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Developing A Geospatial Web Application for Transportation Geotechnical Asset Management

Ayoub Mohammadi

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DEVELOPMENT OF A GEOSPATIAL WEB APPLICATION FOR TRANSPORTATION GEOTECHNICAL ASSET MANAGEMENT

by

AYOUB MOHAMMADI

THESIS

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Supervising Committee:

Prof. Xinbao Yu, Supervising Professor
Prof. Md. S. Hossain
Prof. Suyun Ham

DEDICATION

Firstly, I would like to express my heartfelt dedication to my wife, Parisa Beigvand, whose unwavering support and patience have been indispensable throughout my academic journey. Furthermore, I extend my sincere gratitude to my family for their enduring love and unwavering support throughout this study. I extend my heartfelt thanks to my dear friends, Houtan Khabazi and Hossein Ganji, for their invaluable assistance and support.

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ABSTRACT

Developing A Geospatial Web Application for Transportation Geotechnical Asset Management

Ayoub Mohammadi

The University of Texas at Arlington, 2023

Supervising Professor: Dr. Xinbao Yu

Spatial data has become an increasingly important tool in geotechnical engineering, allowing for managing and analyzing large amounts of spatial data. In recent years, there has been a growing interest in developing applications that can be accessed by geotechnical engineers from anywhere with an internet connection. This thesis provides a comprehensive overview of the current state of the art in transportation earth structure management. It also highlights the potential benefits of these applications for geotechnical engineers, including open-source applications, database management, and user interface design. It identifies areas for future research and development. The research also discusses the various types of geospatial data that can be used in these applications, such as infrastructure data. Several case studies are presented to illustrate the range of applications for geospatial web applications in transportation earth structure management. These include site selection for new construction projects and analysis of the performance of the assets. This research also highlights the advantages and limitations of these applications, including their potential to improve the efficiency and effectiveness of geotechnical assets and some of the challenges associated with data management and data sharing.

CHAPTER 1:

INTRODUCTION

1.1 Overview

This thesis seeks to explore the innovative integration of geospatial web applications in the realm of transportation infrastructure, specifically concerning the management of geotechnical assets, which include earth structures like embankments, retaining walls, and cut slopes. These geotechnical assets are critical components of transportation networks, playing a pivotal role in ensuring the safety, stability, and longevity of roads, railways, and other vital infrastructure. In an era characterized by rapid technological advancements, adopting geospatial web applications presents a promising avenue for enhancing the efficiency and effectiveness of geotechnical asset management.

The first part of this thesis delves into the foundational aspects of geospatial technology and its relevance in civil engineering, specifically focusing on transportation infrastructure and geotechnical assets. It aims to provide a comprehensive understanding of how geospatial data can be employed to collect, analyze, and visualize critical information related to these geotechnical assets. By doing so, this research seeks to reveal the potential of geospatial web applications in improving decision-making processes, particularly in the planning, design, and maintenance phases of transportation projects.

The subsequent section of the thesis provides case studies and practical applications, showcasing real-world examples where geotechnical asset management has been successfully employed. These case studies will underscore the real benefits of this technology, including improved risk assessment, early detection of issues, and optimized maintenance strategies. By examining these cases, the thesis aims to provide valuable insights and best practices to effectively guide future transportation infrastructure projects leveraging geospatial web applications. Ultimately, this research contributes to the advancement of sustainable and data-driven practices in the management of geotechnical assets within transportation networks, paving the way for safer, more resilient, and efficient infrastructure systems.

1.2 Objective and Scope

This research aims to achieve two primary objectives within the field of transportation geotechnical asset management. Firstly, it aims to explore the efficient utilization of geospatial data in developing web applications designed to manage transportation earth structures. Through the evaluation of geospatial web applications, the research seeks to facilitate data integration, real-time monitoring, and predictive analytics.

At the heart of this research lies the establishment of a dynamic framework, made to ensure the efficient management of transportation geotechnical assets. This framework is designed to adapt seamlessly to the unique requirements and operational details of different agencies.

Furthermore, the research offers comprehensive insights into the creation and implementation of geospatial web applications dedicated to the supervision of transportation earth structures. This emphasizes the importance of transparency and reproducibility in the research process, to provide a standardized approach to geotechnical asset management applicable across diverse agency contexts.

The second objective focuses on utilizing data from the web application to conduct a thorough numerical analysis of a slope within a specified project. This detailed assessment, focusing on factors such as soil properties and implementing an anchor system, reveals a profound exploration of slope stability. The key objective is to acquire deep insights into the behavior of geotechnical assets in different conditions.

1.3 Problem Statement

In the context of transportation infrastructure management, the effective and sustainable management of earth structures, such as embankments, retaining walls, and cut slopes, remains a critical challenge. The traditional data collection, analysis, and decision-making methods are often cumbersome, time-consuming, and lack the real-time insights necessary for proactive maintenance and risk mitigation. Additionally, the lack of standardized approaches and tools for geotechnical asset management across various agencies and operational contexts further compounds the problem. As transportation networks face increasing demands for efficiency, safety, and longevity, there is an urgent need to explore innovative solutions that utilize Geographic Information Systems (GIS) and geospatial web applications to optimize earth structure management processes, enhance decision-making, optimize maintenance strategies, and ensure the resilience and sustainability of these crucial components of our infrastructure.

Based on AASHTO 2011, Transportation Asset Management (TAM) represents a strategic and systematic approach that focuses on both business and engineering principles to efficiently allocate resources to assets over their entire lifespans. In more straightforward language, asset management leads to decision-making regarding the maintenance and utilization of infrastructure. It aims to provide services that account for both present and future requirements, effectively handle potential risks and opportunities, and optimize resource utilization (Alberta Municipal Affairs 2015).

By adopting GAM, the research seeks to provide agencies with a structured approach to asset management and promote uniformity in asset management approaches and decision-making processes. The developed tools will empower agencies to adapt the GAM program according to their specific asset portfolios, operational challenges, and strategic objectives. This research aims to optimize the management of geotechnical assets, leading to enhanced performance, minimized risks, and cost efficiencies across diverse transportation networks geotechnical assets, promoting standardized and organized geotechnical asset management practices on a broader scale.

1.4 Thesis Structure

In Chapter 2, a comprehensive review of existing literature related to geospatial technology, transportation earth structures management, and web applications is conducted. It provides the current state of knowledge and a brief description of these areas.

Chapter 3 outlines the research methodology employed in the study. The chapter details the development and implementation of geospatial web applications for managing transportation earth structures, ensuring transparency and reproducibility of the research process.

In Chapter 4, the research employs data from the web application to conduct a comprehensive numerical analysis on a slope within one of the projects. This analysis enables the exploration of the stability of the slope in detail. The research investigates key factors such as soil properties and geometry to assess the safety and performance of the slope. Through this in-depth examination, the research aims to gain valuable insights into the behavior of geotechnical assets and their response to various conditions, ultimately contributing to a more informed and effective asset management strategy.

The final chapter summarizes the main findings and contributions of the research. Additionally, this chapter offers recommendations for future research and practical applications, encapsulating the essence of the entire thesis.

A reference list for the cited research materials is supplied at the end of each chapter where needed.

1.5 References

AASHTO. 2011. AASHTO Transportation Asset Management Guide: A Focus on Implementation. American Association of Highway and Transportation Officials, Washington, D.C.

Alberta Municipal Affairs. 2015. Getting Started: Toolkit User Guide. Quick Start Tools and Templates for Building an Asset Management Program. Edmonton: Municipal Affairs.

CHAPTER 2:

LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive overview of the terminologies employed in this thesis, focusing on utilizing geospatial web applications for managing transportation earth structures. Various terminologies related to Geotechnical Asset Management (GAM) are briefly discussed herein to ensure clarity and consistency in the subsequent sections.

Furthermore, this chapter provides a concise summary of previous research studies that relate to asset management and its specific application in the geotechnical field. The intent is to establish a context for the current research by acknowledging the existing body of knowledge in this field and identifying relevant insights and findings. Studying research allows us to make justifiable decisions and actions about GAM based on social or economic needs by providing evidence-based insights and understanding of complex issues, thereby enabling informed policymaking and resource allocation. It empowers us to address challenges, identify opportunities, and plan for the future effectively.

The objective of this chapter is to provide a clear understanding of the diverse methodologies that have been utilized to accurately study the geotechnical assets within the scope of this study. By exploring these approaches, this chapter aims to set the stage for the subsequent presentation and examination of the geospatial-based geotechnical asset management web application, which represents a novel and data-driven approach to asset management in the geotechnical field.

Geotechnical Asset Management (GAM) is a strategic approach that combines business and engineering principles to efficiently allocate resources to assets over their lifespans (AASHTO 2011). It facilitates decision-making for infrastructure maintenance and utilization, addressing both immediate and future requirements, potential risks, and the optimization of available resources (Alberta Municipal Affairs 2015). This research endeavors to introduce a structured approach to asset management through GAM, promoting uniformity in decision-making processes across agencies. It aims to equip agencies with adaptable GAM tools adapted to their asset portfolios, operational challenges, and strategic objectives. The goal is to enhance the management of geotechnical assets, thereby improving their performance, minimizing risks, and achieving cost efficiencies across diverse transportation networks, while promoting standardized and organized geotechnical asset management practices on a broader scale.

The thesis's primary objective is to provide insight into methodologies employed for accurately studying geotechnical assets within this study's scope. Exploring these approaches sets the stage for the subsequent presentation and examination of a novel and data-driven geotechnical asset management web application like Genetic Algorithms (GA) and Artificial Neural Network (ANN), designed to optimize asset management in the geotechnical field (Dariane and Behbahani 2023).

Geotechnical Asset Management (GAM) focuses on managing geotechnical assets throughout their lifecycles to ensure optimal performance, safety, and reliability. GAM encompasses strategic planning, evaluation, and decision-making related to these assets. Key components include identifying and cataloging geotechnical assets, assessing risks, establishing maintenance and monitoring programs, and informed decision-making. These processes aim to maximize asset performance and minimize lifecycle costs.

The advantages of Geotechnical Asset Management (GAM) are numerous, including significant financial savings with reported values exceeding 30 percent by the U.S. Army Corps of Engineers (USACE 2013) and 60 percent to 80 percent per unit length of embankment in the United Kingdom (Perry et al. 2003), enhanced safety risk management, improved network performance, reduced economic impact, preservation of other assets, demonstrated stewardship, informed decision-making, effective risk management, prioritization of operations and maintenance decisions, flexibility, simplicity, and reduced compliance burdens (NCHRP 2019). These advantages make GAM a valuable tool for modern infrastructure management and optimization.

2.2 Historical Development of the GAM

The historical development of geotechnical asset management is a journey through time that illuminates the evolution of practices and methodologies in managing geotechnical assets. It is a narrative that reflects the growing recognition of the importance of geotechnical assets in infrastructure systems and the need for effective management strategies.

In the early stages, geotechnical asset management was often overlooked or incorporated into broader asset management practices without specific focus (Sanford Bernhardt et al. 2003). However, as infrastructure systems expanded and became more complex, the unique challenges posed by geotechnical assets became increasingly apparent. These assets, including soil slopes, retaining walls, embankments, and subgrades, play a critical role in the stability and performance of transportation networks, building foundations, and various civil engineering structures. The historical development of geotechnical asset management can be categorized into distinct phases, as represented in Figure 1.

Today, geotechnical asset management has become an integral part of overall asset management strategies in infrastructure management agencies. It continues to evolve with the adoption of innovative technologies, data-driven decision-making, and a growing awareness of the critical role that geotechnical assets play in maintaining resilient and sustainable infrastructure systems. Additionally, as articulated by Sanford Bernhardt et al. (2003), the performance and costs of conventional assets are interconnected, whether directly or indirectly, with the performance of geotechnical assets.

2.3 Geotechnical and Geohazard Assets

2.3.1 Identification of Geotechnical Assets, Asset Inventory, and Data Collection

Effective Geotechnical Asset Management begins with the identification of geotechnical assets and the establishment of a comprehensive inventory. This process involves cataloging various infrastructure components, such as retaining walls, embankments, slopes, tunnels, and underground utilities. Simultaneously, geotechnical data management plays a crucial role in ensuring the success of this phase. Geotechnical data management involves the processes and systems used to collect, organize, store, analyze, and maintain geotechnical data throughout its lifecycle. It focuses on effectively managing the data obtained from site investigations, laboratory testing, monitoring, and other sources.

Figure 1. The historical development of geotechnical asset management.

2.3.2 Comparison of geotechnical data and geotechnical asset management

2.3.2.1 Geotechnical Data Management:

Geotechnical data management involves the processes and systems used to collect, organize, store, analyze, and maintain geotechnical data throughout its lifecycle. It focuses on effectively managing the data obtained from site investigations, laboratory testing, monitoring, and other sources. The key characteristics of geotechnical data management include:

- Data Collection and Processing

Geotechnical data management involves the collection of geotechnical data through various methods and instruments. It includes processes such as data entry, quality control, validation, and interpretation. Data processing techniques may involve data normalization, standardization, and integration.

- Data Organization and Storage

Geotechnical data management involves organizing and storing geotechnical data in a structured manner. This includes establishing a database or data management system that enables efficient storage, retrieval, and access to the data. Metadata, such as data source, collection date, and location, are often associated with the data for proper identification and traceability.

- Data Integration and Interoperability

Geotechnical data management involves integrating data from various sources and formats to create a comprehensive dataset. This may involve integrating data from field investigations, laboratory tests, monitoring systems, and external sources. Interoperability ensures that data can be shared, exchanged, and used across different software platforms and applications.

- Data Analysis and Visualization

Geotechnical data management facilitates data analysis and visualization to extract meaningful insights. This may involve statistical analysis, data visualization techniques, and the use of specialized software or tools. Visualizations, such as charts, graphs, and maps, aid in the interpretation and communication of geotechnical data.

2.3.2.2 Geotechnical Asset Management (GAM):

Geotechnical Asset Management (GAM) focuses on the management of geotechnical assets throughout their life cycle to ensure their optimal performance, safety, and reliability. GAM encompasses strategic planning, evaluation, and decision-making related to geotechnical assets. The key characteristics of geotechnical asset management include:

- Asset Identification and Inventory

GAM involves identifying and cataloging geotechnical assets, such as retaining walls, embankments, slopes, tunnels, or underground utilities. This includes documenting asset characteristics, location, condition, and performance history.

- Risk Assessment and Prioritization

GAM includes risk assessment techniques to evaluate potential risks associated with geotechnical assets. This involves assessing factors such as aging, deterioration, environmental impacts, and potential failure modes. Assets are prioritized based on the level of risk and criticality to determine appropriate management strategies.

- Maintenance and Monitoring

GAM involves establishing maintenance and monitoring programs to ensure the ongoing performance and longevity of geotechnical assets. This may include routine inspections, instrumentation, data collection, and analysis to detect any changes or issues with asset behavior.

- Decision-Making and Optimization

GAM supports decision-making processes related to geotechnical assets. This includes prioritizing maintenance and repair activities, considering asset lifecycle costs, and making informed decisions regarding asset investments, upgrades, or replacements. Optimization strategies aim to maximize asset performance and minimize lifecycle costs.

Table 1 illustrates the key attributes of geotechnical data management and highlights its distinctions from Geotechnical Asset Management. In summary, geotechnical data management is concerned with the effective management of geotechnical data, whereas geotechnical asset management focuses on the management, maintenance, and optimization of geotechnical assets. Both components are essential for successful geotechnical engineering practice, with data management supporting asset management processes.

Table 1. Comparison between Geotechnical Data Management and Geotechnical Asset Management

Geotech Aspects	Geotechnical Data Management	GAM
Scope	Effective collection, organization, storage, and analysis of geotechnical data.	Strategic management, maintenance, and optimization of geotechnical assets over their lifecycle.
Timeframe	Primarily occurs during the project development phase.	Extends beyond project completion and aims to ensure ongoing performance and maintenance of assets.
Purpose	The foundation for analysis, design, and decision-making during project development.	Long-term asset management, risk mitigation, and optimizing asset performance.
Geotech Insights	Management of data collected from various sources.	Management of physical assets, including infrastructure, systems, and resources.

2.3.3 Types and Taxonomy of Geotechnical Assets (e.g., slopes, retaining walls)

Apart from ensuring alignment with stakeholder objectives, the consistent utilization of standardized definitions within a geotechnical asset management (GAM) classification that aligns with other asset management systems can facilitate effective communication across disciplines within an organization and among different agencies. Both the American Association of State Highway and Transportation Officials (AASHTO) and the International Organization for Standardization (ISO) provide definitions of assets that endorse the recommended geotechnical asset classification, including walls, slopes, embankments, material sites, and subgrades as physical assets. (NCHRP 2019, Anderson et al. 2016, AASHTO 2011, ISO 55000 2014).

Geotechnical assets include walls, slopes, embankments, and subgrades, playing a crucial role in enabling a transportation agency to fulfill its strategic mission. Historically, these assets have been regarded as unpredictable hazard sites, posing financial liabilities to operations, or have been disregarded until failures occur, necessitating unplanned interventions. The literature extensively documents various direct and indirect economic consequences that result from the inadequate or below-standard performance of geotechnical assets. (NCHRP 2019, AASHTO 2011, Anderson et al. 2016).

Conversely, it is evident that these assets, when functioning optimally, contribute quantifiable value to the transportation network. Walls, slopes, embankments, and subgrades are indisputably assets that warrant comprehensive management to unlock their potential in terms of measurable life-cycle cost reduction, risk mitigation, and enhanced performance, benefiting both owners and users. This assertion finds support in the achievements of sustainable and successful risk-based geotechnical asset management (GAM) programs, demonstrated by those implemented for passenger rail and highway networks in the United Kingdom. Furthermore, the validity of this taxonomy is supported by several years of practical application of GAM in the transportation systems of the United Kingdom (NCHRP 2019, AASHTO 2011, Anderson et al. 2016, Power et al. 2012).

After reviewing various research works, geotechnical assets can be defined as cut slopes (cuttings) and embankment assets located within the agency's boundaries (Network Rail 2017, Power et al. 2012). Sanford Bernhardt et al. (2003) introduced a categorization of assets based on their function, classifying them as 'exclusively geotechnical,' 'partially geotechnical,' or 'minimally geotechnical' to denote their level of interaction with other transportation assets. In the context of the Alaska Department of Transportation and Public Facilities (Alaska DOT&PF) GAM plan, Thompson (2017) determines geotechnical assets as rock and soil slopes, embankments, retaining walls, and material sites. On the other hand, Anderson et al. (2017) provide a summary of Colorado DOT GAM programs, wherein retaining walls are considered a separate unique asset, while slopes, embankments, and subgrade are grouped under a combined geohazards category.

