										
50										
55										
60										

Remarks: PP: Pocket Penetrometer readings in tsf. Groundwater was not encountered during drilling. Northing: 6934278.156, Easting: 2298993.529

The ground water elevation was not determined during the course of this boring.

Driller: Coretest Logger: PK Organization: HVJ Associates®

Cedar Hill State Park

DRILLING LOG

1 of 1

WinCore Version 3.3	County: Dallas	Hole: B-5	District:
	Highway:	Structure:	Date: 08/25/2021
	CSJ:	Station:	Grnd. Elev.: 0.00 ft
		Offset:	GW Elev.: N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
-.5		CONGLOMERATE, Asphalt (6 inch)							
-1.2		LIMESTONE, crushed, base course (8 inch)			27	30	14	123	1.2' - 2' Pass #4(%) = 96.9 Pass #40(%) = 95.8 Pass #200(%) = 75 Sulfates = 22,080 ppm
		CLAY, lean, with sand, stiff, brown (CL)			29				-with weathered shale from 4'
-6.		CLAY, fat, very stiff, brown (CH)			32	64	40		12' - 14' Pass #4(%) = 100 Pass #40(%) = 99.7 Pass #200(%) = 97
					32				
20									BOTTOM @ 20'

Remarks: Groundwater was not encountered during dry-auger drilling. Borehole backfilled with soil cuttings and cold-patched at the surface upon work completion. Ground elevation not available. Zero input for log completion purposes.

Driler: Justin Lovelace | Logger: Shane Dookeran | Organization: Geotechnical Drillers of Texas / TWE

DRILLING LOG

WinCore
Version 3.3

County: Dallas	Hole: B-6	District:	
Highway:	Structure:	Date: 08/25/2021	
CSJ:	Station:	Grnd. Elev.: 0.00 ft	
	Offset:	GW Elev.: N/A	

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
-.5			CONGLOMERATE, Asphalt (6 inch)							
-1.3			LIMESTONE, crushed, base course (10 inch)			24	71	45	113	1.3' 2' Pass #4(%) = 97.5 Pass #40(%) = 81.9 Pass #200(%) = 61 Sulfates = 17,835 ppm
-6.			CLAY, sandy fat, stiff, brown (CH)			33				-with weathered shale from 6'
			CLAY, fat, very stiff, brown (CH)			34	65	40		10' - 12' Pass #4(%) = 100 Pass #40(%) = 99.6 Pass #200(%) = 95
						24				
-18.										REFUSAL @ 18'

Depth scale: 5, 10, 15, 20

Remarks: Groundwater was not encountered during dry-auger drilling. Borehole backfilled with soil cuttings and cold-patched at the surface upon work completion. Ground elevation not available. Zero input for log completion purposes.

Driler: Justin Lovelace Logger: Shane Dookeran Organization: Geotechnical Drillers of Texas / TWE

SH 170 at Westport Pkwy

DRILLING LOG

1 of 3

WinCore
Version 3.3

County	Tarrant	Hole	WP-01	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1134+78.7	Grnd. Elev.	697.73 ft
		Offset	76.3RT	GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		CLAY, soft, moist, brown, with limestone fragments (CL)			33				PP=2.0
695.7		CLAY, very stiff, moist, grayish tan, blocky, shaley (CH)							
					24	61	38		#200(%)-72; PP=4.5+
5									
					18				PP=4.5+
					20	66	40		#200(%)-99; PP=4.5+
10	19 (6) 26 (6)				18				PP=4.5+
15	50 (3) 50 (6)		0	32	19	54	33	123	#200(%)-94; PP=4.5+
			0	31	21			126	
20	43 (6) 50 (4.5)								PP=4.5+
25	50 (4.5) 50 (4.5)								PP=4.5+
671.7		SHALE, soft, gray							
30	50 (5.5) 50 (5.5)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7040640.825 East: 2345523.641

The ground water elevation was not determined during the course of this boring.

Driller: R. Cooper Logger: S. O'Sonnor Organization: Terracon Consultants, Inc.

Exhibit A-63

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clo

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-01	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1134+78.7	Grnd. Elev.	697.73 ft
		Offset	76.3RT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			SHALE, soft, gray							
	35	50 (6) 50 (6)								
	40	50 (2.5) 50 (3)								
655.7			LIMESTONE, very hard, gray							
	45	50 (0.25) 50 (0.25)								
651.7			SHALE, hard to very hard, gray, with limestone seams							
	50	50 (2) 50 (1)								
	55	50 (1.25) 50 (0.75)								
637.7	60	50 (0.75) 50 (0.25)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7040640.825 East: 2345523.641

The ground water elevation was not determined during the course of this boring.

Driller: R. Cooper Logger: S. O'Sonnor Organization: Terracon Consultants, Inc.

Exhibit A-64

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-01	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1134+78.7	Grnd. Elev.	697.73 ft
		Offset	76.3RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, gray							
632.7 65		50 (0.25) 50 (0)								
70										
75										
80										
85										
90										

Remarks: No seepage observed during drilling. Dry at completion. North: 7040640.825 East: 2345523.641

The ground water elevation was not determined during the course of this boring.

Driller: R. Cooper Logger: S. O'Sonnor Organization: Terracon Consultants, Inc.

Exhibit A-65

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore Version 3.3	County: Tarrant	Hole: WP-02	District: Fort Worth		
	Highway: SH-170	Structure: Bridge	Date: 11/8/2019		
	CSJ: 0	Station: 1136+49.2	Grnd. Elev.: 705.07 ft		
		Offset: 151.2LT	GW Elev.: N/A		

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
		CLAY, stiff, moist, dark brown (CH)			43				PP=4.5
					18	64	41		#200(%)-90; PP=4.5+
703.1		CLAY, stiff, moist, brown and light brown (CH)	0	30	17			140	
5			0	64	18	55	32	121	#200(%)-94; PP=4.5+
10			0	76	22	65	38	132	#200(%)-99; PP=4.5+
692.1		CLAY, stiff, moist, reddish brown (CH)							SPT=26/12in.
15									
687.1		CLAY, stiff, moist, dark gray, shaley (CH)							SPT=61/12in.
20									
683.1		SHALE, soft to hard, moist, gray							
25	50 (3) 50 (2)								
30	50 (2.5) 50 (1.5)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7040922.862 East: 2345558.287

The ground water elevation was not determined during the course of this boring.

Driller: Margarito Logger: Frankie Organization: Terracon Consultants, Inc.

Exhibit A-66

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-02	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/8/2019
CSJ	0	Station	1136+49.2	Grnd. Elev.	705.07 ft
		Offset	151.2LT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			SHALE, soft to hard, moist, gray							
35		50 (2.5) 50 (3.25)								
40		50 (3.25) 50 (1.25)								
45		50 (2) 50 (1.5)								
655.1 50		50 (1.5) 50 (0.25)	SHALE, very hard, moist, gray, with limestone layers							
650.1 55		50 (1.5) 50 (0.5)	SHALE, very hard, moist, gray							
60		50 (1) 50 (0.75)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7040922.862 East: 2345558.287

The ground water elevation was not determined during the course of this boring.

Driller: Margarito Logger: Frankie Organization: Terracon Consultants, Inc.

Exhibit A-67

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore Version 3.3	County	Tarrant	Hole	WP-02	District	Fort Worth
	Highway	SH-170	Structure	Bridge	Date	11/8/2019
	CSJ	0	Station	1136+49.2	Grnd. Elev.	705.07 ft
			Offset	151.2LT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, very hard, moist, gray							
640.1 65		50 (1) 50 (0.75)								
70										
75										
80										
85										
90										

Remarks: No seepage observed during drilling. Dry at completion. North: 7040922.862 East: 2345558.287

The ground water elevation was not determined during the course of this boring.

Driller: Margarito Logger: Frankie Organization: Terracon Consultants, Inc.