Further, according to Anderson et al. (2016), geotechnical asset types encompass embankments, slopes, retaining walls, or constructed subgrade within the highway right-of-way (ROW) that contribute to the continuous and safe operation of a transportation network. A taxonomy has been proposed for organizing geotechnical assets into four categories: slopes, embankments, retaining walls, and subgrades. The categories can be further described by their primary material composition, such as soil, rock, debris, or modified, in the case of slopes. Figure 2 shows the taxonomy that Anderson et al. (2016) utilized to categorize geotechnical assets.

Waseem et al. (2022) define geotechnical assets as consisting of natural and constructed soil and rock slopes, earth embankments, and geotechnical structures like retaining walls. This classification also extends to geohazards, such as landslides, erosion sites, and challenging subgrade locations, as they require future capital investments for maintenance or repair.

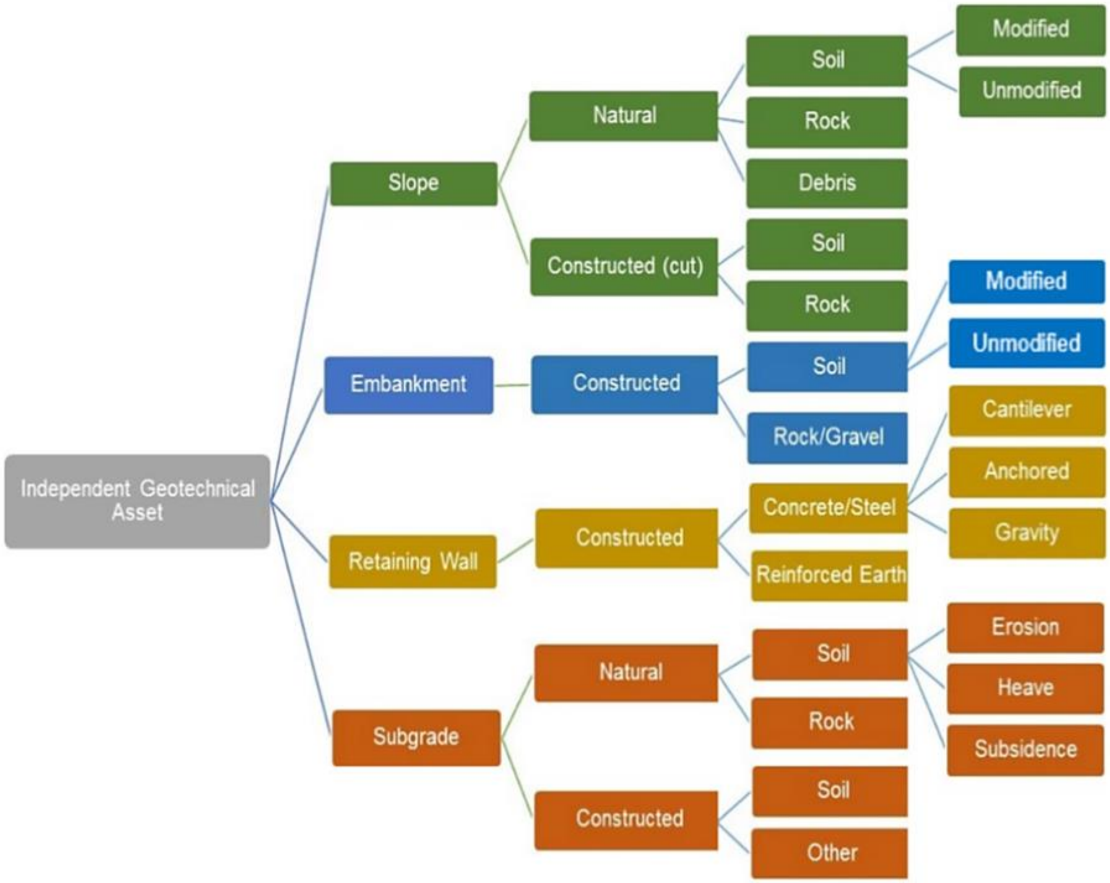


Figure 2- The taxonomy for geotechnical assets proposed by Anderson et al. (2016)

Table 2 provides a concise summary of the various types of geotechnical assets found in different literature.

2.4 Geotechnical Asset Management (GAM)

2.4.1 Definition and Significance

State departments of transportation (DOTs) have long focused on managing bridge and pavement assets, but the management of geotechnical assets, including walls, slopes, embankments, and subgrades, has been overlooked. Throughout the life cycle of a transportation system, it is crucial to recognize the significance of the value and performance of these assets. The effective operation of the transportation system relies not only on the management of bridge and pavement assets but also on the proper handling of geotechnical assets such as walls, slopes, embankments, and subgrades. Neglecting the importance of these assets can have unpleasant consequences, including traveler delays, damage to other assets, and compromised safety. Therefore, by implementing risk-based asset management strategies, system owners and operators can maximize the economic benefits and ensure the smooth and efficient functioning of the entire transportation system (NCHRP 2019).

Table 2. Different types of geotechnical assets in literature.

References	Types of Geotechnical Assets
Sanford Bernhardt et al. (2003)	Indirect assets encompass embankments and slopes (exclusively geotechnical), Direct assets include tunnels, earth retaining structures, culverts, and drainage channel foundations (partially geotechnical), and pavement subgrade (minimally geotechnical).
Network Rail (2017), Power et al. (2012)	Cut slopes (cuttings) and embankments located within the agency's boundaries.
Thompson (2017)	Rock and soil slopes, embankments, retaining walls, and material sites.
Anderson et al. (2017)	Retaining walls and a combined geohazards category contain slopes, embankments, and subgrade.
Anderson et al. (2016)	Embankments, slopes, retaining walls, or constructed subgrade within the right-of-way (ROW).
Waseem et al. (2022)	Natural and constructed soil and rock slopes, earth embankments, retaining walls, and geohazards, such as landslides, erosion sites, and challenging subgrade locations

The lack of legislative instructions for geotechnical asset management (GAM) does not diminish its importance. Without GAM, organizations face unknown risks to traveler safety, mobility, and economic vitality, while potentially making unfavorable investment decisions (NCHRP 2019). The adoption of GAM is crucial to mitigate these risks effectively. It provides a structured approach to identify and assess potential hazards associated with geotechnical assets. Through regular inspections, assessments, and maintenance activities, organizations can proactively address issues before they escalate, ensuring the safety of travelers and minimizing disruptions that can block mobility and economic activities. Moreover, GAM allows organizations to make informed decisions regarding investments in geotechnical assets. By conducting risk assessments and prioritizing resources (considering both performance expectations and risk tolerance), organizations can allocate their funds effectively, focusing on critical areas that require immediate attention. This approach ensures that investments are made strategically and optimally, minimizing unnecessary costs, and maximizing the assets' duration of service.

Fortunately, for owners of geotechnical assets, the implementation of risk-based geotechnical asset management (GAM) can benefit from the practices developed by successful programs. The research revealed successful GAM programs from different countries that were implemented effectively. We can understand the benefits of asset management based on the observed asset performance after implementation. Notably, the United Kingdom has two such programs with over 15 years of implementation experience. Highways England manages 4,400 miles of roadways, encompassing 49,000 slope and embankment earthwork assets that share similarities in age with many geotechnical assets of the Department of Transportation (DOT) in the United States. Similarly, the UK's Network Rail system oversees over 9,800 miles of railway, consisting of 191,000 earthwork assets, a majority of which have surpassed 125 years of age. By combining insights from these programs with other international and domestic geotechnical asset and natural hazard management initiatives, valuable information can be obtained regarding the necessity and benefits of GAM, regardless of asset age. Additionally, implementation concepts derived from these examples can facilitate a rapid return on investment (ROI) (NCHRP 2019, AASHTO 2011, Power et al. 2012).

The primary objective of an asset management system is to establish a logical alignment between asset design, operations, maintenance, and upgrade decisions with the goals and objectives of the organization. To ensure the successful implementation of geotechnical asset management (GAM) throughout the entire organization, the program needs to demonstrate how asset performance impacts both customers and the decision-making process of executives who are primarily focused on agency goals and objectives. To achieve this, it is necessary for asset performance measures related to asset condition, safety impacts, mobility, and economic consequences, to be closely linked to main agency objectives, such as common safety and system performance goals (NCHRP 2019, AASHTO 2016).

A summary of the GAM's significance is presented in Table 3.

Table 3. GAM significances

GAM significance
The effective operation of the transportation system relies not only on the management of bridge and pavement assets but also on the proper handling of geotechnical assets.
Neglecting the importance of these assets can have unpleasant consequences, including traveler delays, damage to other assets, and compromised safety.
Without GAM, organizations face unknown risks to traveler safety, mobility, and economic vitality, while potentially making unfavorable investment decisions.
GAM provides a structured approach to identify and assess potential hazards associated with geotechnical assets.
Through regular inspections, assessments, and maintenance activities, organizations can proactively address issues before they escalate.
Organizations can allocate their funds effectively, focusing on critical areas (considering both performance expectations, risk tolerance, and benefit-cost ratio) that require immediate attention, minimizing unnecessary costs, and maximizing the assets' duration of service.

2.4.2 GAM Framework

The general workflow, as described in the NCHRP (2019) publication, involves maintaining the inventory of assets, and regularly assessing their current condition. This approach uses sophisticated analytical tools to predict how asset conditions or performance may change over time. Furthermore, it includes financial analyses to determine the costs and effectiveness of various treatments, making it easier to reveal significant results or understand the implications of not applying any treatment.

The proposed approach to implementation involves a streamlined process involving the following key stages (Figure 3): 1. Asset Identification and Geolocation: locate and identify assets efficiently considering the asset classification; 2. Condition Class: utilize a categorization system from asset operation to maintenance condition. Use a risk-based GAM rating system applicable to the full range of geotechnical assets, incorporating measures of asset condition and consequences to highway safety and efficiency; 3. Performance Assessment: evaluate the asset performance through supporting field inspection forms for consistent and repeatable asset condition inspections; and 4. Action Recommendations: provide suggestions for enhancing asset performance, determine anticipated investments, and establish priorities for taking action.

Figure 3- Simplified implementation workflow of the GAM

Furthermore, we can consider: Asset List Expansion: start with a limited number of assets and then increase the asset list; Default Asset Model Adjustment: modifying default asset models to enhance accuracy and also adding required features; Staff Involvement: engaging other stakeholders in the application development process; and Outputs: adding the desirable outputs based on stakeholder needs.

2.4.3 Risk Assessment and Decision-Making Systems.

2.4.3.1 Evaluation of Asset State and Performance

- GAM Risk-Based Assessment

In order to better understand and manage risks, it's important to consider the potential impact of uncertainty on our objectives. This includes evaluating the probability of an asset failure or other adverse event, as well as the potential consequences of any damage that might occur as a result. By taking a proactive approach to risk management and mitigation, we can minimize the impact of potential threats and ensure the safety and security of our assets and resources (Waseem et al. 2022)

In the guide to risk and reliability-based engineering for civil structures by the United States Army Corps of Engineers (USACE 2011), the definition of risk is based on the annualized probability of an adverse event occurring and the financial impact of that event on the safety and efficiency of the highway (Equation 1). The USACE approach involves assigning a monetary value to unsatisfactory performance consequences, such as loss of usage. The NCHRP GAM Implementation Manual (2019) also includes a qualitative evaluation of the effects on asset condition and performance.

$$\$Risk = P\text{ (Adverse Event Occurrence) x Monetized Consequence} \qquad (1)$$

Where:
P is the probability of adverse event occurrence, and
Monetized Consequence is the monetary value of the loss in terms of direct cost to the owner and indirect cost to the road users because of the adverse event.

- Probability Level (Condition Class)

The Probability Level for the asset is determined based on its current condition, which ranges from Excellent to Very Poor. This condition serves as an indicator of the probability of experiencing failure or adverse performance in any given year (Waseem et al. 2022). An adverse event is essentially an incident arising from a geotechnical asset that has a noticeable impact on the overall performance of the system (Vessely 2017). This may encompass sudden and isolated incidents like a rockfall reaching the road or a debris flow encroaching upon the right-of-way. It can also relate to cumulative effects from ongoing processes, such as gradual slope failure or the degradation of retaining wall reinforcements. The annualized adverse event rate (AAER) can be computed by utilizing the estimated mean time between adverse events, as described in the equation provided by Vessely (2017) (Equation 2).

$$AAER = 1 - e^{-\frac{1}{t}} \qquad (1)$$

Where:
AAER represents the estimated probability of an adverse event occurring over a full year of use, expressed as a percentage.
t is the mean time between adverse events (in years)

- Consequence Rating

To begin with, as per the work conducted by Waseem et al. (2022), the Consequence Rating for the asset is determined based on the potential effects of adverse performance on highway safety, operational efficiency (resulting in indirect costs to users), and direct expenses for the owner (comprising maintenance, rehabilitation, and reconstruction). This Consequence Rating scale comprises five distinct states: Negligible, Minor, Moderate, Major, and Critical. The primary objective behind establishing this rating scale for consequences was to facilitate the quantification of the impacts on the highway linked to the adverse performance of a geotechnical asset.

- Deterioration Models of Assets

Asset deterioration in geotechnical asset management refers to the gradual or sometimes sudden degradation, wear, or loss of structural or functional integrity of geotechnical assets over time. This deterioration can result from various factors, including environmental conditions, geological changes, usage, and other external forces, leading to a decrease in the asset's performance, safety, or reliability. Effective management of asset deterioration involves monitoring, assessment, and maintenance practices aimed at mitigating or preventing the adverse effects of this degradation to ensure the longevity and optimal functionality of geotechnical assets.

The Colorado DOT's retaining-wall management system, as described by Walters et al. (2016), employs expert judgment to estimate the likelihood of adverse consequences stemming from retaining-wall performance. This system considers maintenance needs and mobility as two key consequence types, which were deemed sufficient to generate risk-based rankings equivalent to those accounting for all types of consequences. In the initial version (Tier 1) of the system, the likelihood of maintenance and mobility consequences were not explicitly estimated. Instead, a wall condition score, based on inspections and ranging from 1 to 4, served as a surrogate. The subsequent version (Tier 2) improved by correlating condition scores with likelihood values from experts and introduced separate scores for maintenance and mobility consequences. The National Bridge Inventory ratings were also used to predict mobility consequences.

One of the most straightforward deterioration models utilizing condition state data is the Markov model. This model quantifies deterioration rates by representing them as the probabilities of transitioning between various condition states on an annual basis (Thompson 2017).

NCHRP (2012) documents the development of Markov deterioration models specifically for geotechnical assets and it was developed by Thompson (2017). The models are predicated on an asset condition or risk rating scale which ranges from State 1 (“Very Good”, no action needed) to State 5 (“Very Poor”, major mitigation required). In addition to the deterioration models proposed by Thompson (2017), the NCHRP (2019) study also presents additional Markov deterioration models for soil and rock slopes, embankments, subgrades, and retaining walls. Notably, this model includes an additional element where, aside from transitioning to the next deteriorated state, they account for a minor probability of sudden asset failure (p_{jf}). The equations used in each model are shown in Table 4.

Table 4. Development of the asset’s deterioration models.

References	Equations
Thompson (2017)	$p_{jj} = 0.5^{\frac{1}{t}}$
NCHRP (2019)	$p_{jk} = 1 - p_{jj} - p_{jf}$

Where:
j is the condition state (before and after 1 year)
t is the transition time in years (the estimated number of years that it takes for 50% of a representative population of assets to deteriorate from each condition state to the next worse one)
p_{jj} is the same state probability one year later in state j.

p_{jk} is the next state probability.
p_{jf} is the probability in one year of failure in state jj.

2.4.3.2 Action Recommendations

The GAM Implementation Manual (NCHRP 2019) classifies various treatment alternatives, providing a range of life-cycle options for assets, from taking no action to implementing robust engineered solutions. This categorization is illustrated in Figure 4, highlighting how these choices impact asset reliability and service life.

Do Minimum

- Performing minimal work necessary for traffic conveyance without adding or preserving life-cycle value.
- Does not imply zero cost for the asset owner.
- Establishes the "base case" for future life cycle cost analyses.

Maintain

- Asset is continually maintained through planned actions.
- Regular, frequent, and short work activities, similar to routine annual maintenance.
- Preservation efforts to fulfill the asset's intended service life, maintaining or surpassing its deterioration rate.

Rehabilitate (Rehab)

- Actions focused on elevating the asset's condition to reach at least the next higher level.
- Typically, rehabilitation treatments aim to extend the asset's service life by improving its condition.

Reconstruct (or Renew)

- Reconstruction treatments reset the asset's condition to Condition State 1, significantly improve O&M performance, and extend the service life before it reaches operational failure.
- They can also address safety and mobility issues while enhancing the asset's condition.

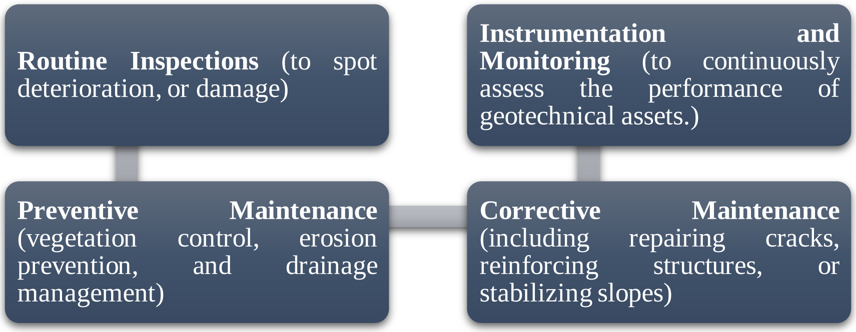
Restore

- A "Restore" treatment is triggered when an asset's O&M Condition level reaches 5 (failure state)
- The cost of restoration treatments is calculated by increasing the reconstruction cost to accommodate the emergency nature of the repairs.

Figure 4. Different categories of treatment action recommended by NCHRP (2019)

2.5 Maintenance and Rehabilitation

Maintenance and rehabilitation are critical components of GAM. These practices aim to ensure the ongoing performance, safety, and reliability of geotechnical assets throughout their lifecycle. By implementing effective maintenance and rehabilitation strategies, agencies can optimize asset longevity and minimize risks. Maintenance practices for geotechnical assets include a range of activities aimed at preserving their functionality and structural integrity (Figure 5). Rehabilitation strategies are employed when geotechnical assets exhibit significant deterioration or require structural improvements (Table 5). Prioritizing maintenance actions for geotechnical assets is a critical decision-making process. It involves assessing asset conditions, evaluating risks, and conducting cost-benefit analyses to determine the most effective strategies.



Routine Inspections (to spot deterioration, or damage)

Instrumentation and Monitoring (to continuously assess the performance of geotechnical assets.)

Preventive Maintenance (vegetation control, erosion prevention, and drainage management)

Corrective Maintenance (including repairing cracks, reinforcing structures, or stabilizing slopes)

Figure 5. Maintenance practices for geotechnical assets

Table 5. Rehabilitation Strategies for Geotechnical Assets

Rehabilitation strategies	**Description**
Structural Repairs	• Addressing structural deficiencies, such as cracks, erosion, or settlement. • Reinforcing retaining walls, stabilizing slopes, or repairing tunnels.
Materials Replacement	• Replacing worn-out or damaged materials, such as reinforcing geotextiles. or drainage systems, to enhance asset performance.
Reconstruction	• When an asset is beyond repair. • When there is a need for design enhancements to meet current standards and requirements.
Slope Stabilization	• Implementing measures to prevent landslides, erosion, or slope failures.

2.6 Case Studies

2.6.1 Real-World Examples of Geotechnical Asset Management Projects

Anderson et al. (2017), NCHRP (2012), and Thompson (2017) provide valuable insights into how GAM enhances geohazard risk management. It expands its view to cover both constructed geotechnical assets and natural hazards within the inventory. GAM takes this a step further by creating deterioration models modified specifically to geotechnical assets. These models are then utilized alongside unit cost estimates to predict future risk levels and funding requirements. Moreover, GAM also calculates the optimal timing for interventions and assesses their benefit-cost ratio.

By extending the analysis to include the potential advantages of investing in geotechnical asset management (GAM) across all U.S. state transportation departments, federal land management agencies, and local jurisdictions, it becomes evident that the necessity for GAM is quantifiable and significant. Furthermore, federal authorizations, including MAP-

21 in 2012 and the FAST Act in 2015 (Moving Ahead for Progress in the 21st Century Act and its current successor, the Fixing America's Surface Transportation Act), explicitly call for risk- and performance-based asset management for bridges and pavements, while also encouraging state transportation agencies to formulate and implement transportation asset management (TAM) strategies for all assets within the right-of-way (ROW) (NCHRP 2019). NCHRP Report 903 provides a strong foundation for supporting the integration of geotechnical assets into an agency's TAM plan. This support package includes a research overview (NCHRP 2019), an implementation manual (NCHRP 2019), and an Excel-based "GAM Planner" tool. These resources serve as indispensable aids for agencies looking to establish and manage GAM programs proficiently.

Anderson et al. (2017) have integrated geotechnical assets and geohazards into the Colorado Department of Transportation (CDOT) TAM Plan. In CDOT's approach, retaining walls are categorized as geotechnical assets, with inspections based on National Bridge Inventory (NBI) ratings. Slopes, embankments, and subgrades are collectively managed as geohazards, factoring in the annual probability of threat occurrence and quantified consequences related to highway functionality, maintenance, and safety. This comprehensive risk assessment is expressed in monetary terms, updating project prioritization, and underscoring the favorable benefit-cost ratio for select proactive interventions.

Thompson (2017) conducted the development of a comprehensive GAM Plan in 2017 for the Alaska Department of Transportation & Public Facilities (Alaska DOT), focusing on slopes, embankments, retaining walls, and material (borrow) sites. This plan incorporated simple Markov deterioration models to enhance the management and predictive needs assessment of geotechnical assets. Concurrently, an extensive multi-year research initiative was undertaken to establish a risk assessment framework for the Alaska DOT. This research covered various aspects of risk-based geotechnical asset management studies, including the identification of geotechnical risks aligned with performance objectives, the integration of risk into the GAM Program, and the implementation of risk management through benefit-cost and life cycle investment analyses (Vessely 2017). It's worth noting that numerous jurisdictions and infrastructure owners across the United States and Canada have adopted similar risk-based management systems modified to specific earth assets, such as retaining wall or rock fall hazard management systems.

In 2019, the U.S. NCHRP published Report 903, titled "Geotechnical Asset Management for Transportation Agencies," which consists of two volumes: the "Research Overview" (Vol. 1) and the "Implementation Manual" (Vol. 2). The NCHRP Implementation Manual laid out a well-defined process aimed at aiding agencies in the initiation of risk-based Geotechnical Asset Management (GAM). This process linked the performance objectives to asset condition, safety, and mobility. (NCHRP 2019). These resources, specifically the Implementation Manual and the associated GAM Planner spreadsheet tool, are widely acknowledged as State-of-the-Art developments in geotechnical asset management.

In Ohio, the Department of Transportation (ODOT) has an extensive asset management system, covering approximately 18,000 inventoried geohazards such as landslides, rock fall sites, and abandoned underground mines. This comprehensive dataset is made available to the public via a geographic information system (GIS) online platform, as highlighted in the Ohio Department of Transportation's report in 2022. To ensure efficient management, relative risk "tiers" are assigned on a scale of 1 to 4, determining both re-inspection frequency and repair priority. Notably, repaired sites are not retired from the inventory but are retained as assets with anticipated future maintenance and rehabilitation or replacement requirements (Merklin 2020).

Beyond North America, asset management principles have found vital implementation across a diverse range of assets, geotechnical assets included, in various parts of the world. For instance, in the United Kingdom, the inclusion of embankments and slopes in risk-based asset management initiatives dates back to the 1990s, as documented by Power et al. (2016) and Arup (2010). Notably, Network Rail and the U.K. Highways Agency have been actively incorporating these principles into their programs. Collectively, these agencies oversee the management of nearly 250,000 slopes and embankments, highlighting the extensive utilization of asset management principles (Vessely et al. 2019).

In 2022, Waseem et al. developed a risk-based Geotechnical Asset Management (GAM) framework and conducted a pilot study with the idea of shifting Alberta Transportation's (AT) Geohazard Risk Management Program (GRMP) into a mature GAM program. This project had two primary purposes: firstly, to precisely develop a GAM Framework for the comprehensive management of existing and future geotechnical assets along the provincial highway network, considering factors like risk and life cycle costs. Secondly, they put this framework into practice on a smaller scale, focusing on a pilot inventory encompassing 27 geotechnical assets specifically selected by AT. After conducting field inspections and closely monitoring active sites, resulting in the relative Risk Level (RL) ratings for each site, they prioritize potential capital repair projects.

2.6.2 Success Stories and Lessons Learned

In the realm of Geotechnical Asset Management (GAM), several notable success stories underscore the effectiveness of this approach. These success stories revolve around the integration of geotechnical assets into comprehensive asset management frameworks, prioritizing proactive interventions based on rigorous risk assessments, and achieving tangible improvements in safety and functionality. These achievements collectively highlight the transformative potential of GAM in enhancing the resilience, safety, and cost-efficiency of transportation infrastructure systems worldwide, the development of risk-based frameworks, and the use of predictive models to optimize asset management.

These case studies collectively illustrate the effectiveness of GAM in improving safety, functionality, and cost-efficiency in managing geotechnical assets across diverse contexts. They highlight the importance of risk assessment, predictive modeling, and data transparency as key elements in successful geotechnical asset management programs.

2.6.3 Challenges Faced and How They Were Overcome

These case studies provide valuable insights into the challenges, strategies, and outcomes related to Geotechnical Asset Management (GAM) in various contexts (Table 6).

Table 6. Challenges faced by literature.

Anderson et al. (2017)	**Challenges Faced:** Integrating geotechnical assets and geohazards into CDOT's TAM Plan required redefining asset categories, conducting risk assessments, and quantifying consequences in monetary terms.	**Strategies Employed:** Retaining walls were categorized as geotechnical assets, while slopes, embankments, and subgrades were managed as geohazards. Proactive interventions were prioritized based on risk assessments.	**Outcomes Achieved:** CDOT's approach highlighted the favorable benefit-cost ratio for select proactive interventions, improving safety and functionality.
Thompson (2017)	**Challenges Faced:** Developing a comprehensive GAM Plan for Alaska DOT required implementing Markov deterioration models and establishing a risk assessment framework.	**Strategies Employed:** Markov deterioration models were used to enhance predictive needs assessment. A multi-year research initiative was undertaken to create a risk assessment framework.	**Outcomes Achieved:** The plan improved geotechnical asset management and risk assessment capabilities for the Alaska DOT, aligning performance objectives with risk-based management.
Merklin (2020)	**Challenges Faced:** Managing a large inventory of geohazards, including landslides and rock fall sites, presented data management challenges.	**Strategies Employed:** ODOT assigned relative risk "tiers" to sites, determining inspection frequency and repair priority. The dataset was made available to the public through a GIS online platform.	**Outcomes Achieved:** The system improved efficiency in managing geohazards and allowed for transparency by making data accessible to the public.
Waseem et al. (2022)	**Challenges Faced:** Shifting AT's Geohazard Risk Management Program (GRMP) into a mature GAM program required the development of a comprehensive framework and conducting pilot studies.	**Strategies Employed:** A risk-based GAM framework was developed, and a pilot study was conducted on a selected inventory of geotechnical assets.	**Outcomes Achieved:** The framework and pilot study laid the groundwork for comprehensive geotechnical asset management, considering factors like risk and life cycle costs.

2.7 Performance Metrics and Key Performance Indicators (KPIs)

Key Performance Indicators (KPIs) for geotechnical asset management help assess the effectiveness of the management program and ensure that geotechnical assets are performing as expected. Figure 6 illustrates a selection of KPI examples. These KPIs can be adapted to the specific goals and objectives of a geotechnical asset management program. By tracking and analyzing these indicators, the performance, effectiveness, and impact of the geotechnical asset management efforts can be assessed.

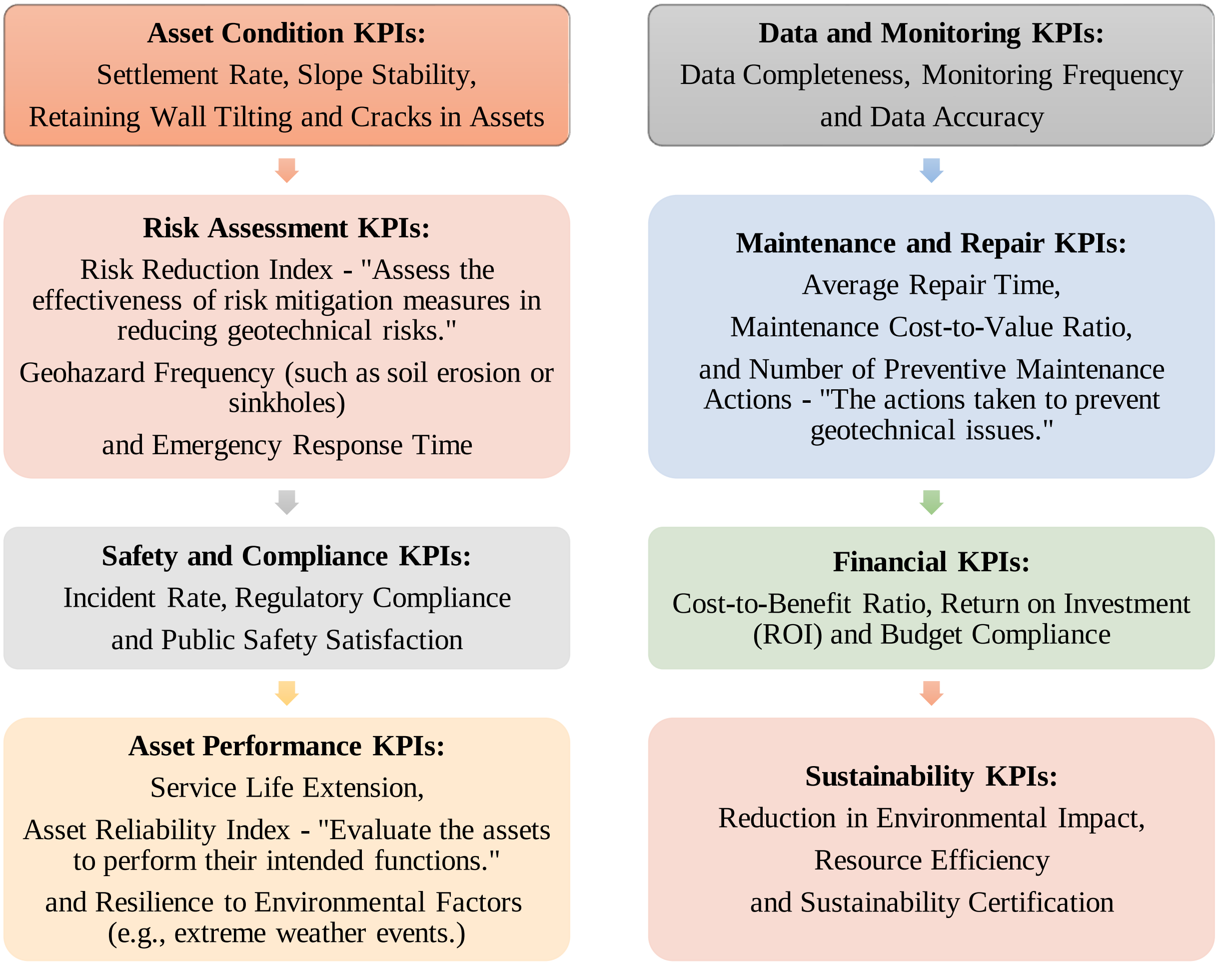


Figure 6. Some examples of the KPIs.

2.8 Technology and Tools

Geotechnical Asset Management (GAM) relies on a variety of technologies to support its implementation and effectiveness. These technologies are essential for collecting, managing, and analyzing data related to geotechnical assets. These technologies, when integrated effectively, enhance the overall management and performance of geotechnical assets, leading to improved safety, reduced risks, and optimized resource allocation. These models are commonly referred to as Decision Support Systems (DSS). In recent times, data-driven models have gained popularity in DSS and have found applications in various fields, including surface water and groundwater assessment (Behbahani and Mazarei 2023).

The ongoing advancement in information and sensing technology is poised to further enhance the development and deployment of Infrastructure Management Systems (IMS) to a broader user base. This progress includes the utilization of technologies such as remote sensing, wireless portable computing for field data collection, remote data uploading, and the integration of database and Geographic Information System (GIS) software for streamlined data entry and display. Notably, significant initiatives in web-based digital libraries along with existing prototype web-based management systems in various sectors like construction, product management, transit, water resources, national parks, and pavement, demonstrate the pervasive influence of the World Wide Web in providing a robust environment for Infrastructure Management Systems (Tsai and Lai 2002, Zang and Hudson 1998, Lam 2002, Liu 2001, Chapman 2003, Wu et al. 2001, Mooney et al. 2005).

There are several technologies available to support geotechnical asset management. Mazzanti (2017) proposes a monitoring plan that accounts for both the technical capabilities of the available monitoring technologies and the specific monitoring needs. Power (2012) discusses the Geotechnical Data Management System as a key tool for the delivery of the Highways Agency Geotechnical Asset Management Strategy. Phoon (2019) explores the availability and nature of geotechnical data and presents two recent advances made in this direction for a specific but important task of estimating soil/rock properties. Sanford Bernhardt (2003) presents a simple framework for managing geotechnical facilities using asset management principles, with consideration given to several unique aspects of geotechnical structures. Overall, the papers suggest that geotechnical asset management can be supported by a range of technologies, including monitoring systems, data management systems, and digital technologies.

Figure 7 presents several key technologies that play a foundational role in supporting GAM. Advanced sensor technologies, including IoT devices, LiDAR, and remote sensing, significantly enhance data collection for geotechnical assets. These sensors and monitoring devices gather real-time information related to aspects like slope stability, ground movement, and soil conditions, enabling early issue detection. Real-time data from sensors enhances asset monitoring and condition assessment. Additionally, remote sensing technologies, like satellite imagery and aerial surveys, offer valuable data for monitoring and assessing geotechnical assets, particularly in extensive and remote locations. Moreover, Machine Learning and Predictive Analytics utilize AI algorithms to predict geotechnical asset behavior and optimize maintenance strategies. By analyzing historical data and current conditions, predictive analytics software can forecast the future performance and risks associated with geotechnical assets, enhancing proactive decision-making and resource allocation. Additionally, remote sensing technologies, like satellite imagery and aerial surveys, offer valuable data for monitoring and assessing geotechnical assets, particularly in extensive and remote locations.

2.9 Web-Based Applications and Decision Support Systems (DSS)

GAM has evolved significantly with the integration of advanced technologies, particularly web-based applications, and decision support systems (DSS). These digital tools play a pivotal role in enhancing asset monitoring, management, and maintenance within the realm of geotechnical engineering. Table 7 provides a comprehensive overview of the key features and corresponding benefits of web-based applications and DSS, showcasing their vital roles in advancing Geotechnical Asset Management (GAM) practices.

The combination of web-based applications and DSS with GAM brings forth an array of benefits as shown in Figure 8. The integration of web-based applications and decision support systems marks a pivotal shift in Geotechnical Asset Management. These digital tools empower agencies and organizations to make data-driven decisions, enhance asset performance, and ensure the safety and reliability of transportation infrastructure in today's data-driven and technologically advanced landscape. In Figure 9, we present an illustrative depiction of the fundamental components that constitute a robust GAM web application.

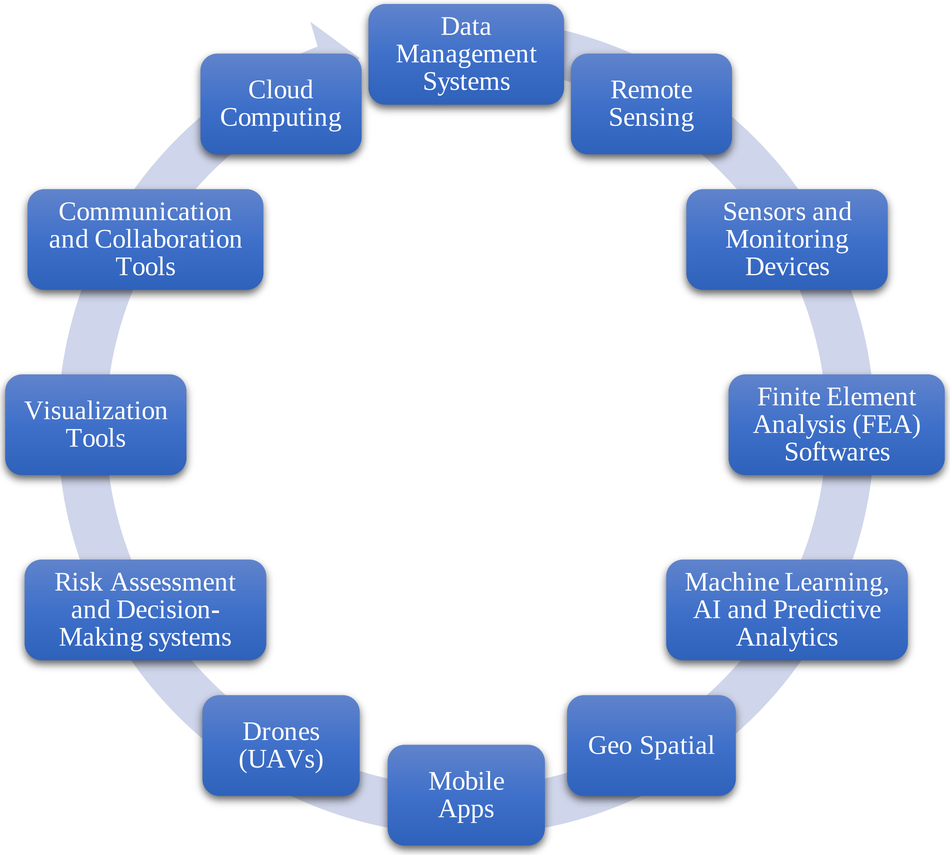


Figure 7. Key Technologies Empowering Geotechnical Asset Management"

Enhanced Data Accessibility

- Geotechnical asset data will be accessible to relevant stakeholders, promoting transparency and collaborative decision-making.