Exhibit A-68

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-03	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1133+97.3	Grnd. Elev.	695.36 ft
		Offset	133.5LT	GW Elev.	673.86 ft

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
		CLAY, soft, moist, tan and gray, with iron oxide staining (CH)			30				PP=0.75
			0	40	21	68	45	130	#200(%)-99; PP=4.5+
									PP=4.5+
					19				PP=4.5+
5	19 (6) 19 (6)				20	64	40		#200(%)-99; PP=4.5+
			0	73	21			134	PP=4.5+
									PP=4.5+
									PP=4.5+
10	35 (6) 47 (6)		0	84	20	64	41	131	#200(%)-93; PP=4.5+
684.4		CLAY, stiff to hard, moist, tan and gray, shaley (CH)							
15	15 (6) 14 (6)		0	45	22			130	PP=4.5+
20	50 (5) 40 (6)		0	62	20	59	38	131	#200(%)-96; PP=4.5+
673.4		SHALE, soft, gray							
25	50 (5) 50 (3.5)								PP=4.5+
30	50 (5) 50 (3.5)								

Remarks: Seepage observed at 21.5' during drilling. Dry at completion. North: 7040783.468 East: 2345349.67

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: M. Estrada Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-69

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

2 of 3

WinCore
Version 3.3

County	Tarrant	Hole	WP-03	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1133+97.3	Grnd. Elev.	695.36 ft
		Offset	133.5LT	GW Elev.	673.86 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, soft, gray							
35		50 (4.25) 50 (2)								
658.4			LIMESTONE, very hard, light gray and gray, with shale layers							
40		50 (1) 50 (0.75)								
45		50 (1) 50 (1.5)								
50		50 (2.25) 50 (2.25)								
55		50 (1) 50 (1.25)								
60		50 (1) 50 (0.5)								

Remarks: Seepage observed at 21.5' during drilling. Dry at completion. North: 7040783.468 East: 2345349.67

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: M. Estrada Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-70

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-03	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/9/2019
CSJ	0	Station	1133+97.3	Grnd. Elev.	695.36 ft
		Offset	133.5LT	GW Elev.	673.86 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, light gray and gray, with shale layers							
630.4 65		50 (0.5) 50 (0.25)								
70										
75										
80										
85										
90										

Remarks: Seepage observed at 21.5' during drilling. Dry at completion. North: 7040783.468 East: 2345349.67

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: M. Estrada Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-71

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-07	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/8/2019
CSJ	0	Station	1137+09.9	Grnd. Elev.	705.20 ft
		Offset	84.9RT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, soft, moist, dark brown (CH)							
704.2			CLAY, stiff, dry, reddish brown, with limestone fragments (CH)			28	60	40		#200(%)-85; PP=3.25
				0	36	14			135	PP=4.5+
700.2	5	50 (6) 42 (6)				17				PP=4.5+
			LIMESTONE, soft, tan, weathered, with clay seams							
697.2			CLAY, very stiff, moist, reddish brown, shaley (CH)							
	10	21 (6) 25 (6)		0	40	21	67	43	132	#200(%)-100; PP=4.5+
	15	30 (6) 44 (6)		0	49	21	67	42	134	#200(%)-94; PP=4.5+
				0	75	20			132	
685.2	20	40 (6) 50 (6)								PP=4.5+
			CLAY, hard, moist, gray, shaley (CH)							
	25	37 (6) 45 (6)		0	26	21	63	38	130	#200(%)-99
	30	50 (5) 48 (6)				15				

Remarks: No seepage observed during drilling. Dry at completion. North: 7040749.006 East: 2345729.128

The ground water elevation was not determined during the course of this boring.

Driller: K. Hurst Logger: S. O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-72

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-07	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/8/2019
CSJ	0	Station	1137+09.9	Grnd. Elev.	705.20 ft
		Offset	84.9RT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			CLAY, hard, moist, gray, shaley (CH)							
672.2			SHALE, hard, gray							PP=4.5+
	35	50 (2.25) 50 (1.5)								
	40	50 (1.75) 50 (1.25)								
	45	50 (1.25) 50 (1)								
657.2			LIMESTONE, very hard, gray, with shale seams							
	50	50 (0.5) 50 (0.25)								
	55	50 (0.75) 50 (0.25)								
	60	50 (1.25) 50 (0.5)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7040749.006 East: 2345729.128

The ground water elevation was not determined during the course of this boring.

Driller: K. Hurst Logger: S. O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-73

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	WP-07	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	11/8/2019
CSJ	0	Station	1137+09.9	Grnd. Elev.	705.20 ft
		Offset	84.9RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			LIMESTONE, very hard, gray, with shale seams							
640.2 65		50 (1.5) 50 (75)								
70										
75										
80										
85										
90										

Remarks: No seepage observed during drilling. Dry at completion. North: 7040749.006 East: 2345729.128

The ground water elevation was not determined during the course of this boring.

Driller: K. Hurst Logger: S. O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-74

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs - 2.clg

SH 170 at N Main St

DRILLING LOG

1 of 3

WinCore
Version 3.3

County	Tarrant	Hole	DH-01	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	10/16/2019
CSJ	0	Station	1250+82.7	Grnd. Elev.	640.81 ft
		Offset	79RT	GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		FILL, SAND, very dense, moist, tan and brown, clayey, with gravel (CL)				34	18		
					3				#200(%)-47; SPT=56/11in.
637.8		CLAY, very stiff, moist, gray and brown, shaley (CH)			7				SPT=37/12in.; SS=5,680ppm
5	19 (6) 39 (6)								
630.8 10	50 (4.5) 50 (3.75)				16	55	32		#200(%)-98; PP=4.5+
		SHALE, soft, dark gray							
									SPT=66/12in.
15	18 (6) 50 (3.5)								
									SPT=84/11in. -gravel below 18'
20	11 (6) 37 (6)								
									SPT=71/12in.
25	23 (6) 50 (1.5)								
									CORE RUN 25-30' REC=70%. RQD=58%
			0	41	14			137	
30	50 (1) 50 (0.25)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7044615.055 East: 2356051.988

The ground water elevation was not determined during the course of this boring.

Driller: B. Flemming Logger: Sean O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-3

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.dlg

DRILLING LOG

	County	Tarrant	Hole	DH-01	District	Fort Worth
WinCore	Highway	SH-170	Structure	Bridge	Date	10/16/2019
Version 3.3	CSJ	0	Station	1250+82.7	Grnd. Elev.	640.81 ft
			Offset	79RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, soft, dark gray							
				0	159	14			138	CORE RUN 30-35' REC=78%, RQD=57%
605.8 35		50 (5) 50 (0.5)	SHALE, hard to very hard, dark gray							
				0	20	16			134	CORE RUN 35-40' REC=88%, RQD=32%
40		50 (1.25) 50 (0.25)								CORE RUN 40-45' REC=95%, RQD=93%
45		50 (1) 50 (0.5)								
				0	116	15			137	CORE RUN 45-50' REC=95%, RQD=43%
50		50 (1) 50 (0.75)								
589.8			SHALE, very hard, gray, with shale seams							CORE RUN 50-55' REC=95%, RQD=90%
585.8 55		50 (0.5) 50 (0.25)	SHALE, very hard, dark gray							CORE RUN 55-60' REC=95%, RQD=63%
				0	148	13			140	
60		50 (0.75) 50 (0.5)								-weathered shale below 60'

Remarks: No seepage observed during drilling. Dry at completion. North: 7044615.055 East: 2356051.988

The ground water elevation was not determined during the course of this boring.

Driller: B. Flemming Logger: Sean O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-4

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.dlg

DRILLING LOG

WinCore	County	Tarrant	Hole	DH-01	District	Fort Worth
Version 3.3	Highway	SH-170	Structure	Bridge	Date	10/16/2019
	CSJ	0	Station	1250+82.7	Grnd. Elev.	640.81 ft
			Offset	79RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, very hard, dark gray							CORE RUN 60-65' REC=85%, RQD=18%
575.8 65		50 (1.25) 50 (0.5)								
70										
75										
80										
85										
90										

Remarks: No seepage observed during drilling. Dry at completion. North: 7044615.055 East: 2356051.988

The ground water elevation was not determined during the course of this boring.

Driller: B. Flemming Logger: Sean O'Connor Organization: Terracon Consultants, Inc.

Exhibit A-5

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

DRILLING LOG

WinCore	County	Tarrant	Hole	DH-02	District	Fort Worth
Version 3.3	Highway	SH-170	Structure	Bridge	Date	10/23/2019
	CSJ	0	Station	1251+52.1	Grnd. Elev.	640.55 ft
			Offset	65.7LT	GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
		FILL, CLAY, very stiff, moist, dark brown							
639.6		FILL, GRAVEL, very dense, light gray, with boulders			3				SPT=50/4in.
									SPT=50/1in.
636.6		SHALE, soft, gray			5	22	8		#200(%)-43; SS=1,560ppm
5	40 (6) 42 (6)								
					16	58	33		#200(%)-100; SS=2,000ppm
									-hard below 9'
					15	57	32		#200(%)-100; SPT=77/11.5in.
10	50 (5.25) 50 (4)								
15	50 (3) 50 (2)								-very hard below 15'
20	50 (3) 50 (2.5)								
615.6 25	50 (1.5) 50 (1)	SHALE, hard to very hard, gray							
610.6 30	50 (1.75) 50 (1.75)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7044760.334 East: 2356119.922

The ground water elevation was not determined during the course of this boring.

Driller: T. Young Logger: J. Persyn Organization: Terracon Consultants, Inc.

Exhibit A-6

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	DH-02	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	10/23/2019
CSJ	0	Station	1251+52.1	Grnd. Elev.	640.55 ft
		Offset	65.7LT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, dry, dark gray and gray							
	35	50 (2.5) 50 (1)								
	40	50 (1.25) 50 (1)								
	45	50 (0.75) 50 (0.75)								
	50	50 (1.75) 50 (1)								
588.6			LIMESTONE, very hard, gray, with shale seams							
585.6	55	50 (0.25) 50 (0)								
	60									

Remarks: No seepage observed during drilling. Dry at completion. North: 7044760.334 East: 2356119.922

The ground water elevation was not determined during the course of this boring.

Driller: T. Young Logger: J. Persyn Organization: Terracon Consultants, Inc.

Exhibit A-7

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

WinCore
Version 3.3

DRILLING LOG

County	Tarrant	Hole	DH-03	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	10/28/2019
CSJ	0	Station	1254+47.2	Grnd. Elev.	640.40 ft
		Offset	72.5RT	GW Elev.	N/A

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		FILL, GRAVEL, very dense, moist, brown and tan, with clay			10				SPT=50/6in.
638.4		LIMESTONE, hard, light gray							
5	50 (0.25) 50 (0)								
633.4		SHALE, stiff, moist, gray and brown, weathered							
					17	58	36		#200(%)-98; #40(%)-99.2 SPT-45/12in.
10	50 (5.25) 50 (4.5)								
628.4		SHALE, soft to hard, gray							
15	50 (3) 50 (3)		0	58	15	62	41	122	#200(%)-98; #40(%)-99; PP=4.5+
					16				SPT=86/11in.
20	50 (2.25) 50 (1.75)								
					15				SPT=50/4in.
615.4 25	50 (2.25) 50 (1.75)		0	91	15			131	
		SHALE, very hard, gray							CORE RUN 25-30' REC=98%, RQD=83%
30	50 (1.75) 50 (1.25)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7044625.12 East: 2356416.347

The ground water elevation was not determined during the course of this boring.

Driler: P.M Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-8

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	DH-03	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	10/28/2019
CSJ	0	Station	1254+47.2	Grnd. Elev.	640.40 ft
		Offset	72.5RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, very hard, gray	0	85	14			137	
										CORE RUN 30-35' REC=97%, RQD=53%
35		50 (1.25) 50 (1.5)		0	165	15			140	
										CORE RUN 35-40' REC=88% RQD=75%
40		50 (1) 50 (0.75)								
45		50 (1.25) 50 (1)								
50		50 (1.25) 50 (1)								
55		50 (1) 50 (1)								
581.4			LIMESTONE, very hard, gray							
580.4 60		50 (0.5) 50 (0.25)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7044625.12 East: 2356416.347

The ground water elevation was not determined during the course of this boring.

Driller: P.M Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-9

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

DRILLING LOG

1 of 3

WinCore	County	Tarrant	Hole	DH-04	District	Fort Worth
Version 3.3	Highway	SH-170	Structure	Bridge	Date	10/18/2019
	CSJ	0	Station	1253+61.5	Grnd. Elev.	640.07 ft
			Offset	65.1LT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	Properties MC	Properties LL	Properties PI	Properties Wet Den. (pcf)	Additional Remarks
			FILL, CLAY, moist, tan and brown, silty, with gravel (CL)							
						11				SPT=20/12in.
						7	46	27		#200(%)-59; PP=0.0
636.1			CLAY, soft to stiff, moist, brown, with gravel (CL)			13				SPT=10/12in.
5		5 (6) 3 (6)								
				0	6	26			124	PP=0.75; SS=2,100ppm
10		4 (6) 26 (6)				25	42	27		#200(%)-70; PP=0.5
627.6			SHALE, soft to hard, dark gray							
15		50 (2.5) 50 (2.25)		0	105	15			135	PP=4.5+
										SPT=50/5.5in.
20		50 (2) 50 (1.75)		0	126	15			135	-trace gravel below 20'
										CORE RUN 20-25' REC=60%, RQD=25%
25		50 (3) 50 (2)								
										CORE RUN 25-30' REC=72%, RQD=48%
610.1 30		50 (1.75) 50 (0.5)								

Remarks: No seepage observed during drilling. Dry at completion. North: 7044761.86 East: 2356329.396

The ground water elevation was not determined during the course of this boring.

Driller: T. Young Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-10

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

DRILLING LOG

WinCore
Version 3.3

County	Tarrant	Hole	DH-04	District	Fort Worth
Highway	SH-170	Structure	Bridge	Date	10/18/2019
CSJ	0	Station	1253+61.5	Grnd. Elev.	640.07 ft
		Offset	65.1LT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SHALE, hard to very hard, dark gray	0	107	15			135	
										CORE RUN 30-35' REC=88%, RQD=45%
35		50 (0.75) 50 (0.75)								
										CORE RUN 35-40' REC=53%, RQD=32%
				0	55	13			133	
40		50 (1.5) 50 (1)								
										CORE RUN 40-45' REC=100%, RQD=80%
45		50 (1) 50 (0.5)								
				0	83	19			137	
										CORE RUN 45-50' REC=100%, RQD=93%
50		50 (0.75) 50 (0.5)								
										CORE RUN 50-55' REC=98%, RQD=98%
55		50 (0.75) 50 (0)								
				0	162	12			141	
										CORE RUN 55-60' REC=65%, RQ=37%
60										

Remarks: No seepage observed during drilling. Dry at completion. North: 7044761.86 East: 2356329.396

The ground water elevation was not determined during the course of this boring.

Driller: T. Young Logger: J. Perysn Organization: Terracon Consultants, Inc.

Exhibit A-11

N:\Projects\2019\94195021\Working Files\Diagrams-Drawings-Figures\CAD\CLGs\94195021-bridge logs.clg

IH 30 at Mary's Creek

DRILLING LOG

WinCore Version 3.1	County: Tarrant	Hole: B-852	District: Fort Worth		
	Highway: IH-30	Structure: Bridge	Date: 09/15/20		
	CSJ: 1068-01-214	Station: 852+48.02	Grnd. Elev.: 732.12 ft		
		Offset: 65.12' RT	GW Elev.: N/A		

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	Properties MC	Properties LL	Properties PI	Properties Wet Den. (pcf)	Additional Remarks
			FILL, sandy lean clay, moist, light brown to brown, with gravel							PP: 4.5
										PP: 3.5
	5	6 (6) 6 (6)								
					21.4	12			135	PP: 4.5
723.1	10	11 (6) 11 (6)	CLAY, lean, with sand, stiff to very stiff, moist to wet, light brown to brown, with gravel (CL)			11				PP: 3
	15	26 (6) 25 (6)				10				PP: 3.5
712.6	20	50 (1.3) 50 (0.8)	LIMESTONE, highly weathered, hard to very hard, gray to dark gray, with shale seams and fossils			15				
	25	50 (1) 50 (0.5)				5				25ft-30ft:REC:6%,RQD:10%
	30	50 (0.3) 50 (0.3)								30ft-35ft:REC:93%,RQD:30%
	35	50 (0.3) 50 (0.3)								35ft-40ft:REC88%,RQD:38%
	40	50 (0.3) 50 (0)			128.2	5			154	40ft-45ft:REC:63%,RQD:25%
687.6	45	50 (0.3) 50 (0.3)	SANDSTONE, moderately to completely weathered, very hard, light gray to gray							45ft-50ft:REC:28%,RQD:0%
	50	50 (0.5) 50 (0.3)				13				50ft-55ft:REC:27%,RQD:13%
	55	50 (0.3) 50 (0.3)								55ft-60ft:REC:98%,RQD:58%
672.1	60	50 (0.3) 50 (0)								

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was encountered at 18 feet during drilling.

The ground water elevation was not determined during the course of this boring.

Driller: Rubicon | Logger: TF | Organization: HVJ Associates, Inc.

g:\houston\hou ps\geo\lab info\gint logs\hg1710319.7.2.gpj

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-851	District	Fort Worth
Highway	IH-30	Structure	Bridge	Date	09/18/20
CSJ	1068-01-214	Station	851+51.25	Grnd. Elev.	730.58 ft
		Offset	30.57' RT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	MC	LL	PI	Wet Den. (pcf)	Additional Remarks
			CLAY, lean, soft, moist, brown, dark brown and light brown, with gravel and sandy at 2'-5' (CL)			23				PP: 2
						9	38	22		PP: 3.5 %Pass #200 Sieve: 86
		10 (6) 10 (6)								PP: 4.5
725.1	5		CLAY, lean, sandy, soft, moist, brown to light brown, with gravel and weathered limestone fragments (CL)							PP: 4.5
		5 (6) 5 (6)				9	38	19		PP: 4.5 %Pass #200 Sieve: 50
	10									
717.6		50 (0.8) 50 (0.3)	LIMESTONE, slightly to highly weathered, hard to very hard, light brown and gray, with fossils and intermittent sandstone and shale seams							
	15									15ft-20ft: REC:35%,RQD:11%
		50 (0.3) 50 (0.3)								
	20									20ft-25ft: REC:72%,RQD:71%
		50 (0.5) 50 (0.3)								
705.1	25		SANDSTONE, highly weathered, very hard, dark gray, with fossils							25ft-30ft: REC:87%,RQD:13%
		50 (0.5) 50 (0.3)								
700.1	30		LIMESTONE, completely weathered, very hard, dark gray, with fossils and sandstone seams							30ft-35ft: REC:100%,RQD:8%
		50 (0.3) 50 (0.5)				6				
	35									35ft-40ft: REC:80%,RQD:7%
		50 (0.5) 50 (0.3)								
690.1	40		SANDSTONE, moderately to completely weathered, hard to very hard, gray, with intermittent shale seams							40ft-45ft: REC:63%,RQD:0%
		50 (0.5) 50 (0.5)								
	45									45ft-50ft: REC:62%,RQD:7%
		50 (0.8) 50 (0.5)								
	50				2085.2	23			113	50ft-55ft: REC:100%,RQD:67%
		50 (0.5) 50 (0.5)								
	55									55ft-60ft: REC:58%,RQD:10%
		50 (0.8) 50 (0.8)								
670.6	60									

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.