Real-Time Monitoring

- Facilitate real-time monitoring of asset performance, allowing for proactive maintenance and risk mitigation.

Informed Decision-Making

- DSS empower decision-makers with data-driven insights, reducing reliance on subjective judgment and enhancing decision quality.

Cost Efficiency:

- Through resource optimization, web-based applications and DSS contribute to cost savings in asset management, ensuring efficient utilization of available resources.

Figure 8. Benefits of Web-Based Applications and DSS in GAM

Table 7. Features and Benefits of Web-Based Applications and DSS in GAM

Features	Benefits	Examples
1. Automates Asset Performance Analysis	• Automates data collection, analysis, and reporting. • Integrates data from various sources for real-time performance reports.	• Continuous monitoring and analysis of retaining wall stability, settlement rates, etc. • Immediate alerts for potential issues.
2. Provides Actionable Insights for Decision-Makers	• Offers insights derived from data analysis. • Provides risk predictions and mitigation for asset behavior.	• Correlation analysis between rainfall and slope stability. • Insights from historical data to plan preventive maintenance.
3. Resource Allocation and Optimization	• Optimizes resource allocation, including budget, manpower, and time. • Prioritization of critical assets.	• Integration of budget data and asset conditions for optimal resource allocation. • Identification of assets requiring immediate attention.
4. Scenario Planning and Predictive Capabilities	• Provides scenario planning capabilities. • Incorporates predictive features for asset deterioration.	• Simulation of slope stability scenarios with conditions, such as heavy rainfall or seismic activity • Proactive planning and response strategies.

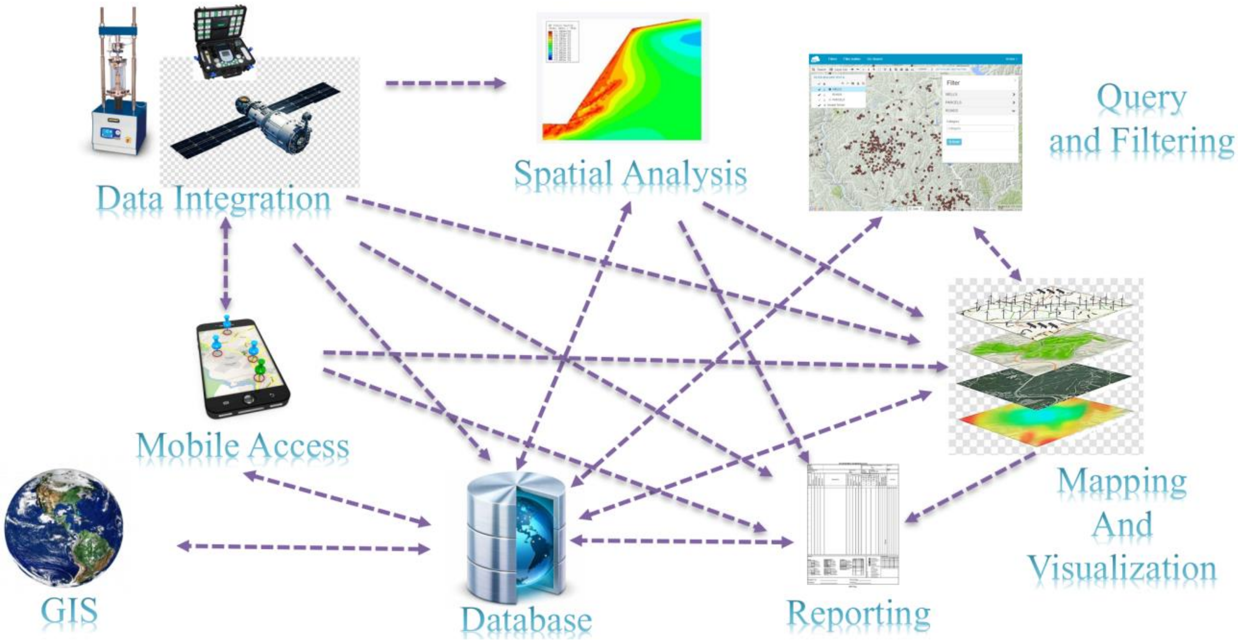


Figure 9. Key Components of a GAM Web Application

2.10 Conclusion

In conclusion, Geospatial Web Applications for Transportation Geotechnical Asset Management is a valuable resource for transportation infrastructure professionals, researchers, and policymakers. The paper provides a comprehensive overview of the principles and practices of geotechnical asset management and highlights the importance of data-driven decision-making in ensuring the safety, resilience, and sustainability of transportation infrastructure. The introduction of web-based applications has the potential to revolutionize the asset management system, providing real-time data and analytics that can inform maintenance and repair decisions, optimize resource allocation, and improve overall infrastructure performance. As transportation infrastructure continues to evolve, it is essential to embrace new technologies and approaches to ensure that our infrastructure remains safe, resilient, and sustainable for generations to come.

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CHAPTER 3:

GAM WEB APPLICATION IMPLEMENTATION PROCESS

3.1 Introduction

In the area of modern transportation infrastructure management, geospatial web applications have emerged as essential tools. They offer a dynamic platform for the efficient and data-driven management of geotechnical assets, ensuring the safety, stability, and longevity of transportation earth structures. Within the context of this thesis, we delve into the intricate process of designing a Geotechnical Asset Management (GAM) web application, a cornerstone of our broader efforts to reshape the management of transportation earth structures.

As previously emphasized, it's crucial to emphasize the importance of geotechnical assets. Their performance directly influences traveler safety, operational efficiency, and economic vitality. However, effective management necessitates not only a profound understanding of asset conditions and risks but also a systematic and user-friendly means of translating this knowledge into actionable insights. This is precisely where the GAM web application comes into play.

The GAM web application, at the heart of our transformative approach, serves as an innovative solution for the comprehensive management of geotechnical assets. This web application empowers asset managers, engineers, and decision-makers to make informed choices that enhance the reliability and resilience of transportation earth structures.

In this chapter, we embark on a detailed exploration of the design process that drives the development of this critical tool. We will uncover the details of user interface design and the incorporation of geospatial asset data. Our journey through the GAM web application design process underscores not only its significance but also its potential to revolutionize how we manage geotechnical assets, ensuring a safer and more sustainable transportation infrastructure for the future.

3.2 Geospatial Web-Based Application

A geospatial web-based application is a purpose-built application developed using web technologies to deliver specific GIS functionalities and capabilities. It can be developed using various frameworks, libraries, and tools, and is not limited to a specific vendor or software provider. Here are some key characteristics of a geospatial web-based application:

- Custom Development: A geospatial web-based application is typically custom-developed based on specific requirements and needs. It can be developed using programming languages such as JavaScript, Python, or Ruby, and web frameworks such as React, Angular, or Django.

- Personalized Functionality: A geospatial web-based application designed to address specific GIS-related tasks, workflows, or use cases. It offers functionalities and tools specifically adapted to meet the requirements of a particular industry, domain, or project.
- Data Integration and Visualization: A geospatial web-based application can integrate and visualize various types of data, including spatial data, attribute data, and real-time data. It allows users to view, analyze, query, and interact with the data in a meaningful and customized manner.
- Extensibility and Integration: geospatial web-based applications can be extended and integrated with other systems, data sources, or technologies. They often provide APIs or SDKs to allow customization, integration with external data sources or services, or integration with other software systems.
- Independent Support and Maintenance: The support and maintenance of a geospatial web-based application are typically the responsibility of the development team or organization that created the application. Support can be provided through documentation, user forums, and direct contact with the development team.

In summary, on the other hand, a geospatial web-based application is a custom-developed application that can be created by any organization or development team using web technologies to provide specific GIS functionalities and capabilities and it is a more general term referring to any web application developed for GIS purposes.

3.3 Web Application Design

Web application development is the process of creating software applications that run on web browsers. These applications can be accessed over the Internet, making them accessible to users from anywhere with an Internet connection. Web application development has become increasingly popular in recent years due to the widespread use of the Internet and the increasing demand for online services.

The development of web applications involves several stages, including planning, designing, coding, testing, and deployment. The first step in the process is to identify the requirements of the application and create a plan for its development. This involves determining the target audience, features and functionalities of the application, and the technologies and tools to be used.

The next stage is designing the user interface (UI) and user experience (UX) of the application. This involves creating wireframes and mockups to visualize the layout, navigation, and overall look and feel of the application. The design should be user-friendly and intuitive to ensure a positive user experience.

3.3.1 Internet Resources for Web Applications

3.3.1.1 Web Application Hosting Platforms

A hosting platform is needed to deploy the web application on the internet. This can be a cloud-based hosting service like Amazon Web Services (AWS), Microsoft Azure, Heroku cloud application platform, or Google Cloud Platform (GCP). These platforms provide the infrastructure and server resources to run the web application.

There are several types of hosting platforms available, each offering different features and capabilities. Here are some of the common types:

a. Shared Hosting: Shared hosting is a type of hosting where multiple websites are hosted on the same server. Resources such as CPU, RAM, and disk space are shared among all the websites. It is an affordable option suitable for small to medium-sized websites with moderate traffic.

b. Virtual Private Server (VPS) Hosting: VPS hosting provides a virtualized server environment where each website is allocated its dedicated resources within a shared physical server. It offers more control and flexibility compared to shared hosting and is suitable for websites with higher traffic and resource requirements.

c. Dedicated Server Hosting: With dedicated server hosting, you have an entire physical server dedicated to hosting your website. You have full control over the server's resources, and it offers high-performance and customization options. Dedicated hosting is typically used by large websites or businesses with high traffic volumes and specific security or performance requirements.

d. Cloud Hosting: Cloud hosting utilizes a network of interconnected servers to host websites. It provides scalability, as resources can be easily scaled up or down based on demand. Cloud hosting is reliable and can handle high traffic spikes. It is suitable for websites with varying resource needs and scalability requirements.

e. Managed WordPress Hosting: Managed WordPress hosting is specifically designed for hosting WordPress websites. The hosting provider takes care of tasks like WordPress updates, security, backups, and performance optimization. It simplifies WordPress website management and is suitable for WordPress users who want a hassle-free hosting experience.

f. Reseller Hosting: Reseller hosting allows individuals or businesses to sell hosting services to their clients. It provides a white-label hosting platform where you can create and manage multiple hosting accounts under your brand. Reseller hosting is suitable for web developers, designers, or agencies who want to offer hosting services as part of their business.

g. Colocation Hosting: Colocation hosting involves hosting your servers in a data center facility provided by a hosting provider. The hosting provider takes care of the physical infrastructure, power, cooling, and network connectivity, while you maintain and manage your servers. Colocation hosting offers control and customization options for businesses that require complete control over their hardware and software.

These are just a few examples of hosting platforms available in the market. The choice of hosting platform depends on factors such as website requirements, budget, scalability needs, technical expertise, and desired level of control.

3.3.1.2 Comparison of Hosting Platforms

In summary, the choice of a hosting platform is a crucial decision that should align with the unique needs and characteristics of the web application. It involves balancing factors such as cost, performance, scalability, and the level of control required for effective and efficient web hosting. The differences among various hosting platforms are outlined in the following.

a. Shared Hosting:

Suitability: Ideal for small to medium-sized websites with moderate traffic.

Pros: Cost-effective, easy to set up.

Cons: Limited resources, and potential performance issues if other sites on the same server experience high traffic.

Examples: Personal blogs, and small business websites.

b. Virtual Private Server (VPS) Hosting:

Suitability: Suitable for websites with higher traffic and resource requirements.

Pros: More control and flexibility compared to shared hosting, and dedicated resources.

Cons: Costs more than shared hosting.

Example: E-commerce sites, medium-sized business websites.

c. Dedicated Server Hosting:

Suitability: Typically used by large websites or businesses with high traffic volumes.

Pros: Full control over resources, high performance, and customization options.

Cons: Expensive, requires technical expertise for management.

Example: High-traffic e-commerce platforms, and large corporate websites.

d. Cloud Hosting:

Suitability: Suitable for websites with varying resource needs and scalability requirements.

Pros: Scalability, reliability, and ability to handle high traffic spikes.

Cons: Costs can scale with usage.

Example: SaaS applications, startups with unpredictable traffic.

e. Managed WordPress Hosting:

Suitability: Specifically designed for hosting WordPress websites.

Pros: Hassle-free management, specialized support for WordPress.

Cons: Limited flexibility for non-WordPress applications.

Example: WordPress blogs, content-heavy websites.

f. Reseller Hosting:

Suitability: Suitable for web developers, designers, or agencies offering hosting services.

Pros: White-label platform, ability to create and manage multiple hosting accounts.

Cons: Dependency on the hosting provider.

Example: Web development agencies hosting client websites.

g. Colocation Hosting:

Suitability: Offers control and customization options for businesses.

Pros: Complete control over hardware and software.

Cons: Requires significant technical expertise, and higher upfront costs.

Example: Enterprises with specific security or compliance requirements.

3.3.1.3 Online cloud space

Cloud services are a type of web-based computing that allows users to access and use applications and resources over the Internet. These services are provided by cloud computing companies, such as Amazon Web Services, Microsoft Azure, and Google Cloud Platform. In this section, we will discuss what cloud services are, their benefits, and some examples of popular cloud services.

Cloud services provide users with access to a variety of resources and applications, including storage, servers, databases, software, and development tools. These resources are hosted and managed by the cloud computing company, and users can access them through the Internet. This eliminates the need for users to invest in expensive hardware and infrastructure and allows them to scale their usage as needed (Gupta, 2018).

One of the main benefits of using cloud services is cost savings. With traditional on-premises solutions, businesses must invest in hardware, software licenses, and maintenance costs. With cloud services, businesses only pay for what they use, making it a more cost-effective option. Additionally, cloud services offer flexibility and scalability, allowing businesses to easily increase or decrease their usage based on their needs (Gupta, 2018).

There are various types of cloud services, including Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). IaaS provides users with access to virtualized computing resources such as servers, storage, and networking. PaaS offers a platform for developers to build and deploy applications without having to manage the underlying infrastructure. SaaS provides users with access to software applications over the Internet (Gupta, 2018).

Some popular examples of cloud services include Dropbox for cloud storage, Salesforce for customer relationship management (CRM), and Google Drive for document collaboration. Amazon Web Services (AWS) is also a popular cloud service provider, offering a wide range of services such as Amazon EC2 for virtual servers, Amazon S3 for storage, and Amazon RDS for databases (Amazon Web Services, n.d.).

In conclusion, cloud services are an essential component of web application development. They provide users with access to a variety of resources and applications over the Internet, offering cost savings, flexibility, and scalability. With the increasing demand for cloud services, it is becoming an integral part of modern web application development.

3.3.1.4 Domain registration and management

A domain name is required to make the web application accessible through a unique URL. Domain registration services, such as GoDaddy, Namecheap, or Google Domains, allow you to register a domain name that suits your project and organization.

3.3.1.5 Mapping Services

Access to mapping services like Google Maps API, Mapbox, or OpenStreetMap can provide the necessary geospatial data and mapping functionalities for displaying and interacting with geotechnical data on the map.

We will use OpenWeatherMap, OpenStreetMap, and IPGgeolocation APIs.

3.3.1.6 Databases

Web applications often require a database to store and retrieve data efficiently. Popular database systems include MySQL, PostgreSQL, MongoDB, or cloud-based database services like Amazon RDS or Microsoft Azure Cosmos DB.

3.3.2 Web Application Development

The coding stage involves writing the code that will bring the application to life. This includes front-end development, which deals with the visual elements of the application, and back-end development, which involves creating the logic and functionality of the application. Popular programming languages used in web application development include HTML, CSS, JavaScript, PHP, and Python.

3.3.2.1 Overview of programming languages used for web application development.

Developers typically utilize programming languages such as JavaScript, Python, or PHP for web application development. Frameworks like React, Angular, or Django can aid in the development process. Integrated Development Environments (IDEs) like Visual Studio Code or PyCharm are often used for coding, testing, and debugging.

We will use JavaScript programming languages and frameworks such as React, and Visual Studio Code IDE.

3.3.2.2 Front-end, back-end, database, and API

Front-end, back-end, database, and API are all important components of web application development. These components work together to create a functional and user-friendly web application. In this section, we will discuss each of these components in detail and their role in web application development.

Front-end development is the process of creating the visual elements of a web application that users interact with. This includes designing the user interface (UI) and user experience (UX) of the application. Front-end developers use languages such as HTML, CSS, and JavaScript to create the layout, design, and functionality of the application. They are responsible for ensuring that the application is visually appealing, easy to use, and works seamlessly on different devices and browsers (Mishra 2020).

Back-end development, on the other hand, involves creating the logic and functionality of the web application. This includes server-side programming, which deals with the processing and storage of data on the server. Back-end developers use languages such as PHP, Python, and Java to write code that handles data requests from the front end and performs operations on the database (Mishra 2020). They also ensure that the back end of the application is secure and can handle a large number of users.

The database is an essential component of web application development as it stores and manages the data used by the application. It is where all user information, content, and other data related to the application are stored. Databases use a structured query language

(SQL) to retrieve and manipulate data. There are different types of databases used in web application development, including relational databases like MySQL and NoSQL databases like MongoDB (Fowler and Highsmith 2001).

Application Programming Interface (API) is a set of protocols and tools used to build software applications. APIs allow different systems to communicate with each other, enabling data exchange and integration between different applications. In web application development, APIs are used to connect the front-end and back-end of the application, allowing data to be transferred between the two (Fowler and Highsmith 2001). APIs also allow developers to integrate third-party services and tools into their applications, making them more robust and feature-rich.