The ground water elevation was not determined during the course of this boring.

Driller: Rubicon   Logger: AM   Organization: HVJ Associates, Inc.

g:\houston\hou ps\geo\lab info\gint logs\hg1710319.7.2.gpj

IH 30 at Chapel Creek

DRILLING LOG

WinCore	County	Tarrant	Hole	HM-904	District	Fort Worth
Version 3.1	Highway	IH-30	Structure	High Mast Lamp Post	Date	10/8/21
	CSJ	1068-01-214	Station	903+65.19	Grnd. Elev.	763.68 ft
			Offset	68.99' RT	GW Elev.	N/A

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			SAND, clayey, very dense, moist, light brown, with limestone fragments (SC)		25.7	10	41	24	136	PP: 3.0
		50 (2.5) 50 (1)				9				PP: 4.5 % Pass #200 Sieve: 47.1
760.2		50 (0.5) 50 (0.3)	LIMESTONE, moderately to highly weathered, very hard, light gray and gray, with intermittent shale layers at 20'-30' and 35'-40'							
5										5ft-10ft: REC: 81%, RQD: 35%
		50 (0.5) 50 (0.3)								
10					178.9	12			146	10ft-15ft: REC: 96%, RQD: 73%
		50 (0.3) 50 (0.3)								
15										15ft-20ft: REC: 98%, RQD: 60%
		50 (0.5) 50 (0.3)								
20										20ft-25ft: REC: 100%, RQD: 25%
		50 (0.3) 50 (0.3)								
25						5				25ft-30ft: REC: 100%, RQD: 47%
		50 (0.3) 50 (0.3)								
30										30ft-35ft: REC: 96%, RQD: 66%
		50 (0.3) 50 (0.3)								
35					79.1	9			146	35ft-40ft: REC: 96%, RQD: 42%
		50 (0.5) 50 (0.3)								
40										40ft-45ft: REC: 98%, RQD: 80%
719.2		50 (0.5) 50 (0.3)								
45			SHALE, slightly weathered, very hard, dark gray, with intermittent limestone layer at 45'-48'			2				45ft-50ft: REC: 100%, RQD: 100%
		50 (0.5) 50 (0.3)								
713.7 50										

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.

The ground water elevation was not determined during the course of this boring.

Driller: Rubicon Logger: AH Organization: HVJ Associates, Inc.

g:\houston\hou ps\geo\lab info\gint logs\hg1710319.7.2.gpj

DRILLING LOG

		County	Tarrant	Hole	O(RW)-907	District	Fort Worth
WinCore		Highway	IH-30	Structure	Overhead Sign	Date	11/17/21
Version 3.1		CSJ	1068-01-214	Station	907+02.04	Grnd. Elev.	768.89 ft
				Offset	63.13' RT	GW Elev.	N/A

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	Properties MC	Properties LL	Properties PI	Properties Wet Den. (pcf)	Additional Remarks
			CLAY, lean, sandy, hard to very hard, moist, brown and gray, with gravel (CL)			10	27	14		PP: 4.5
		50 (4.5) 50 (2.5)				12				% Pass #200 Sieve: 62.3 PP: 4.5
		50 (0.8) 50 (0.5)								
763.4	5		LIMESTONE, highly weathered, very hard, gray		579.7	7			157	5ft-10ft: REC: 81%, RQD: 7%
		50 (0.3) 50 (0.3)								
	10	50 (0.5) 50 (0.3)								10ft-15ft: REC: 100%, RQD: 27%
753.4	15		SHALE, moderately to highly weathered, very hard, gray, with intermittent limestone layers							15ft-20ft: REC: 96%, RQD: 59%
		50 (0.5) 50 (0.3)								
	20				657.8	8			150	20ft-25ft: REC: 96%, RQD: 43%
		50 (0.5) 50 (0.3)								
743.4	25		LIMESTONE, highly to completely weathered, very hard, gray, with intermittent clay layers at 45'-50'			2				25ft-30ft: REC: 100%, RQD: 0%
		50 (0.3) 50 (0.3)								
	30									30ft-35ft: REC: 100%, RQD: 15%
		50 (0.5) 50 (0.3)								
	35									35ft-40ft: REC: 96%, RQD: 6%
		50 (0.5) 50 (0.3)								
	40				143.2	9			143	40ft-45ft: REC: 96%, RQD: 35%
		50 (0.5) 50 (0.3)								
	45									45ft-50ft: REC: 86%, RQD: 8%
		50 (0.5) 50 (0.3)								
718.9	50									

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.

The ground water elevation was not determined during the course of this boring.

Driller: Rubicon Logger: BK Organization: HVJ Associates, Inc.

g:\houston\hou ps\geo\lab info\gint logs\hg1710319.7.2.gpj

IH 20 – Site 1

DRILLING LOG

WinCore	County	Tarrant	Hole	P-4	District	Fort Worth
Version 3.1	Highway	IH20	Structure	Pavement	Date	02/10/2022
	CSJ		Station		Grnd. Elev.	877.11 ft
			Offset		GW Elev.	ft

Elev. (ft)	Depth	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, lean, very stiff, moist, brown, with sand and organics (CL)			16.3				PP: 1.5 Sulfate Content < 100 ppm
875.1			CLAY, lean, sandy, very stiff, moist, brown, with iron oxides, iron staining, and limestone fragments below 2.5 feet (CL)			13.1	48	35		%Pass #4 Sieve: 85.2 %Pass #40 Sieve: 72.7 %Pass #200 Sieve: 66.8 SPT: 5,6,7
						17.0				Sulfate Content: 2773 ppm SPT: 4,4,11
	5	50 (6) 7 (6)								
870.6			CLAY, fat, hard, moist, dark brown, with limestone fragments (CH)			16.6	53	38		%Pass #4 Sieve: 84.9 %Pass #40 Sieve: 74.9 %Pass #200 Sieve: 71.1 SPT: 7,12,11
						17.1				PP: 1.0
	10	50 (4) 42 (6)								
864.1			CLAY, fat, very soft to stiff, moist, brown, with iron oxides, iron staining, and limestone fragments (CH)			18.5	52	37		%Pass #4 Sieve: 85.1 %Pass #40 Sieve: 79.6 %Pass #200 Sieve: 76.6 PP: 2.5
	15	1 (6) 1 (6)								
						12.9				PP: 1.5
857.1	20	33 (6) 9 (6)								

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.
Northing: 6942107.513, Easting: 6942107.513

The ground water elevation was not determined during the course of this boring.

Driller: Savage Logger: JS Organization: HVJ Associates®

g:\dal ps\geo\projects\21\dg-21-10446 - walsh ranch parkway and minor 1 underpasses at ih 20, htnb\1.2_boring logs\walsh ranch -as 5-13-2022.gpj

IH 20 – Site 2

DRILLING LOG

1 of 4

WinCore
Version 3.1

County	Tarrant	Hole	B-1	District	Fort Worth
Highway	IH20	Structure	Bridge	Date	02/10/2022
CSJ		Station		Grnd. Elev.	921.68 ft
		Offset		GW Elev.	ft

Elev. (ft)	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
		CLAY, fat, sandy, stiff, moist, brown, with organics (CH)	0	45	25.4			124.3	PP: 1.5
919.7		CLAY, lean, stiff, moist, light brown, trace sand, gravel, iron oxides and iron staining (CL)			12.5	45	32		%Pass #4 Sieve: 98.9 %Pass #40 Sieve: 92.7 %Pass #200 Sieve: 87.7 PP: 1.5
					13.3				SPT: 8,6,6
5	12 (6) 7 (6)								
					12.1	36	14		%Pass #4 Sieve: 97.0 %Pass #40 Sieve: 88.5 %Pass #200 Sieve: 82.3 PP: 4.5
913.7		CLAY, lean, stiff, moist, light brown, with sand and trace gravel (CL)							
					13.1	34	21		%Pass #4 Sieve: 93.3 %Pass #40 Sieve: 80.9 %Pass #200 Sieve: 76.2 PP: 4.5 Sulfate Content < 100 ppm
10	8 (6) 13 (6)								
908.2		CLAY, lean, sandy, hard, moist, light brown, with gravel and limestone fragments (CL)			8.2	37	23		%Pass #4 Sieve: 78.7 %Pass #40 Sieve: 59.8 %Pass #200 Sieve: 55.5 SPT: 24,27,50/6"
15	50 (3) 50 (3.25)								
903.2		SHALE, highly weathered, soft, dark gray			20.6				SPT: 11,50/3"
901.7 20	50 (1) 50 (0.12)								

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.
Northing: 6943784.983, Easting: 2258458.691

The ground water elevation was not determined during the course of this boring.

Driller: Savage Logger: JS Organization: HVJ Associates®

g:\dal psigeo\projects\21\dg-21-10446 - walsh ranch parkway and minor 1 underpasses at ih 20, htnb\1.2_boring logs\walsh ranch -as 5-13-2022.gpj

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-1	District	Fort Worth
Highway	IH20	Structure	Bridge	Date	02/10/2022
CSJ		Station		Grnd. Elev.	921.68 ft
		Offset		GW Elev.	ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test Lateral Press. (psi)	Triaxial Test Deviator Stress (psi)	Properties MC	Properties LL	Properties PI	Properties Wet Den. (pcf)	Additional Remarks
			LIMESTONE, hard to very hard, gray, with interbedded shale seams							
										20ft-25ft: REC:100%, RQD:55%
		50 (2.25) 50 (1.25)								
25										
				0	1186.3	6.4			152.1	
										25ft-30ft: REC:93%, RQD:78%
30		50 (0.5) 50 (0.75)								
										30ft-35ft: REC:88%, RQD:67%
35		50 (0.75) 50 (0.25)								
				0	1069.1	5.8			153	35ft-40ft: REC:87%, RQD:55%
40		50 (0.5) 50 (0.25)								

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.
Northing: 6943784.983, Easting: 2258458.691

The ground water elevation was not determined during the course of this boring.

Driller: Savage Logger: JS Organization: HVJ Associates®

g:\dal ps\geo\projects\21\dg-21-10446 - walsh ranch parkway and minor 1 underpasses at ih 20, htnb\1.2_boring logs\walsh ranch -as 5-13-2022.gpj

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-1	District	Fort Worth
Highway	IH20	Structure	Bridge	Date	02/10/2022
CSJ		Station		Grnd. Elev.	921.68 ft
		Offset		GW Elev.	ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, hard to very hard, gray, with interbedded shale seams							
										40ft-45ft: REC:90%, RQD:62%
45		50 (0.5) 50 (0.25)								
										45ft-50ft: REC:93%, RQD:48%
50		50 (0.75) 50 (0.25)								
										50ft-55ft: REC:83%, RQD:57%
55		50 (0.25) 50 (0.5)								
										55ft-60ft: REC:100%, RQD:60%
60		50 (0.5) 50 (0.25)								

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.
Northing: 6943784.983, Easting: 2258458.691

The ground water elevation was not determined during the course of this boring.

Driler: Savage Logger: JS Organization: HVJ Associates®

g:\dal ps\geo\projects\21\dg-21-10446 - walsh ranch parkway and minor 1 underpasses at ih 20, htnb\1.2_boring logs\walsh ranch -as 5-13-2022.gpj

DRILLING LOG

WinCore
Version 3.1

County	Tarrant	Hole	B-1	District	Fort Worth
Highway	IH20	Structure	Bridge	Date	02/10/2022
CSJ		Station		Grnd. Elev.	921.68 ft
		Offset		GW Elev.	ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			LIMESTONE, hard to very hard, gray, with interbedded shale seams							
										60ft-65ft: REC:93%, RQD:53%
65		50 (0.5) 50 (0.25)								
										65ft-70ft: REC:100%, RQD:53%
70		50 (0.5) 50 (0.25)								
										70ft-75ft: REC:100%, RQD:55%
846.7 75		50 (0.5) 50 (0.25)								
80										

Remarks: PP: Pocket Penetrometer readings are in tsf. Groundwater was not encountered during drilling.
Northing: 6943784.983, Easting: 2258458.691

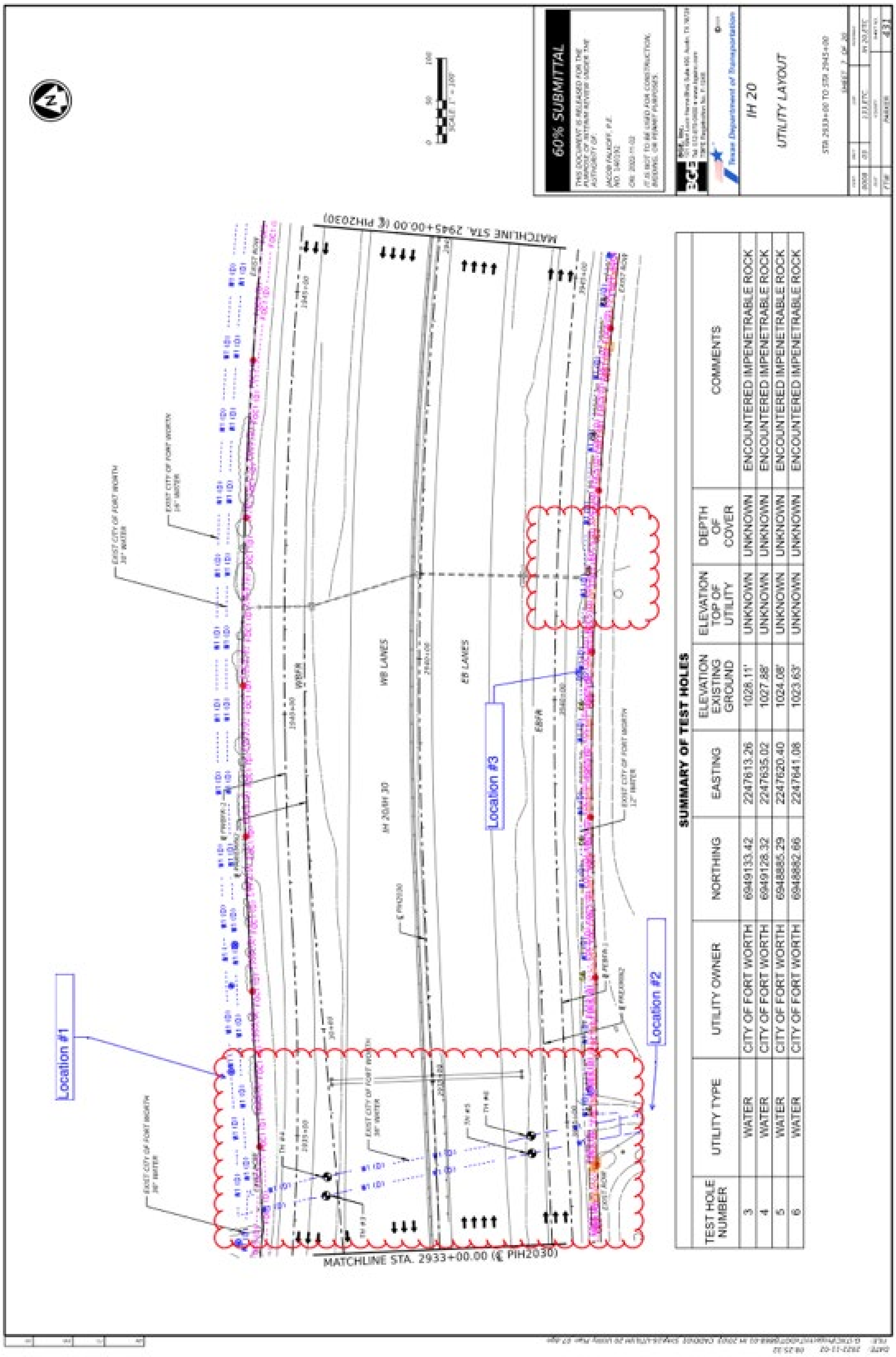
The ground water elevation was not determined during the course of this boring.