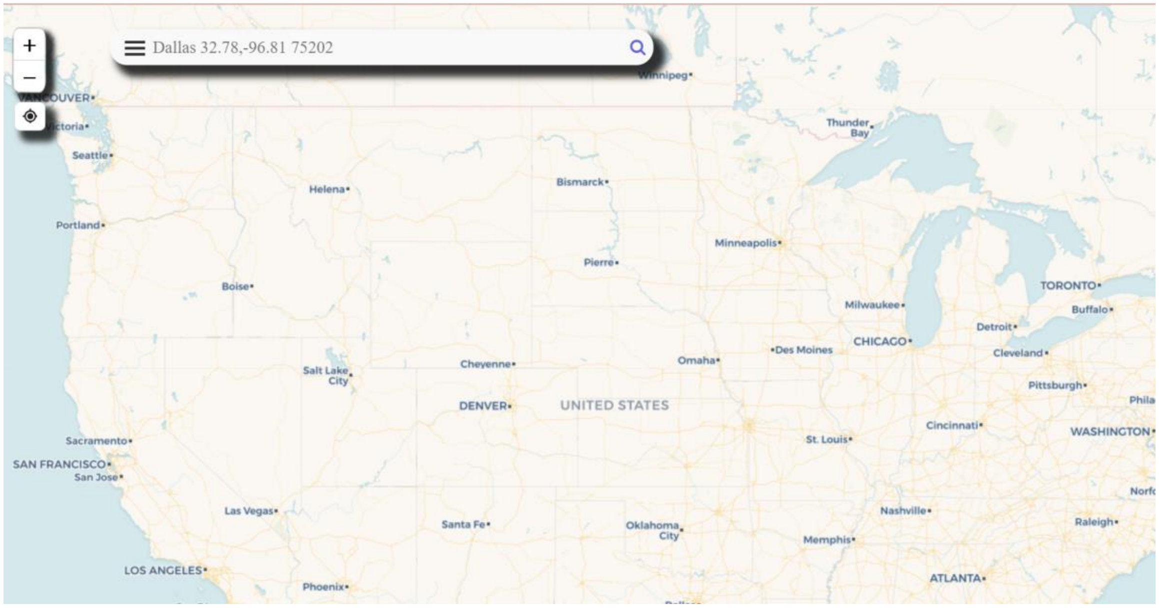
In conclusion, front-end, back-end, database, and API are all crucial components of web application development. Each component plays a specific role in creating a functional and user-friendly web application. Front-end developers focus on the visual elements of the application, back-end developers handle the logic and functionality, databases store and manage data, and APIs enable communication between different components. Understanding these components and how they work together is essential for successful web application development.

3.4 Embarking on Web App Excellence

The meticulously crafted web application is an embodiment of tailored precision, aligning seamlessly with the unique needs and objectives of our project. This digital platform is the result of thoughtful design, integrating cutting-edge technology and user-centric principles to deliver an intuitive and efficient user experience. The user interface is a testament to our commitment to excellence, characterized by a clean and visually appealing design that prioritizes ease of navigation and accessibility. Functionality takes center stage, with features meticulously aligned to streamline user interactions and elevate overall usability.

Furthermore, the robust architecture of the web application ensures scalability and adaptability to meet the dynamic requirements of our evolving project. Rigorous testing and quality assurance measures have been systematically implemented throughout the development lifecycle, establishing a secure and reliable digital environment. In essence, the designed web application stands as a symbol of our unwavering dedication to technological excellence, user satisfaction, and the successful realization of project objectives.

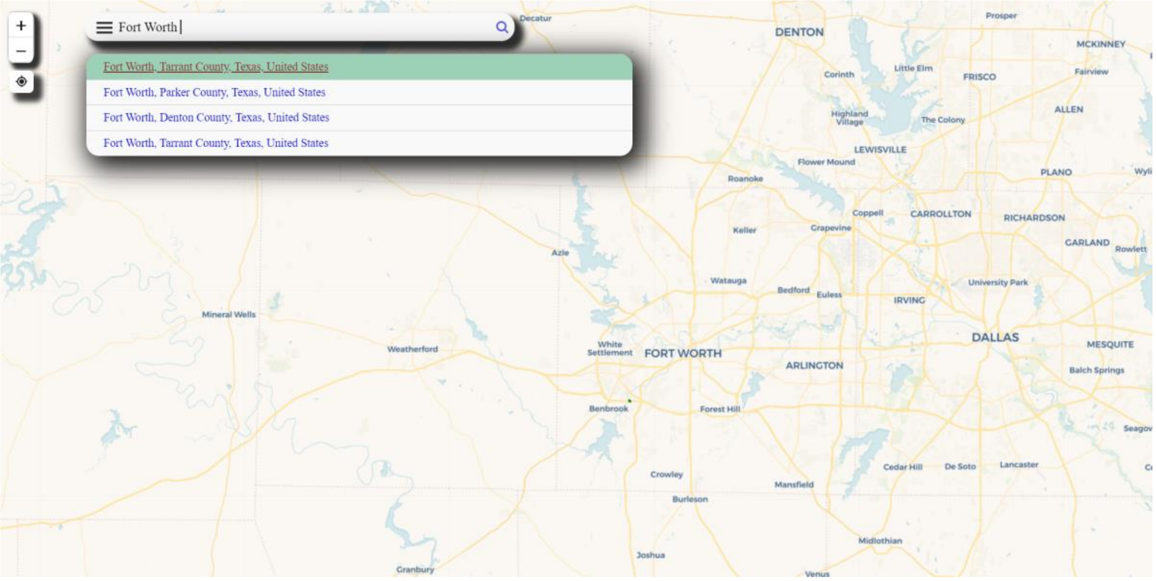
This dynamic web application, as shown in Figure 10 and Figure 11, empowers users to seamlessly leverage coordinates and location data, facilitating the implementation of geospatial project data. This intuitive feature enhances the user experience, underscoring the application's versatility and its ability to efficiently integrate geospatial elements into project workflows.



Dallas 32.78,-96.81 75202

Figure 10- The web application start page

Figure 11 illustrates the effective utilization of location attributes within the web application, highlighting a pivotal aspect of its functionality. This depiction underscores the web application's capacity to leverage diverse location-based attributes, allowing users to navigate based on coordinates, location names, zip codes, and their current location for the precise implementation of geospatial project data. This enhanced versatility aligns seamlessly with the broader objectives of our project. The inclusion of location attributes in Figure 11 serves as a visual testament to the web application's dynamic capabilities, emphasizing its integral role in facilitating efficient and accurate geospatial data management within the project framework.



Fort Worth

Fort Worth, Tarrant County, Texas, United States
Fort Worth, Parker County, Texas, United States
Fort Worth, Denton County, Texas, United States
Fort Worth, Tarrant County, Texas, United States

Figure 11- Using Location Attributes in the Web App for Advanced Geospatial Project Implementation

The comprehensive functionality of the web application is exemplified in Figure 12, showcasing a portion of the menu dedicated to displaying projects (Figure 13) and creating boreholes (Figure 21). Within the "Projects List" window (Figure 13), users have access to all projects incorporated into the web application, facilitating the effortless creation of new projects. In Figure 14, the implementation of project coordinates on the map is demonstrated, with the dynamically added project visible in the project's list (Figure 15) post-creation. Clicking on a project within this list provides users with immediate access to its location. Figure 16 introduces the "Project Data" window, granting users access to project documents illustrated in Figure 17.

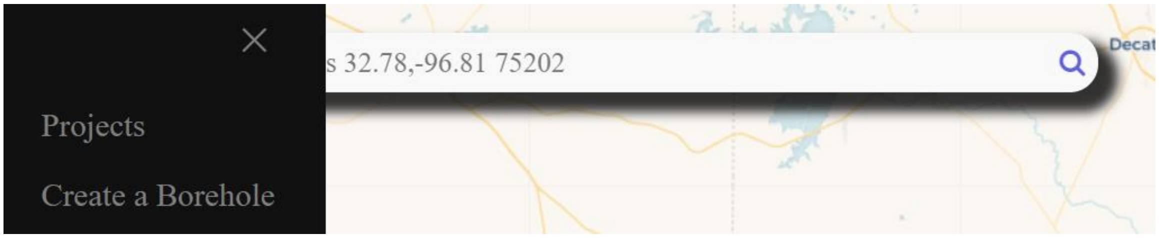


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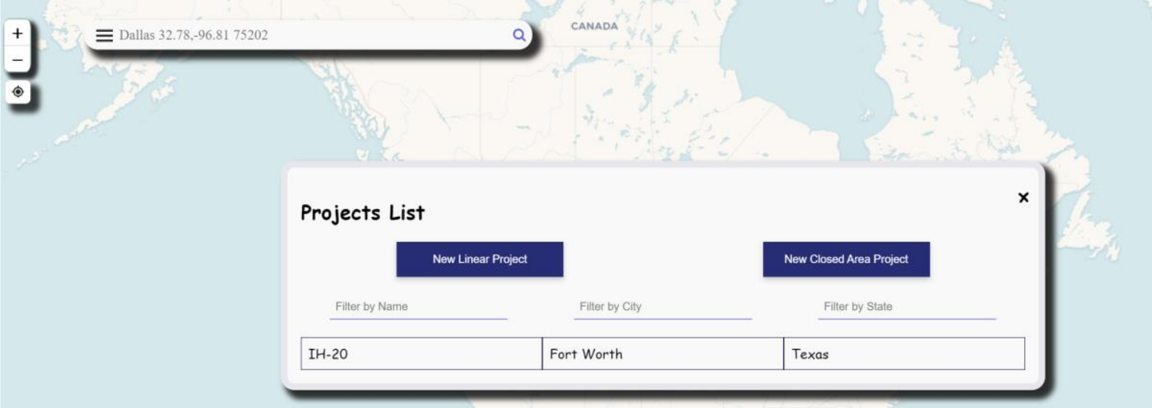
Figure 12- The menu to access the projects' list.



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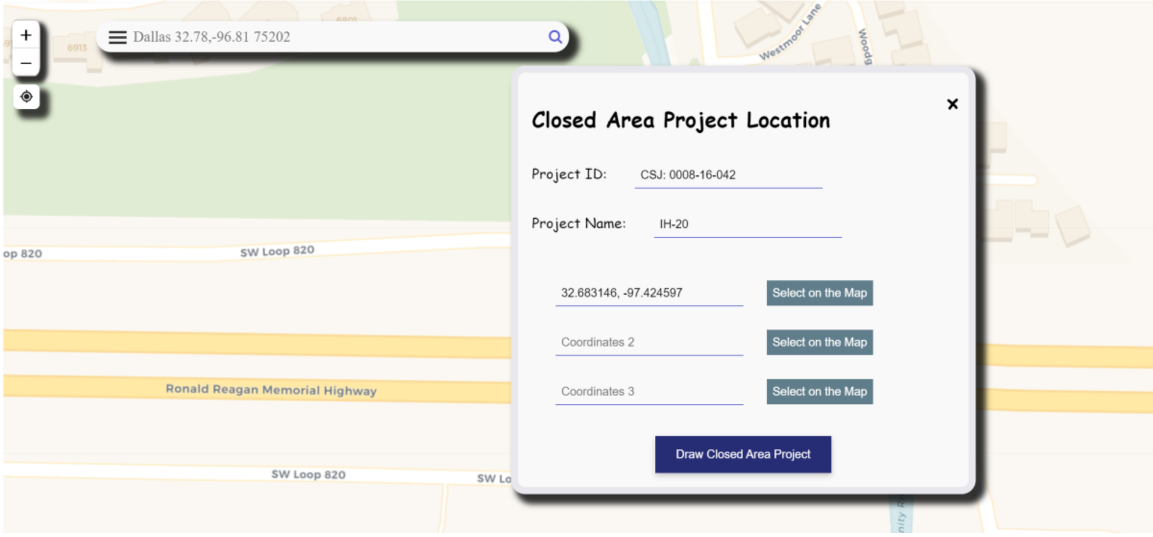
IH-20	Fort Worth	Texas

Figure 13- The "Projects List" window



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Project ID: CSJ: 0008-16-042

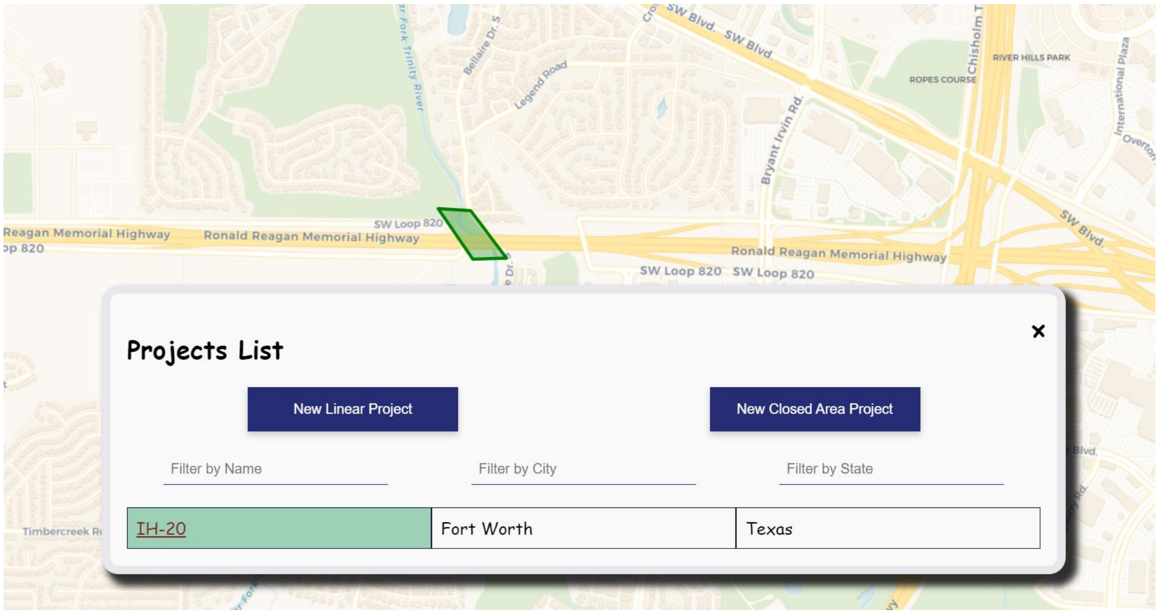
Project Name: IH-20

32.683146, -97.424597

Coordinates 2

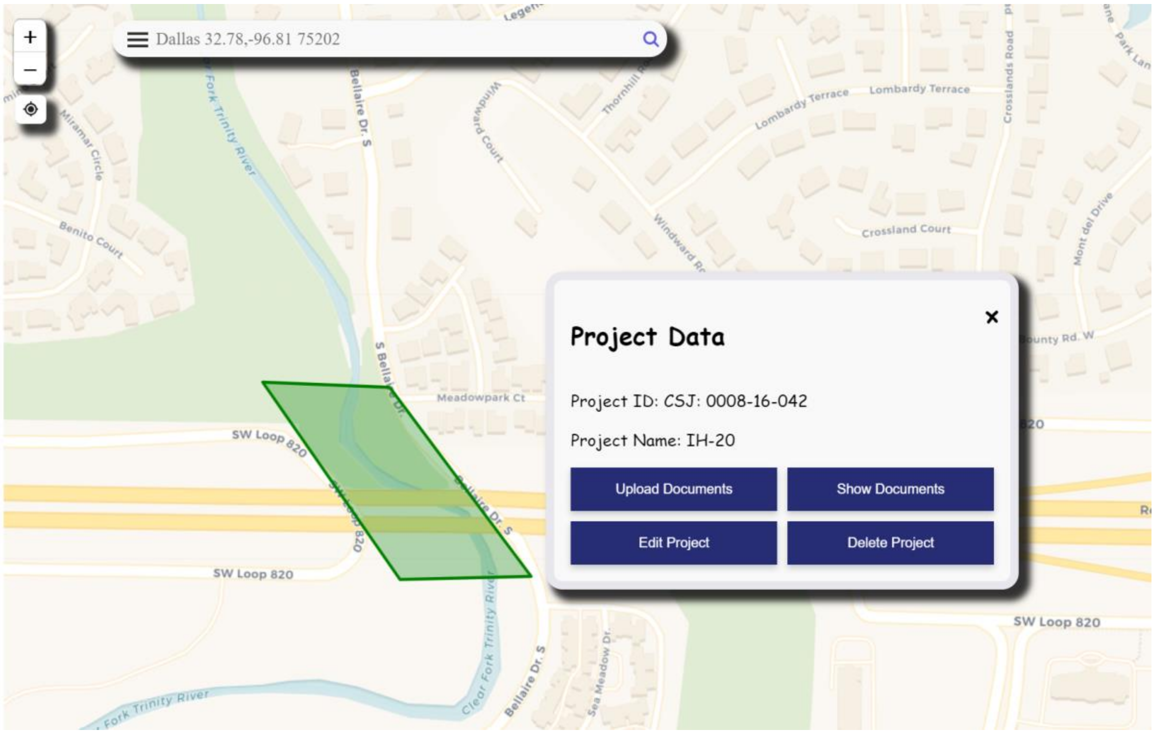
Coordinates 3

Figure 14- The window to create a new project.



IH-20	Fort Worth	Texas

Figure 15- Finding the project's location inside the "Projects List" window.

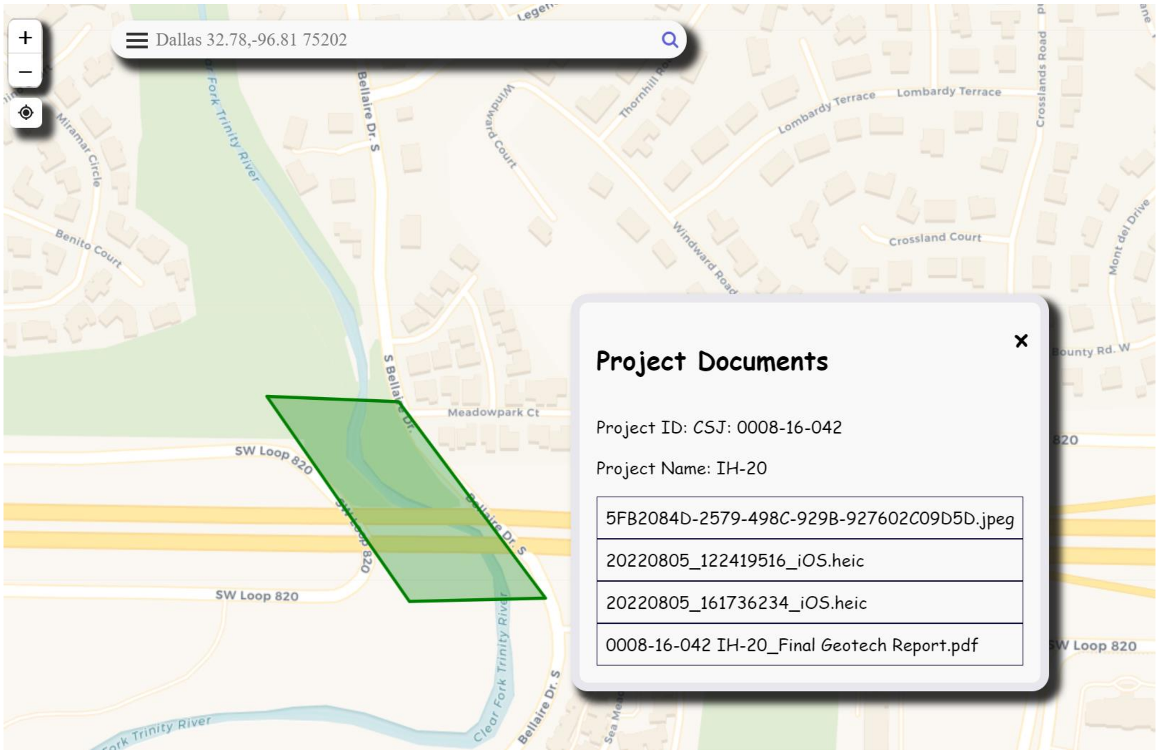


Project ID: CSJ: 0008-16-042

Project Name: IH-20

Figure 16- The "Project Data" window.