Driller: Savage Logger: JS Organization: HVJ Associates®

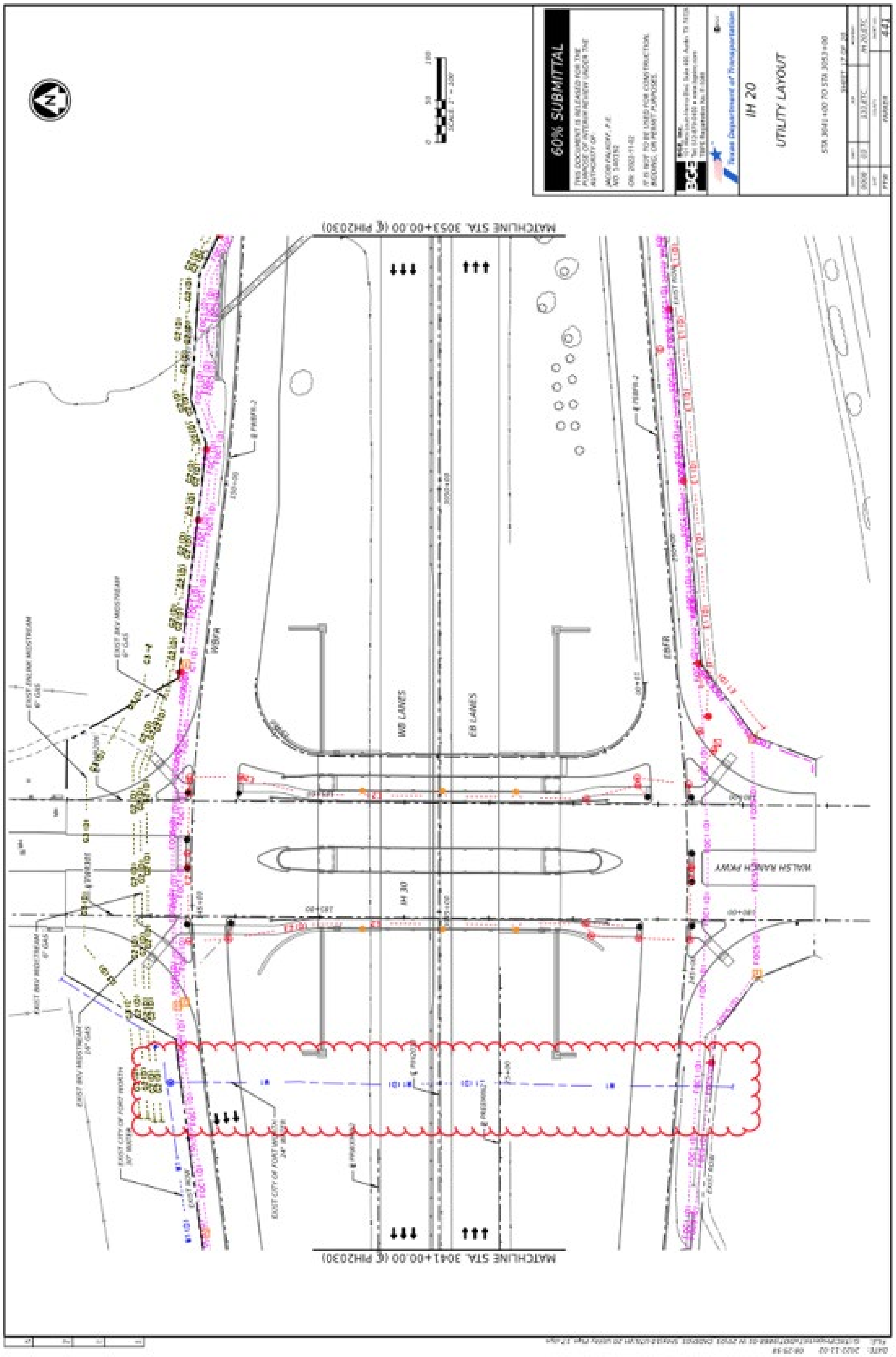
g:\dal ps\geo\projects\21\dg-21-10446 - walsh ranch parkway and minor 1 underpasses at ih 20, htnb\1.2_boring logs\walsh ranch -as 5-13-2022.gpj

APPENDIX B – ADDITIONAL DOCUMENTS

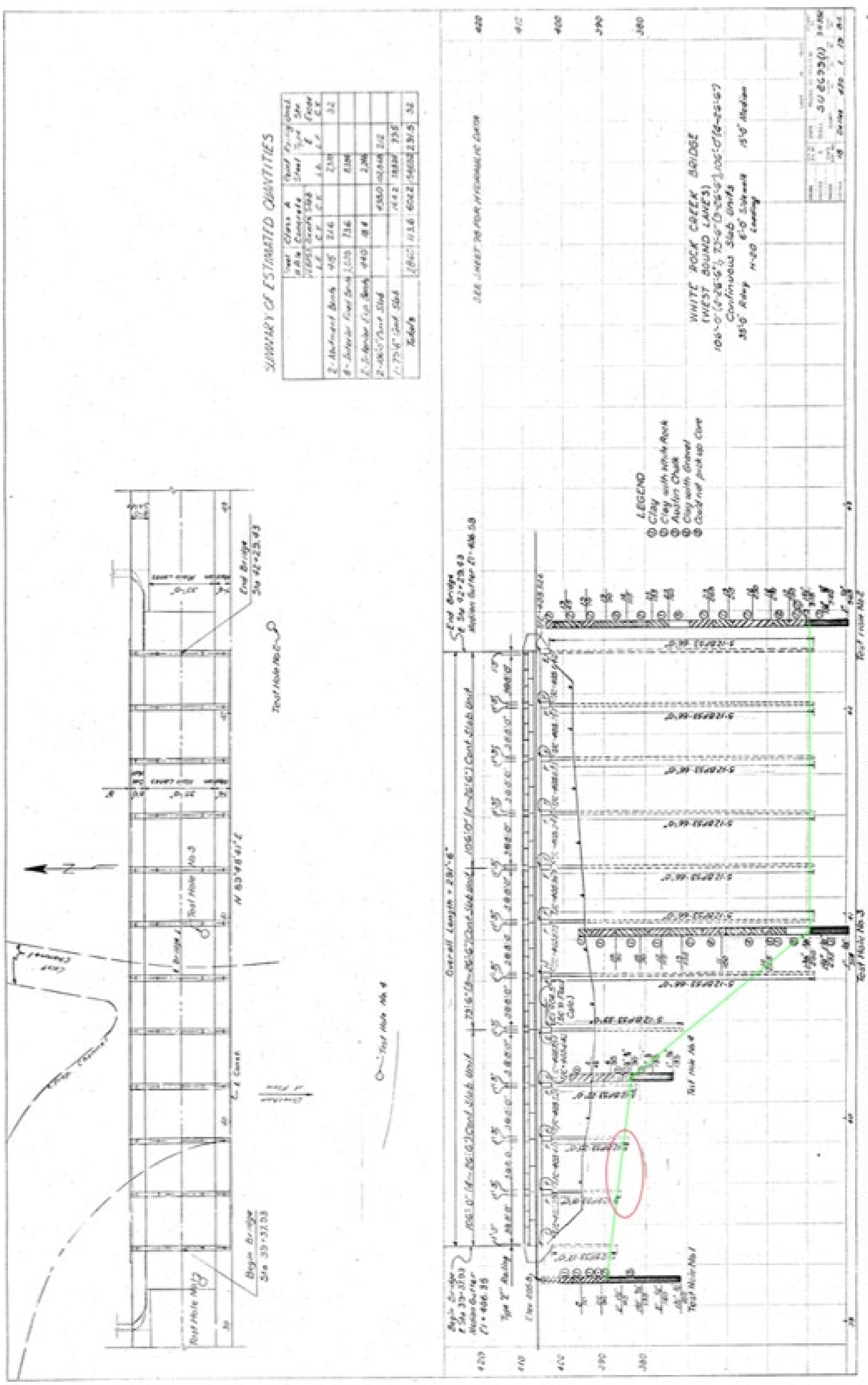
Utility Layout – IH 20 East of Farmer Rd



Utility Layout – IH 30 at Walsh Ranch Pkwy



Bridge Layout – SH 352 at White Rock Creek



APPENDIX C – TYPICAL RANGES OF RESISTIVITY OF EARTH MATERIALS

Typical ranges of electrical resistivity of different earth materials (Shahandashti et al., 2021)

Earth Material		Resistivity (ohm-m)
Sedimentary rocks	Conglomerate	2×10^3 - 10^4
	Sandstone	$8 – 7.4\times10^8$
	Consolidated shale	20 - 2×10^3
	Limestone	50 - 10^7
	Dolomite	3.5×10^2 - 5×10^3
Terrain materials	Unconsolidated wet clay	20
	Clays (moist to dry)	1 - 100
	Alluvium and sands	10 - 800
	Clay and marl	1 - 100
	Loam	5 - 80
	Gravel (moist to dry)	$100 – 1.4\times10^3$
	Topsoil	50 - 120
	Clayey soil	100 - 150
	Sandy soil	8×10^2 - 5×10^3
	Loose sands	10^3 - 10^5
	River sand and gravel	10^2 - 9×10^4
	Glacial till	50 - 100
Igneous rock	Granite (weathered to unweathered)	3×10^2 - 1.3×10^6
	Diorite	1.9×10^3 - 10^5
	Andesite	4.5×10^4 - 1.7×10^7
	Basalt	10 - 1.3×10^7
	Gabbro	10^2 - 10^6
Metamorphic rock	Hornfels	8×10^3 - 6×10^7
	Schist (calcareous and mica)	20 - 10^4
	Schist (graphite)	10 - 5×10^2
	Marble	10^2 - 2.5×10^8
	Quartzite	2.5×10^2 - 2.5×10^8
	Gneiss	6.8×10^4 - 3×10^6
	Slate	5×10^2 - 4×10^7
Water	Fresh groundwater	10 – 100
	Seawater	2×10^{-1}
	Ice	10^3 - 10^5
Permafrost		$10^2 <$

APPENDIX D – CASE STUDIES

CASE STUDIES

Implementation of Electrical Resistivity Imaging (ERI) Manual

JUN 2023

Mohsen Shahandashti, Ph.D., P.E.
(Principal Investigator)

TxDOT Project #0-7008-01 and 5-7008-01

University of Texas at Arlington
in collaboration with
Texas Department of Transportation

ERI FOR MAPPING SULFATE CONCENTRATION ZONES

CASE STUDY 1

LOCATION

- Eagle Ford and Shady Ridge loops, Dallas County, Dallas, Texas.

GENERAL SITE INFORMAION

- Eagle Ford Formation.
- A dense crushed limestone layer (<1.5 feet depth) at the top.
- Stiff to hard, fat (CH) and lean (CL) clays from 1.5 feet up to 20 feet.
- Plasticity index in the range of 14 to 45.
- Sulfate concentration up to 22,080 ppm.

Implemented in April 2022.

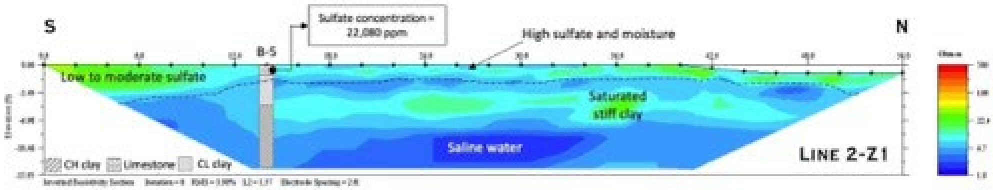
ERI LINE CONFIGURATIONS

- Three lines using 28 electrodes with 3-feet spacings to penetrate to a depth of 15 feet.
- Eight lines using 28 electrodes with 2-feet spacing to penetrate to a depth of 10 feet.

Page 1

THE RESULTS

(EXAMPLES OF RESISTIVITY IMAGES)

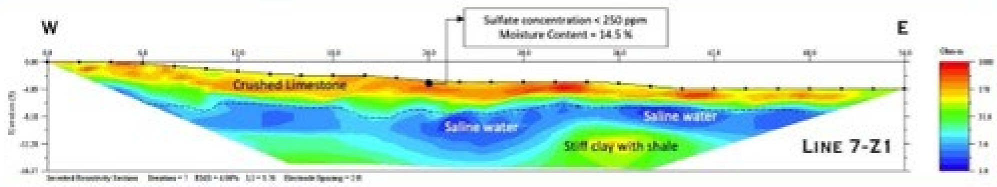


Interpretations

- Low variations in the electrical resistivity between 1 to 50 Ω.m through the profile depth, indicating the existence of similar earth materials.
- Less resistive areas below 10 Ω.m at the top, indicating **high** sulfate concentration levels (above 8000 ppm).

Additional Information

- Laboratory test results show a sulfate concentration of 22,080 ppm at 14 feet distance.
- Electrical resistivity of crushed limestone is above 50 Ω.m.



Interpretations

- Significant resistivity contrast ranging from 1 to 1000 Ω.m.
- High resistive areas at the top above 60 Ω.m associated with dense crushed limestone, indicating **low** sulfate concentration level (below 3000 ppm).

Additional Information

- Laboratory test results show low water and sulfate concentration levels at 24 feet distance.

LESSONS LEARNED

- The ERI will assist TxDOT in determining roadway segments that are unlikely to suffer from sulfate-induced heaving as well as areas that may contain critical sulfate concentrations.
- Sulfate concentration maps can be generated based on the ERI results to help eliminate unnecessary site investigations that are costly and time-consuming.

Generated Sulfate Concentration Map

Page 2

ERI FOR DELINEATING GROUNDWATER TABLE

CASE STUDY 2

LOCATION

- Ronald Reagan Memorial Highway, Parker County, Fort Worth, Texas.

GENERAL SITE INFORMAION

- Kiamichi Formation with alternating clay and limestone layers.
- Fat (CH) and lean (CL) clays with limestone fragments up to 18 feet.
- Highly weathered shale with 2 feet thickness underlaid clays.
- Hard to very hard limestone from 20 to 75 feet.
- Plasticity index in the range of 14 to 32.
- No groundwater at the site during drilling up to 75 feet.

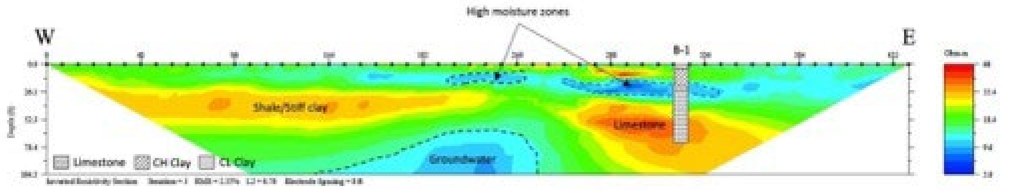
Implemented in December 2022.

ERI LINE CONFIGURATIONS

- One line using 56 electrodes with 8-feet spacings to penetrate to a depth of 88 feet.

Page 3

THE RESULTS



Interpretations

- Two resistive zones on either sides with a maximum electrical resistivity of 68 Ω.m, representing relatively hard materials such as limestone, shale, and stiff clays.
- Resistive layers are bound with less resistive areas with electrical resistivities of about 5 Ω.m, indicating recharge zones centered at 10 and 20 feet depths.
- Conductive zone with electrical resistivity below 10 Ω.m on the bottom-middle of profile at 78 feet depth indicates a potential groundwater table.

Additional Information

- Electrical resistivity of limestone, shale, stiff clays are above 50 Ω.m.
- An 0.08 inches of precipitation was recorded at the site within a week before surveys.
- Electrical resistivity of saturated materials are below 10 Ω.m.

LESSONS LEARNED

- The ERI will help TxDOT identify the potential groundwater table and recharge zones (where water infiltrates the subsurface and replenishes groundwater resources) between the boreholes, allowing proper site characterization and design considerations.

- Potential groundwater table can be inferred by observing saturated zones, characterized by electrical resistivities below 10 Ω.m, that extend down to the bottom of resistivity images.

ERI FOR INSPECTING RETAINING WALLS

CASE STUDY 3

LOCATION

- South freeway at the rail road, Tarrant County, Fort Worth, Texas.

GENERAL SITE INFORMAION

- Fort Worth Limestone and Duck Creek Formation.

Drainage problem behind the wall.

ERI LINE CONFIGURATIONS

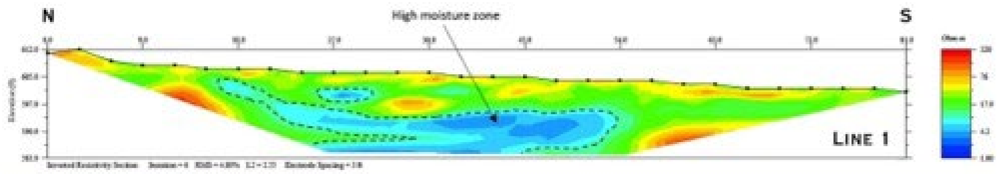
- Two lines on south side of the railroad using 28 electrodes with 3-feet spacings to penetrate to a depth of 16 feet.
- Two lines on north side of the railroad using 28 electrodes with 4-feet spacings to penetrate to a depth of 22 feet.

Implemented in February 2023.

Page 5

THE RESULTS

(EXAMPLES OF RESISTIVITY IMAGES)

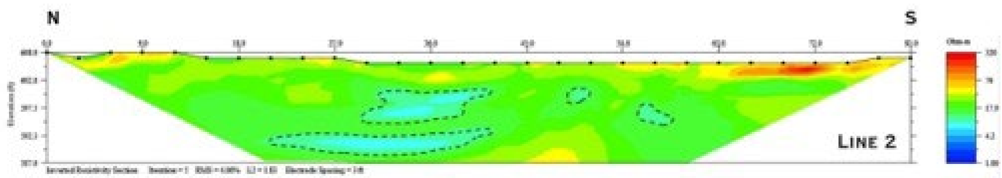


Interpretations

- Intermittent high resistive areas with electrical resistivities up to 320 Ω.m at the top 6 feet, indicating dry and relatively hard subsurface materials.
- Less resistive areas close to the retaining wall, representing saturated subsurface conditions.
- Source of water seepage is potentially observed at six (6) feet depth on the south side of the railroad.

Additional Information

- An 0.57 inches of precipitation was recorded at the site a week before surveys.



Interpretations

- High resistive areas at the top, representing dry and relatively hard materials
- Lower extent of saturated zones as the distance from the wall increases, compared to Line 1.

LESSONS LEARNED

- Without additional site information, it is expected that the ERI will help TxDOT to gain insights into the distribution of high moisture zones to conduct hydrological site assessments and address drainage issues.

- High moisture zones in resistivity images can be indicators of potential locations with drainage problems.

ERI FOR ASSESSING SLOPE STABILITY

CASE STUDY 4

LOCATION

- IH 30 at Chapel Creek Blvd, Tarrant County, Fort Worth, Texas.

GENERAL SITE INFORMAION

- Goodland Limestone Formation.
- Clayey sand (SC) and lean clay (CL) in the shallow subsurface up to 6 feet.
- Limestone and weathered shale from 6 to 50 feet.
- Plasticity index in the range of 14 to 24.
- No groundwater at the site during drilling up to 50 feet.