Figure 18 to Figure 20 represent the project with emphasis on the exact positions of the boreholes. Furthermore, users can create boreholes (Figure 21) by selecting coordinates and associating them with the corresponding project, dynamically updating the "Select Project" dropdown upon project creation. The web application extends user accessibility to borehole documents, as depicted in Figure 22. Additionally, users can effortlessly edit the location of the borehole (Figure 23), highlighting the user-friendly and dynamic nature of the web application's interface.



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Project Documents

Project ID: CSJ: 0008-16-042

Project Name: IH-20

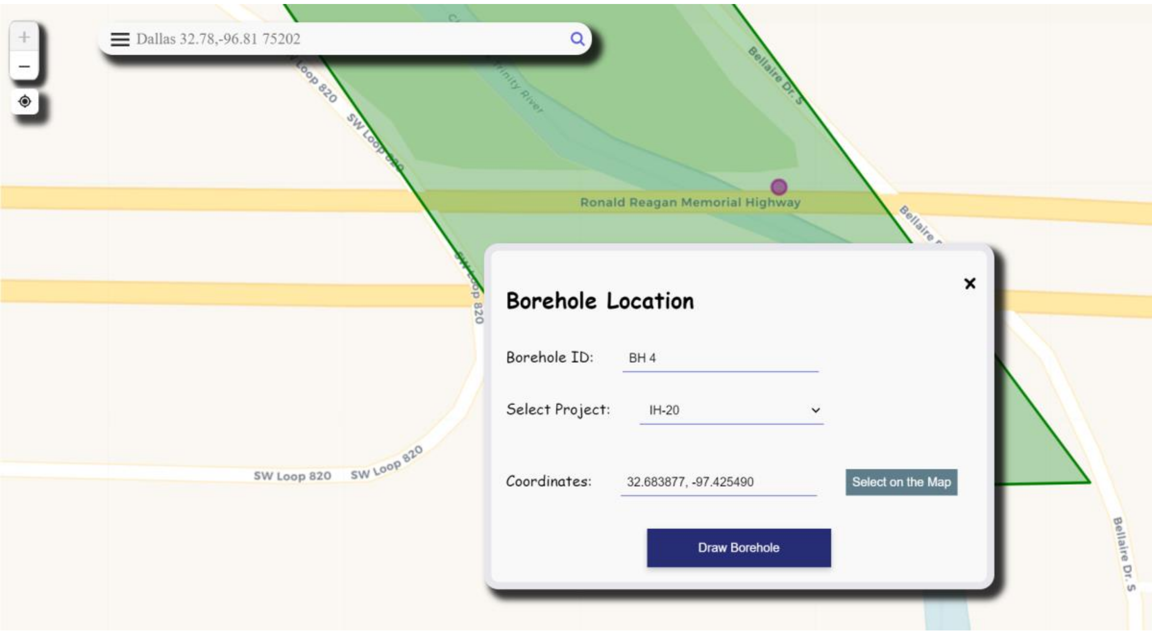
5FB2084D-2579-498C-929B-927602C09D5D.jpeg
20220805_122419516_iOS.heic
20220805_161736234_iOS.heic
0008-16-042 IH-20_Final Geotech Report.pdf

Figure 17- The "Project Documents" window.

Figure 18- Borehole locations of the IH-20 project.

Figure 19- IH-20 project – BH-3

Figure 20- IH-20 project – BH-4



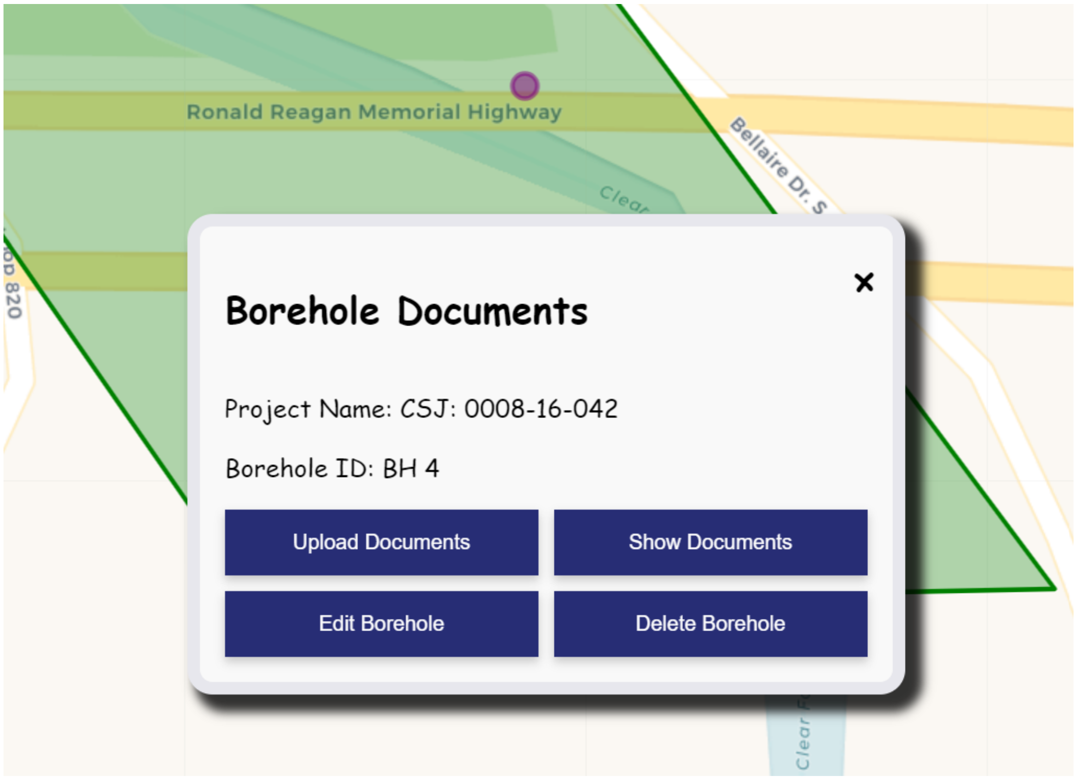
Borehole Location

Borehole ID: BH 4

Select Project: IH-20

Coordinates: 32.683877, -97.425490

Figure 21- The window to create a borehole on the map.

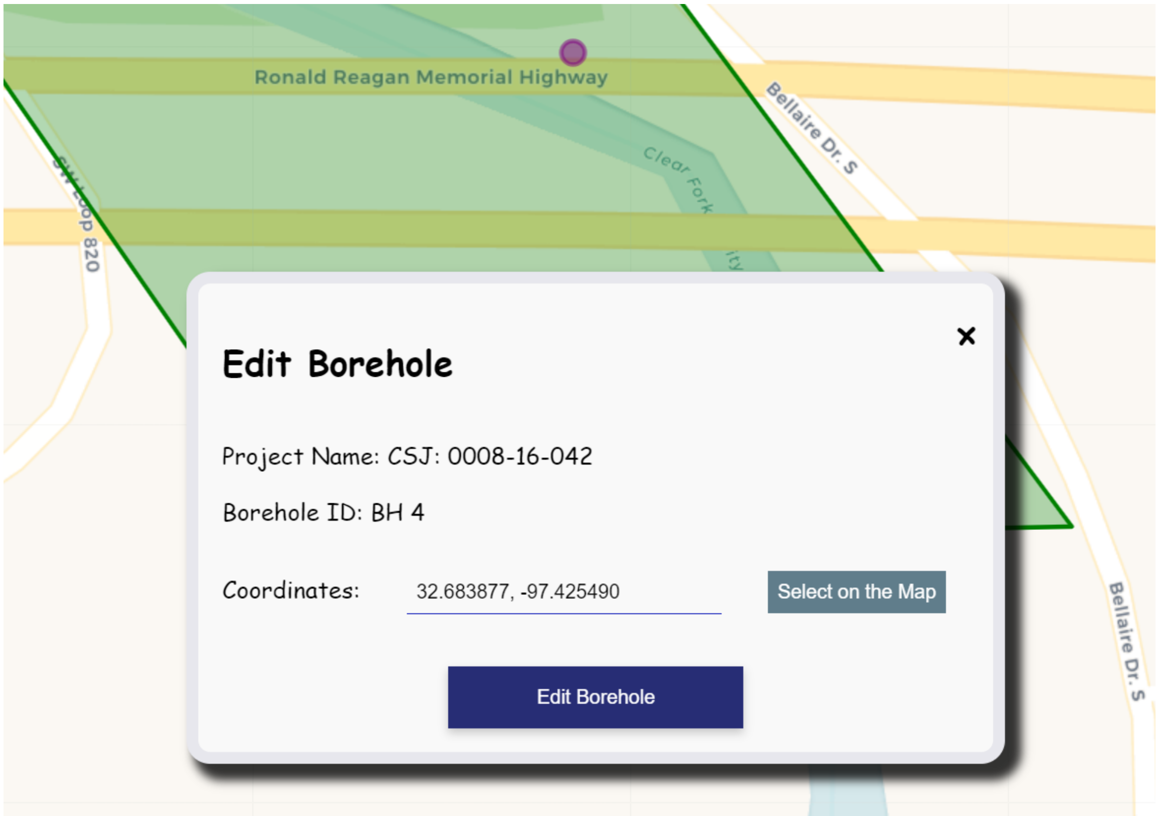


Borehole Documents

Project Name: CSJ: 0008-16-042

Borehole ID: BH 4

Figure 22- The "Borehole Documents" window.



Edit Borehole

Project Name: CSJ: 0008-16-042

Borehole ID: BH 4

Coordinates: 32.683877, -97.425490

Figure 23- The "Edit Borehole" window.

3.5 Conclusion

3.5.1 Summary of the potential benefits of a geospatial web application for geotechnical engineering projects in the modern world.

- A geospatial web application for geotechnical engineering integrates geotechnical data with GIS technology to improve decision-making and project planning.
- It allows geotechnical engineers to access and analyze data from anywhere with an internet connection.
- The application can be used for geotechnical site selection and suitability analysis while reviewing the data available in the application such as borehole data.
- It can help in the identification of potential geotechnical hazards, such as landslides, subsidence, and liquefaction, and assess the risk associated with them.
- It allows for real-time collaboration and data sharing between team members.
- Geospatial web applications for geotechnical engineering can be adapted to meet specific project needs and can be used for a wide range of projects, from small-scale construction projects to large infrastructure developments.

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CHAPTER 4:

SLOPE STABILITY NUMERICAL ANALYSIS – A CASE STUDY

4.1 Introduction

Slope stability refers to the ability of a slope or embankment to resist movement or failure. It is a critical factor in asset management and risk management, as unstable slopes can pose a significant threat to infrastructure, property, and human lives. As such, slope stability is often used as a Key Performance Indicator (KPI) in assessing the health and safety of slopes in various industries, including transportation, mining, and construction.

As an asset management tool, slope stability helps organizations monitor and maintain the condition of their slopes, ensuring that they are safe and functional. By regularly measuring and evaluating slope stability, asset managers can identify potential issues and take preventive measures to avoid costly repairs or failures. This proactive approach can also help organizations optimize their maintenance schedules and prioritize resources for areas that require immediate attention.

In terms of risk management, slope stability is a crucial factor in assessing the potential hazards and risks associated with slopes. Unstable slopes can cause landslides, rockfalls, and other types of slope failures, which can result in significant financial losses and even loss of life. By monitoring and managing slope stability as a KPI, organizations can identify high-risk areas and implement mitigation strategies to reduce the likelihood of slope failures. This approach can help minimize the impact of natural disasters and improve overall safety for both workers and the public.

Slope stability can also be influenced by various factors, such as soil type, weather conditions, and human activities. For example, heavy rainfall or construction activities can increase the risk of slope failures by changing the soil properties and increasing the weight on the slope. Therefore, it is essential for organizations to regularly monitor and assess slope stability to identify potential risks and take appropriate measures to mitigate them.

In addition to asset management and risk management, slope stability also plays a crucial role in environmental protection. Unstable slopes can lead to erosion and sedimentation, which can have adverse effects on the surrounding ecosystem. By maintaining slope stability, organizations can prevent soil erosion and protect the natural environment. This approach aligns with sustainable development goals and helps organizations fulfill their social and environmental responsibilities.

4.2 Slope Stability Case Study

Employing the data available on the project's web application, I engaged in a thorough numerical analysis focused on evaluating the slope stability within the designated project area. This comprehensive examination involves a thorough exploration of crucial parameters, including soil properties and geometric attributes, with the primary objective of assessing the safety and performance of the slope. Through this in-depth study, this thesis aims to derive valuable insights into the intricate behavior of geotechnical assets, elucidating their response to diverse environmental conditions. The outcomes of this analysis will be instrumental in informing and enhancing our asset management strategy, facilitating a proactive approach to mitigate potential risks and optimize the overall stability and functionality of the slope within the project parameters. This effort emphasizes our commitment to rigorous scientific inquiry and strategic decision-making in the realm of geotechnical engineering.

Focused on enhancing the slopes of Clear Fork Creek at IH-20 (refer to Figure 24), the project aims to implement improvements according to the plan and profile drawing for channel enhancement. The proposed modifications involve flattening the channel to a 2H:1V slope and securing the slope with an articulated concrete block (ACB) mat supported by an anchor system. Also, the paper presented by Ebrahimi et al. (2017), serves as the numerical verification model, with detailed results outlined in Appendix I.

Figure 24- IH-20 project's slope before stabilization.

This project, administered by the Texas Department of Transportation (TxDOT), involves the expansion of the IH-20 bridge over the lower Clear Fork of the Trinity River. Specifically, the undertaking includes the addition of auxiliary lanes spanning the stretch between Bryant Irvin Road and Winscott Road, as illustrated in Figure 25. A schematic environmental and Plans, Specifications, and Estimates (PS&E) have been thoroughly developed for this segment of the project. This initiative aligns with the objectives outlined in the Mobility Transportation Planning 2045; a comprehensive plan articulated by the North Central Texas Council of Governments (NCTCOG) to ultimately widen the highway to eight lanes. The widening of the bridge over the Clear Fork of the Trinity River stands as an integral element within this broader project framework. Within the scope of the bridge expansion, measures will be implemented to stabilize and treat the river channel bank slope. An erosion control system utilizing articulated concrete blocks will be employed to ensure the structural integrity of the slope and the adjoining roadway, thereby safeguarding the well-being of the traveling public. It is noteworthy that concurrent with this widening project, the City of Benbrook is planning the construction of an emergency access bridge immediately downstream of the TxDOT IH-20 bridge. The development of both bridges is anticipated to impact the overall hydrology of the lower Clear Fork of the Trinity River watershed. The existing and recommended channel cross-sections are illustrated in Figure 26. (Asfaw, 2023).

Recognizing the uncertainties and variables, the mitigation of slope failure risk to absolute zero remains impractical. Instead, our objective is to diligently minimize the risk to a reasonable and acceptable level, taking into account the potential consequences of failure.

Global stability analyses were completed, following a minimum factor of safety of 1.5 for the conservation pool and 1.3 for rapid drawdown, based on standards and TxDOT. It is essential to emphasize the importance of periodic inspections for the slopes to ensure ongoing stability and to address any emerging concerns. This proactive approach aligns with our commitment to risk reduction and the overall success of the project.

Figure 25- IH-20 project's location (from Asfaw, 2023)

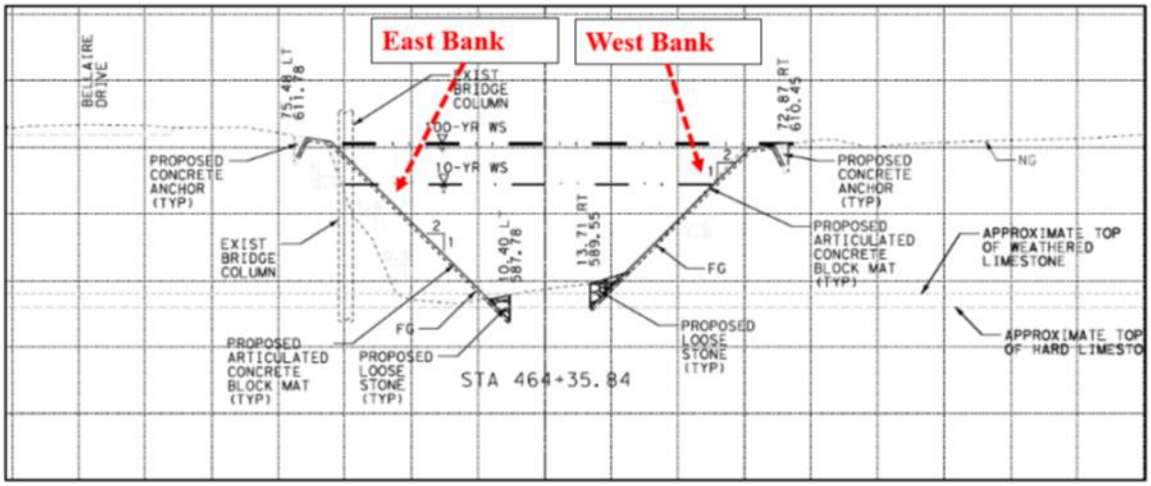


Figure 26- existing and recommended channel cross-sections (from Asfaw, 2023)

4.3 IH-20 Slope Geometry and Anchors and Soil Parameters

The slope stability model incorporates both un-stabilized and stabilized 2H:1V cross-sectional geometries, along with defined soil strata, represented in Figure 27 through Figure 29. The selection of the 2H:1V slope ratio is grounded in the confirmation of its stability through thorough analysis, affirming its efficacy in ensuring a secure and resilient slope configuration. The finite element model adopts a plane-strain configuration, featuring 15-noded elements over an area measuring 180 feet in width and 70 feet in height. Notably, a very fine mesh comprising 2592 elements has been employed to enhance the accuracy of the model.

In terms of boundary conditions, the constraints in the x-direction for minimum and maximum boundaries are normally fixed. Meanwhile, in the y-direction, the minimum boundary is fully fixed, while the maximum boundary is left free, allowing for unconstrained movement.

The details of the anchor system, as outlined in Table 8, cover important aspects like anchor spacing and orientation. The PDEA anchor (Duckbill 138-II) paired with a 5/16-inch stainless steel wire tendon was employed for slope stabilization. A "node-to-node" anchor element was utilized in numerical analysis to simulate the anchor system. The results of the field pullout test were incorporated as the anchor's Ultimate Pullout Load, as detailed in Table 8. Notably, the anchors, crucial for stabilizing the slope, are installed perpendicular to it. It's highlighted that these anchors are positioned with a 4-foot center-to-center spacing both vertically and horizontally.

Table 9 lists the essential properties of the soil under study, offering a clear understanding of its composition for stability analysis. Together, Table 8 and Table 9 serve as key references, providing clear insights into the components that influence the outcomes of the study.

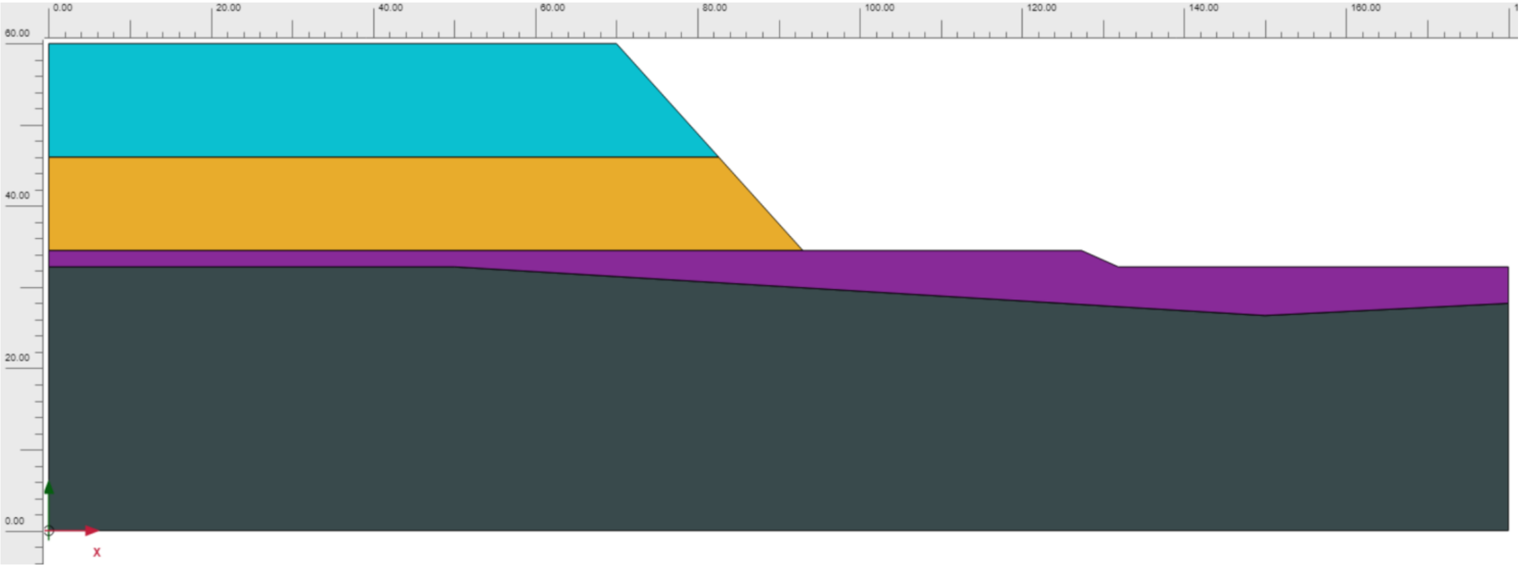


Figure 27- Geometry of the slope before stabilization

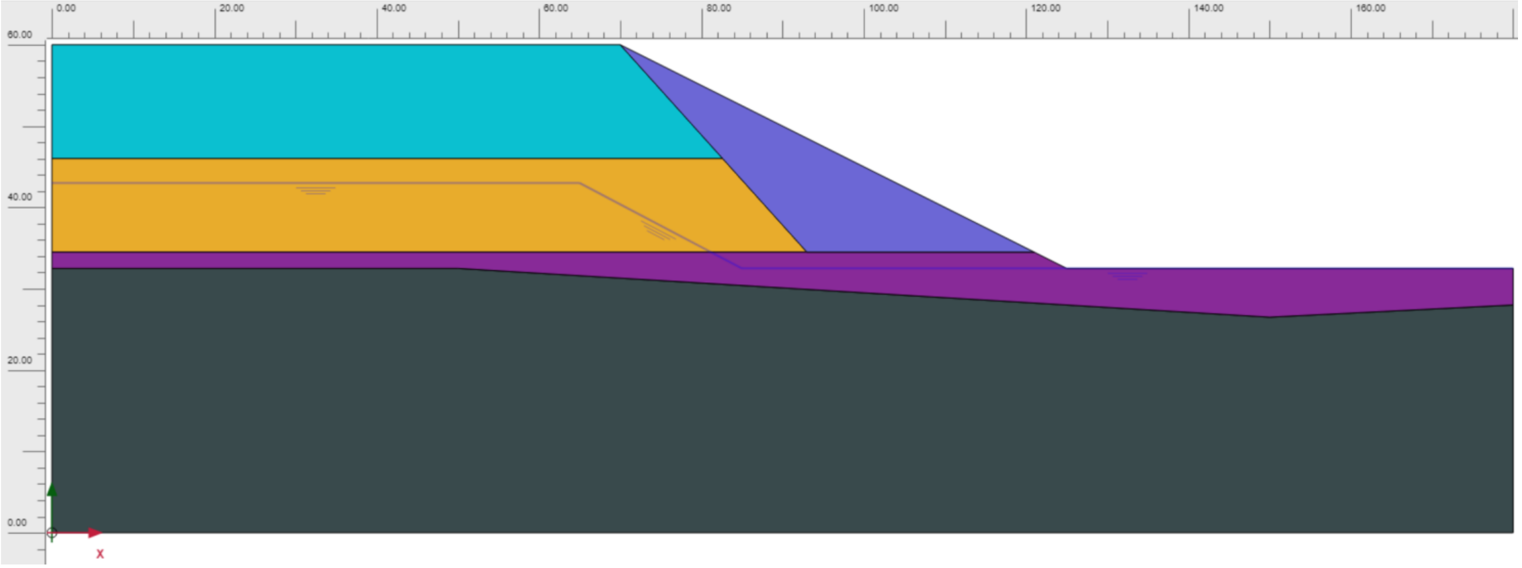


Figure 28- Geometry of the slope after fill

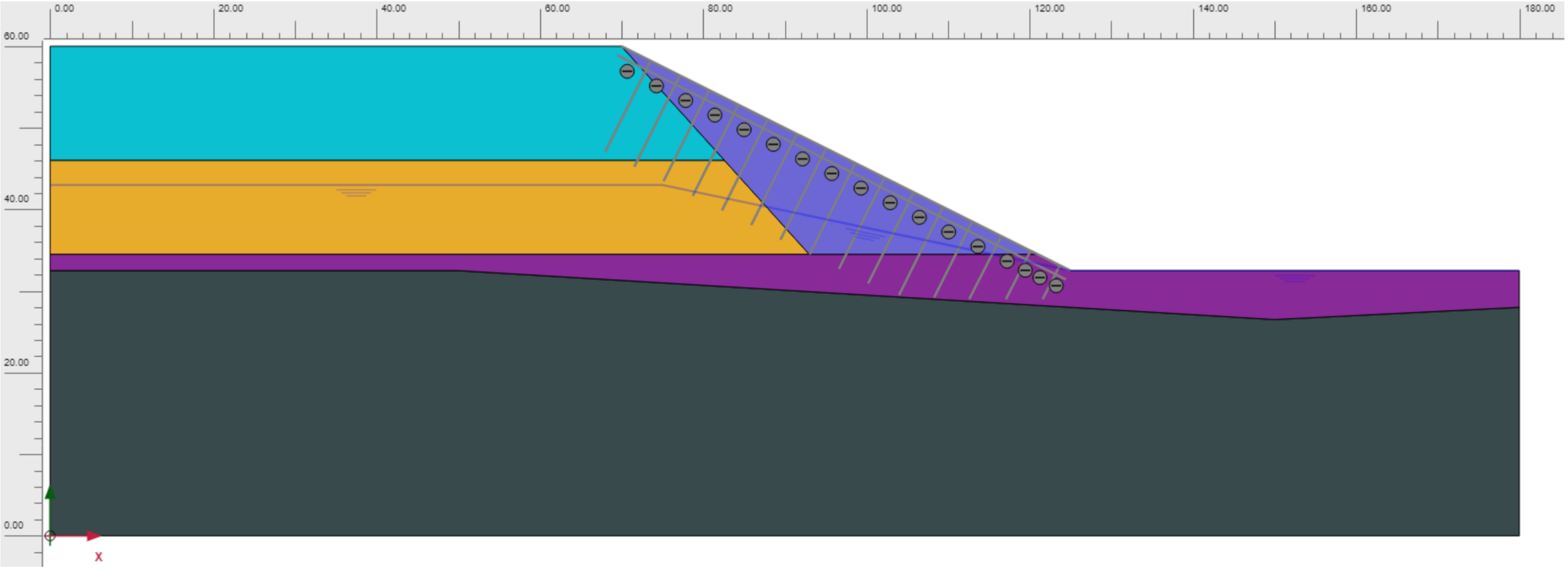


Figure 29- Geometry of the slope after fill, ACB, and anchor

Table 8- Anchors Parameters

Anchors Parameters		
Length (ft)	**Spacing (ft)**	**Ultimate Pullout Load (lbs.)**
12.5 (max)	4	3900

Table 9- IH-20 Slope Soil Properties

Classification **Parameters**		**Fill Soil**	**CL**	**SC**	**Limestone (weathered)**	**Limestone**
Unit Weight, γ (pcf)		118.5	125	125	135	145
Effective Stress	**Cohesion, C' (psf)**	0	100	0	0	Rigid
	Friction Angle, φ' (º)	29	22	30	38	Rigid
Total Stress	**Cohesion, S_u (psf)**	500	-	-	-	-
	Friction Angle, φ_u (º)	0	-	-	-	-
CU state **(Drawdown Condition)**	**Cohesion, C_{CU} (psf)**	275	275	-	-	-
	Friction angle, φ_{CU} (º)	10	10	-	-	-
Permeability, k (ft/day)		0.07	0.07	1.98	1.2	Non-porous
Young's modulus, E (psf)		1.0E6	3.0E5	1.25E6	2.0E6	4.0E8
Poisson's modulus, ν		0.28	0.3	0.25	0.28	0.35

4.4 IH-20 Slope Stability Analyses Scenarios

Table 10 comprehensively outlines various analysis scenarios, encompassing assessments both before and after the stabilization of the slope. Additionally, the table incorporates a parametric study that explores diverse scenarios involving the geometry, soil properties, and anchor characteristics. This inclusive reference serves as a valuable guide, providing a detailed overview of the different analytical contexts considered in the study, thereby enriching the understanding of the impact of stabilization measures on slope behavior.

4.5 Slope Stability Analyses Results

Table 11 provides a comprehensive overview of diverse scenarios related to slope stability, both before and after the implementation of stabilization measures, accompanied by their corresponding factors of safety. The impact of various drawdown conditions on the slope is visually represented in Figure 30.

Additionally, Table 12 through Table 14 present distinct cases of parametric slope stability, undrained cohesion of the fill soil, and different water levels in the channel, respectively. The slope failure planes for these scenarios are further detailed in Appendix II.

Graphs in Figure 31 through Figure 34 specifically illustrate the factor of safety across different scenarios within the parametric study, ranging from Case 2 to Case 5.

Notably, the results offer an insight into the efficacy of the stabilization strategies, showcasing a significant reduction in the risk of slope failures. The observed increase in the factor of safety, surpassing the allowable threshold, indicates the success of the described stabilization measures in mitigating potential risks and enhancing overall slope stability.

Table 10- Overview of the Numerical Simulation:

Type	**Cases**	**Purpose**	**Comments**		
			Slope Profile	**Soil Properties**	**Anchor Parameters**
Single Anchor	Current Slope (Total Stress Analysis)	Anchor Pullout Capacity	2 H:1V (Figure 28)	Table 9	Table 8
Slope Verification	Before Stabilization (Effective Stress Analysis)	Calculation of the slope's factor of safety in different Cases	Figure 27	Table 9	Table 8
	Fill Construction (Total Stress Analysis)		2 H:1V (Figure 28)	Fill: Total stress parameters	
	Fill Construction (Total Stress Analysis) (water table rise)				
	Fill (Effective Stress Analysis)			Table 9	
	Fill + ACB + Anchor (Effective Stress Analysis)		Figure 29	Table 9	
	Rapid and Slow Drawdown			Fill and CL: CU parameters	
Parametric Study	Anchors Parameters	Calculation of the slope's factor of safety in different Cases	Figure 29	Table 9	Table 12
	Fill Soil's S_u Properties				Table 8
	Water Level (Effective Stress Analysis)				

Table 11- Slope stability analysis – before and after stabilization

Cases	F.S.	Comments		
		Slope Profile	**Soil Properties**	**Anchor Parameters**
Before Stabilization (Effective Stress Analysis)	0.525	Figure 27	Table 9	-
Fill Construction (Total Stress Analysis)	1.313	2 H:1V (Figure 28)	Fill: Total stress parameters	
Fill Construction (Total Stress Analysis) (water table rise) (Fill S_u = 350 psf)	1.110			
Fill (Effective Stress Analysis)	1.291		Table 9	
Fill + ACB + Anchor (Effective Stress Analysis)	1.418	(Figure 29)	Table 9	Table 8
Rapid Drawdown (Instantaneous drawdown) (Fill Soil Only)	1.126Figure 30		Fill and CL: CU parameters	
Rapid Drawdown (Instantaneous drawdown) (Fill + Anchor + ACB)	1.309			
Slow Drawdown (25 ft drawdown in 5 days) (Fill Soil Only)	1.210			
Slow Drawdown (25 ft drawdown in 5 days) (Fill + Anchor + ACB)	1.428			

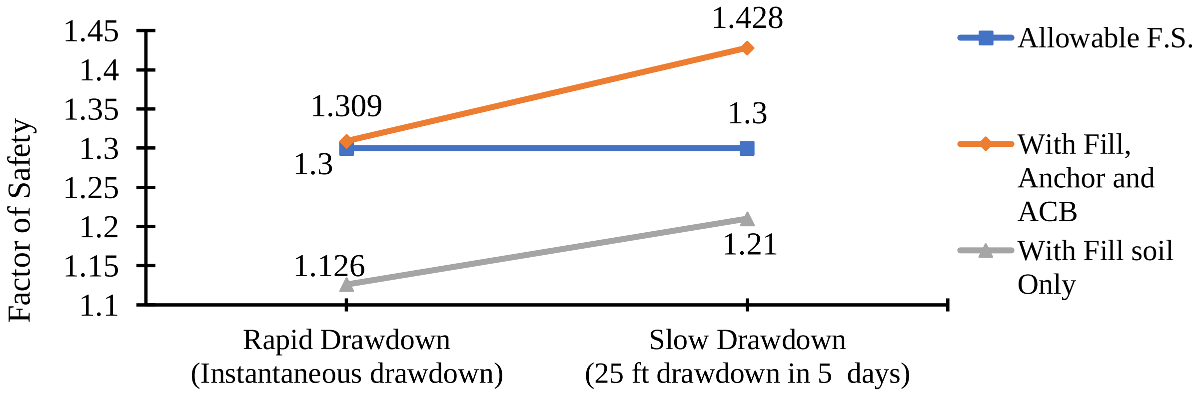


Figure 30- Factor of Safety for different water level drawdown conditions.

Table 12- Anchor parametric study – effective stress analysis.

Case	**Scenarios**	**Length (ft)**	**Spacing (ft)**	**Ultimate Pullout Load (lbs.)**	**F.S.**	**Comments**
1	A	12.5 (max)	4	3900	1.418	Soil Properties: Table 9 Geometry: Figure 29
	B	18.5 (max)			1.436	
2	A	12.5 (max)	4	1950	1.369	
	B			3900	1.418	
	C			7800	1.449	
3	A	12.5 (max)	4	3900	1.418	
	B		8		1.369	
	C		8 (both direction)		1.348	

Table 13- Fill soil parametric study - total stress analysis.

Case	**Scenarios**	**Cohesion, S_u (psf)**	**Friction Angle, φ_u (^{o})**	**F.S.**	**Comments**
4	A	250	0	0.937	Other Soils Properties: Table 9 Geometry: Figure 29
	B	500	0	1.313	
	C	750	0	1.530	

Table 14- Water level parametric study – effective stress analysis.