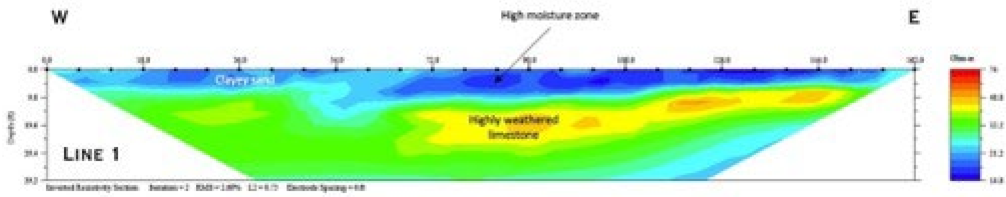
Implemented in December 2022.

ERI LINE CONFIGURATIONS

- Two lines using 28 electrodes with 6-feet spacings to penetrate to a depth of 33 feet.

Page 7

THE RESULTS

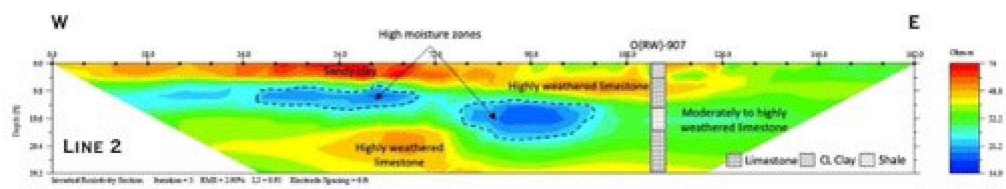


Interpretations

- Low variation in the electrical resistivity through the depth of the profile, ranging from 14 to 50 Ω.m.
- Top clayey sand layer, retaining high moisture up to 10 feet, may be concerning in terms of shallow slope failure.

Additional Information

- An 0.49 inches of precipitation was recorded within a week before surveys.
- Electrical resistivity of saturated materials are below 10 Ω.m.



Interpretations

- Top high resistive layer with electrical resistivity of 74 Ω.m, representing dry to moist sandy clay.
- Top layer is underlaid by two high moisture zones at depths of 10 feet (west side) and 20 feet (east side), which may cause shallow slope failure.
- Relatively high resistive layer at the bottom indicates limestone formation with varying depths.

LESSONS LEARNED

- The ERI will provide a continuous subsurface condition assessment to help TxDOT locate zones with weak shear strength and evaluate shallow slope failure susceptibility between the boreholes or in areas with no borehole information.

- The high moisture and less resistive zones are the potential locations that may initiate slope instability.

Page 8

ERI FOR IDENTIFYING CRITICAL SULFATE CONCENTRATION ZONES

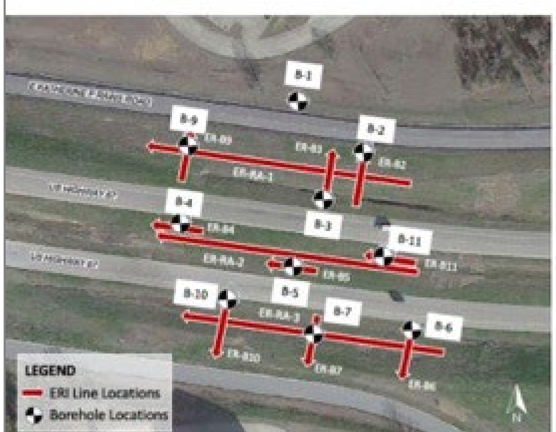
CASE STUDY 5

LOCATION

Highway US 67, Johnson County, Fort Worth, Texas.

GENERAL SITE INFORMAION

- Woodbine Formation.
- Lean clay (CL) and fat clay (CH).
- Clayey sandy (SC) with varying depth from one to nine feet at some locations.
- Dense layer (shale) at a depth of at least 9 feet at some locations.
- Trace of water at a minimum depth of 10 feet at a few soil borings.
- Sulfate concentrations of above 16,000 ppm.



Implemented in December 2021.

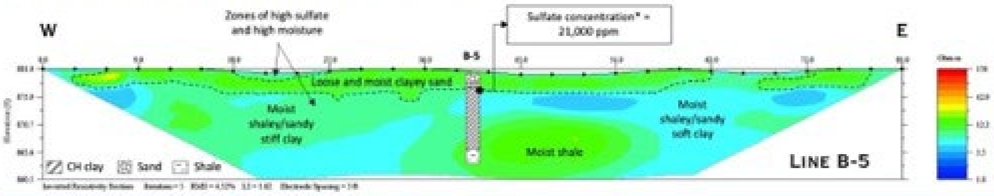
ERI LINE CONFIGURATIONS

- Eight lines using 28 electrodes with 3-feet spacings to penetrate to a depth of 16 feet.
- Three lines using 56 electrodes with 6- and 8-feet spacings to penetrate to a depth of minimum 66 feet.

Page 9

THE RESULTS

(EXAMPLES OF RESISTIVITY IMAGES)

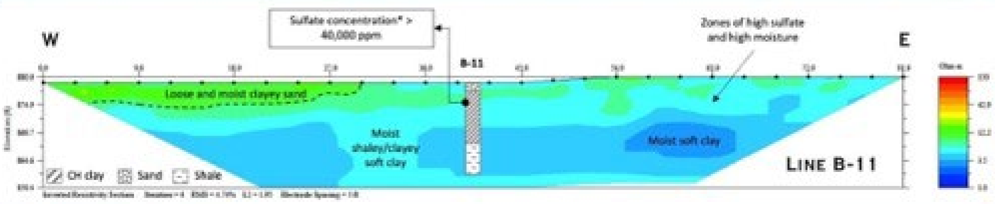


Interpretations

- Low variations in the electrical resistivities, ranging from 3 to 18 Ω.m, indicating the existence of similar earth materials.
- Less resistive zones (<5 Ω.m) within clayey soil at deeper depths, indicating **high** sulfate concentration.

Additional Information

- Boreholes shows different earth materials up to about 15.5 feet, consisting of a clayey sand layer, soft to hard CH with trace of gypsum lenses, and shale.
- Typical ranges of electrical resistivities for sands and shale are above 10 and 20 Ω.m.
- Laboratory test results show a sulfate concentration of 21,000 ppm at 40 feet distance.
- An 0.33 inches of precipitation was recorded within two days before surveys.



Interpretations

- Less resistive zones with a larger extent than Line B-5, indicating a considerable amount of sulfate minerals in the vicinity of borehole B-11.

Additional Information

- Laboratory test results show a sulfate concentration of 40,000 ppm at 40 feet distance.

LESSONS LEARNED

- The ERI will help TxDOT in identifying the extent of critical sulfate concentration zones that cannot be understood from the boreholes since the sulfate concentration in soils varies widely over time and space .
- Inconsistencies between ranges of electrical resistivities and additional information from the site help determine potential locations where alternative materials and pavement designs are needed.

Contact Information

Mohsen Shahandashti, Ph.D., P.E.
Associate Professor
Department of Civil Engineering
College of Engineering
The University of Texas at Arlington
Phone: 817-272-0440
Email: mohsen@uta.edu

APPENDIX E – OUTREACH SUMMARY

WORKSHOP

Electrical Resistivity Imaging Technique for Geotechnical Analysis

TxDOT RTI Projects 0-7008 and 5-7008

Mohsen Shahandashti, Ph.D., P.E.
The University of Texas at Arlington
Summer 2023

The application of advanced geophysical tools, such as the Electrical Resistivity Imaging (ERI) technique, could improve site investigations in the Texas Department of Transportation (TxDOT). It could mitigate cost overruns and delays due to inadequate subsurface investigations. The Electrical Resistivity Imaging technique provides a unique opportunity to reduce these costs and delays by providing (1) continuous subsurface images along with estimated soil properties and potential anomalies (e.g., karst, void) between the boreholes, and (2) additional information about the required drilling and sampling intervals. The ERI technique provides continuous assessment of the subsurface condition using a non-invasive, rapid, and cost-effective method.

This workshop focuses on:

- Significance of subsurface investigations in infrastructure projects
- Benefits/Value of the ERI technology in subsurface characterization
- Deterrents of using the ERI technology and practices to overcome those deterrents
- Presentation of the ERI research manual developed for TxDOT in RTI Project 0-7008 and its application in practice including:
  - Planning considerations for ERI surveys
  - Step-by-step procedures and guidelines for performing ERI surveys
  - Practical considerations regarding different operational environments and extreme weather conditions
- Interpretation of continuous subsurface resistivity images along with the borehole findings
- Demonstration of a training video explaining the field data collection procedure and processing the field data using a software
- Potential applications (e.g., pavement design, maintenance) of the ERI technology
- Statistical analysis and machine learning techniques for determining relationships between the geotechnical and geophysical parameters based on extensive data collection (from 5 different districts)
- Results and findings from successful implementation of the ERI manual in the TxDOT Fort Worth and Dallas Districts (RTI Project 5-7008)