Case	**Scenarios**	**Water level, H (ft)**	**F.S.**	**Geometry**	**Soils Properties**	**Anchor Parameters**
5	A	0	1.418	Figure 29	Table 9	Table 8
	B	15	1.747			
	C	20	2.009			

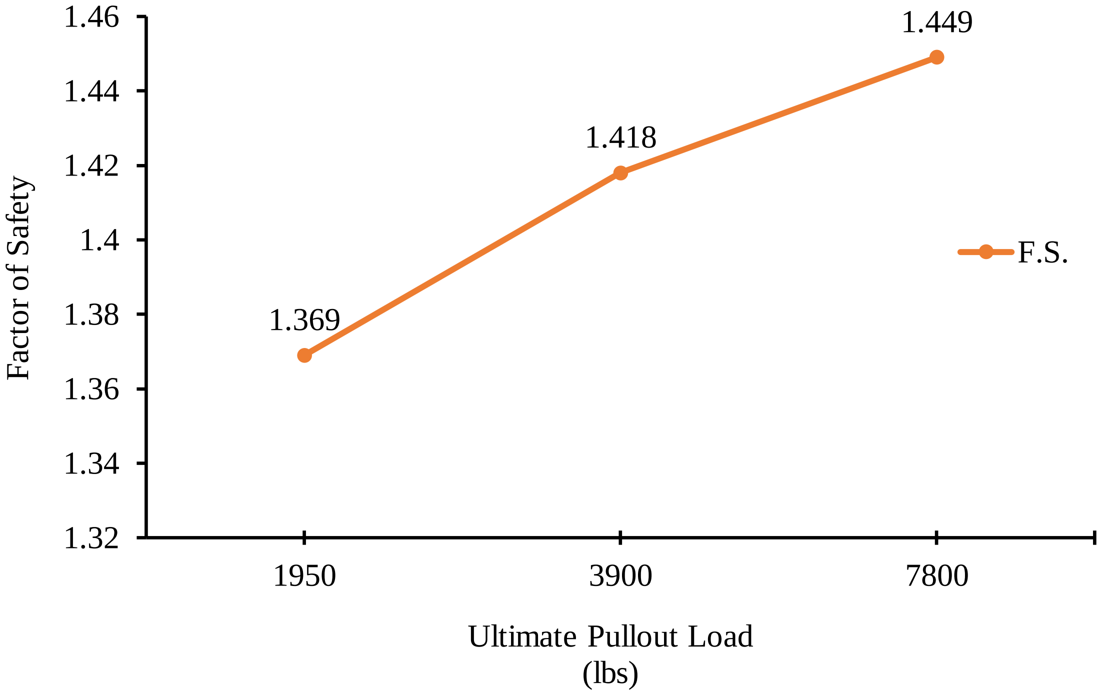


Figure 31- Factor of safety for various ultimate pullout loads - parametric study case 2.

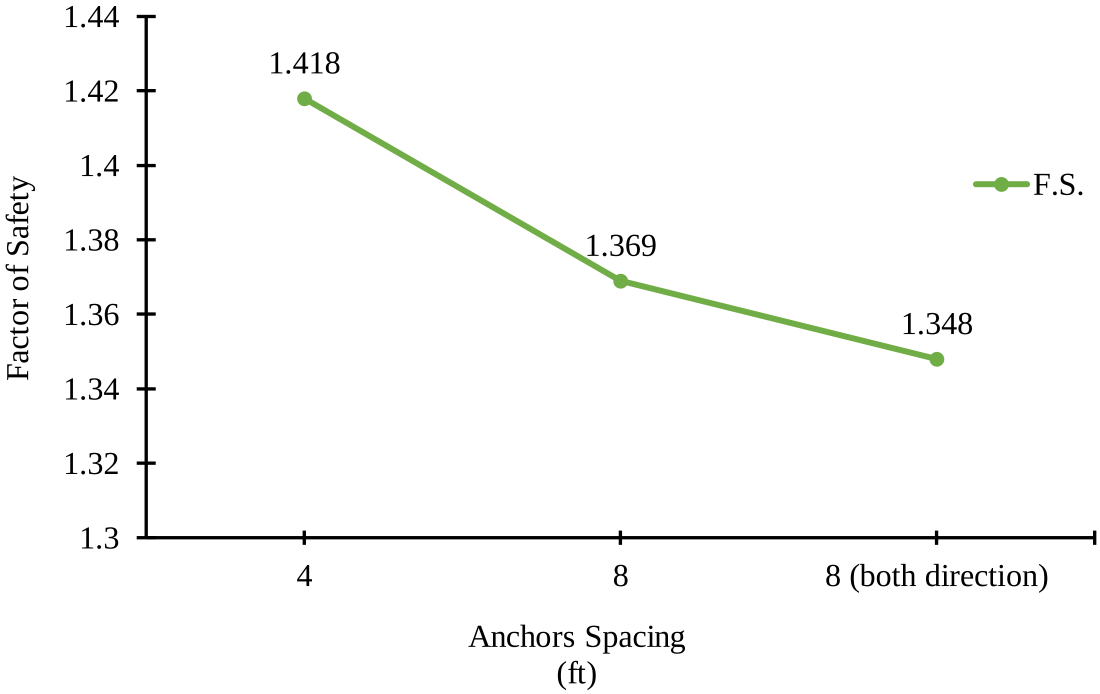


Figure 32- Factor of safety for various anchor spacing - parametric study case 3.

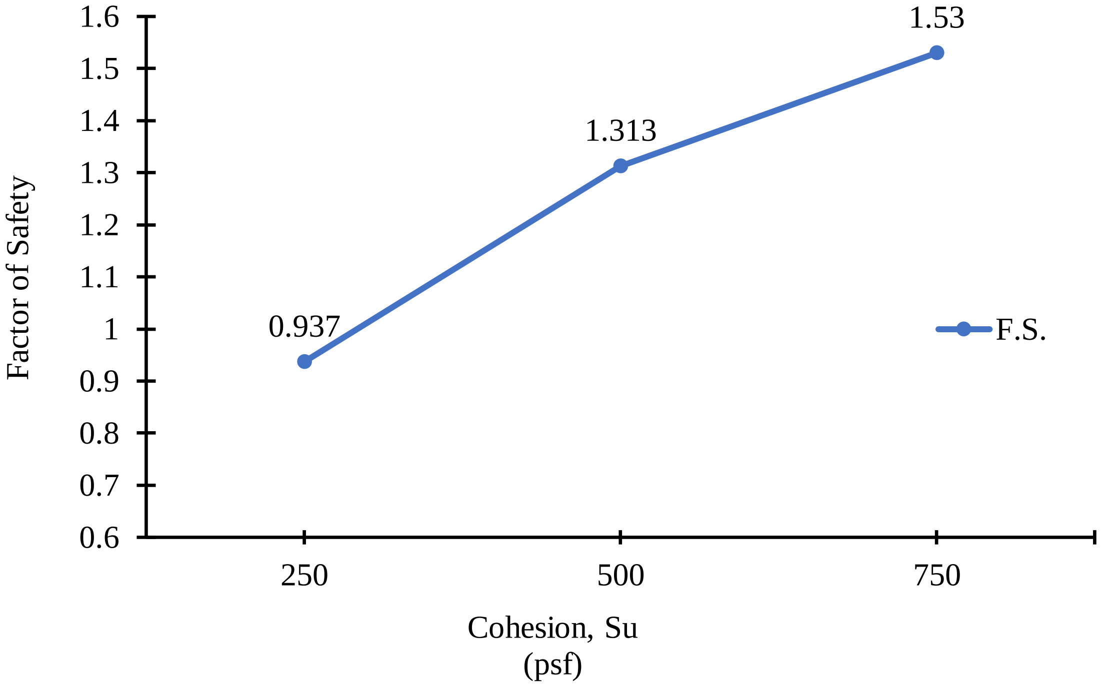


Figure 33- Factor of safety for various fill soil undrained shear strength- parametric study case 4.

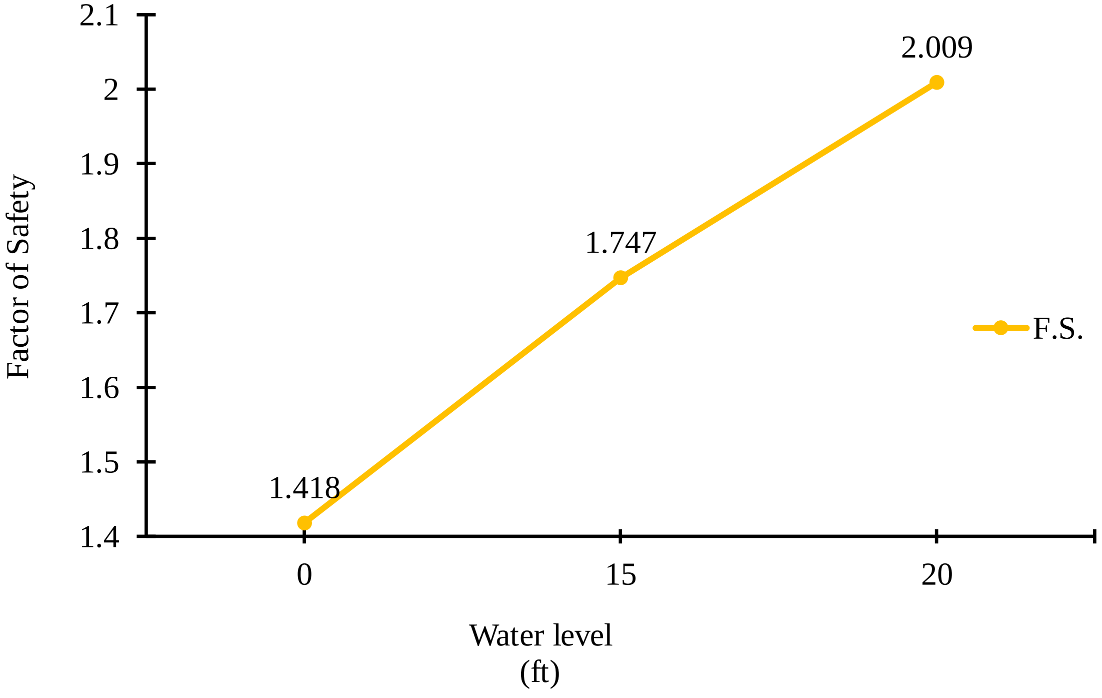


Figure 34- Factor of safety for various water levels- parametric study case 5.

Figure 35 visually captures the appearance of the project's slope following the implementation of stabilization measures. This illustration provides a concrete depiction of the physical changes and improvements achieved through the stabilization efforts. It serves as a tangible representation of the successful outcomes, offering a before-and-after snapshot that communicates the enhanced stability and resilience of the slope.

Figure 35- IH-20 project's slope after stabilization.

4.6 References

Asfaw, N.T., 2023. Performance Of Percussion Driven Earth Anchors for Riverbank Slope Stabilization: Comprehensive Laboratory and Field Studies (Doctoral dissertation).

Ebrahimi, A., Zhu, M., Loizeaux, D. and Manning, S., 2017. Numerical study of an anchor-reinforced vegetation system. In Geotechnical Frontiers 2017 (pp. 406-415).

CHAPTER 5:

SUMMARY AND CONCLUSIONS

5.1 Summary

The integration of geospatial data in geotechnical engineering has become increasingly crucial, empowering professionals to manage and analyze substantial spatial information efficiently. With a rising interest in web applications accessible anywhere with an internet connection, this thesis explored the contemporary landscape of transportation earth structure management. The research underscored the applications' advantages, limitations, and their role in enhancing the efficiency and effectiveness of geotechnical assets, along with challenges related to data management and sharing.

This thesis aimed to pioneer the integration of geospatial web applications into transportation infrastructure management, focusing on geotechnical asset management. Geotechnical assets, including embankments and retaining walls, are vital components influencing safety, stability, and longevity in transportation networks. The adoption of geospatial web applications emerges as a promising avenue for elevating the efficiency of geotechnical asset management, especially in an era marked by rapid technological advancements.

The initial part explored geospatial technology's foundational aspects in civil engineering, spotlighting its relevance in managing transportation infrastructure and geotechnical assets. It endeavors to offer a comprehensive grasp of utilizing geospatial data to collect, analyze, and visualize critical information about geotechnical assets. The subsequent section showcases real-world case studies, demonstrating the tangible benefits of geotechnical asset management, such as risk assessment improvement, early issue detection, and optimized maintenance strategies. The thesis aims to distill valuable insights and best practices from these cases, guiding future transportation projects in leveraging geospatial web applications effectively.

The methodology chapter outlined the research approach, detailing the development and implementation of geospatial web applications for managing transportation earth structures. It ensures transparency and reproducibility in the research process, focusing on facilitating data integration, real-time monitoring, and predictive analytics.

The central focus shifts to the innovative design of a GAM web application. This application stands as a transformative solution for the comprehensive management of geotechnical assets, aiming to empower decision-makers and engineers. The design process exploration encompasses user interface design and geospatial asset data incorporation. This journey underscores the application's potential to revolutionize geotechnical asset management, ensuring a safer and more sustainable transportation infrastructure.

A significant portion of the thesis concentrated on numerical analysis of a slope within a project, utilizing data from the web application. The analysis explored crucial factors like soil properties and geometry for a comprehensive parametric study, providing valuable insights into geotechnical assets' behavior and response. It contributed to a more informed asset management strategy, emphasizing the commitment to rigorous scientific inquiry and strategic decision-making.

5.2 Conclusions

In conclusion, this thesis has extensively explored the integration of geospatial web applications in geotechnical engineering, focusing on transportation infrastructure and earth structure management. The foundational sections established the significance of geospatial data, and the literature review provided insights from existing studies. The innovative design and implementation of a Geotechnical Asset Management (GAM) web application emerged as a transformative solution for effective decision-making in managing geotechnical assets.

Practical applications were demonstrated through a numerical analysis of a slope within a project, utilizing data from the web application. This in-depth examination, exploring soil properties and geometry, provided valuable insights into the behavior of geotechnical assets and their responsiveness to varying conditions. The numerical analysis served as a testament to the commitment to rigorous scientific inquiry and its practical application in asset management strategy. The conclusion highlighted the potential benefits of geospatial web applications, emphasizing improved decision-making, real-time collaboration, and tailored project applications.

In essence, this thesis contributes to the advancement of sustainable, data-driven practices in geotechnical engineering. The integration of geospatial web applications stands as a visionary approach to reshaping transportation infrastructure management, ensuring safety, resilience, and efficiency for future generations.

5.3 Recommendations

For future research and development in the realm of geotechnical engineering and geospatial web applications, several recommendations emerge from the findings and insights gained in this thesis:

1. Enhanced Data Integration: Further exploration can focus on refining and expanding the capabilities of geospatial web applications to seamlessly integrate diverse datasets. This includes incorporating advanced geotechnical data sources, environmental variables, and real-time monitoring data to enhance the comprehensiveness of the information available to decision-makers.

2. User Interface Refinement: Continuous efforts should be directed towards refining the user interface design of geospatial web applications. User feedback and usability studies can guide improvements to ensure intuitive navigation, efficient

data visualization, and enhanced user experience, thereby maximizing the applications' effectiveness.

3. Predictive Analytics: Future research can delve into the development of predictive analytics within geospatial web applications. Using historical data and advanced modeling techniques, these applications can anticipate potential geotechnical challenges, allowing for proactive decision-making and risk mitigation strategies.

4. Integration with IoT Technologies: Exploring the integration of Internet of Things (IoT) technologies can further elevate the capabilities of geospatial web applications. Incorporating sensor data from the field into the application can provide real-time insights, enhancing the applications' responsiveness to dynamic geotechnical conditions.

5. Machine Learning Applications: Investigating the application of machine learning algorithms within geospatial web applications holds promise for automating data analysis, anomaly detection, and decision support. This could contribute to more efficient asset management and early identification of potential issues.

6. Standardization and Interoperability: Efforts should be directed towards standardizing data formats and ensuring interoperability between different geotechnical data systems and applications. This will facilitate seamless collaboration, data sharing, and integration with existing infrastructure management systems.

7. Stakeholder Collaboration: Encouraging collaboration between researchers, practitioners, and policymakers is essential for the continued development and refinement of geospatial web applications. Interdisciplinary efforts can lead to holistic solutions that address the varied needs and challenges within geotechnical engineering.

By addressing these recommendations, future research endeavors can contribute to the evolution of geospatial web applications, fostering innovation and effectiveness in the management of geotechnical assets within transportation infrastructure.

APPENDICES

Appendix I – Numerical Verification Model

Model Geometry and Material Properties (Ebrahimi et al. 2017)

In the modeling phase, a soil slope featuring a 30-degree angle was specifically chosen for analysis, as presented in. This selected slope stands at a height of 15 ft and is characterized by an 8 ft thick upper layer composed of "weaker" soil, positioned atop a foundation of "stronger" soil.

The proposed mitigation strategy involves the implementation of an anchor-reinforced vegetation system, employing five earth anchors strategically placed on/into the slope. These anchors are assumed to be perpendicular to the slope face, spaced at intervals of 5 ft along the slope surface, as illustrated in Figure 36. In the direction perpendicular to the paper space, the anchors are spaced at 4 ft intervals. Key material properties of the soils and anchors are summarized in Table 15 and Table 16 respectively, providing essential information for the subsequent stages of analysis and design within the slope stability model.

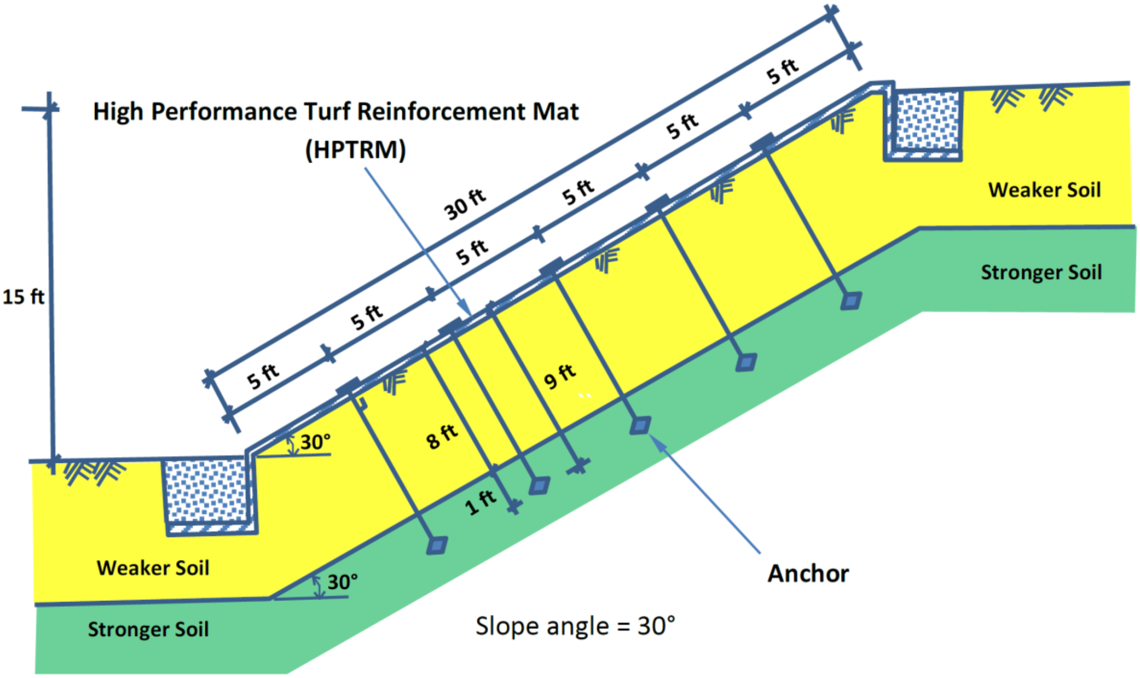


Figure 36- The geometry of the slope for the verification model (not to scale)

Table 15- Soil properties of the slope for the verification model

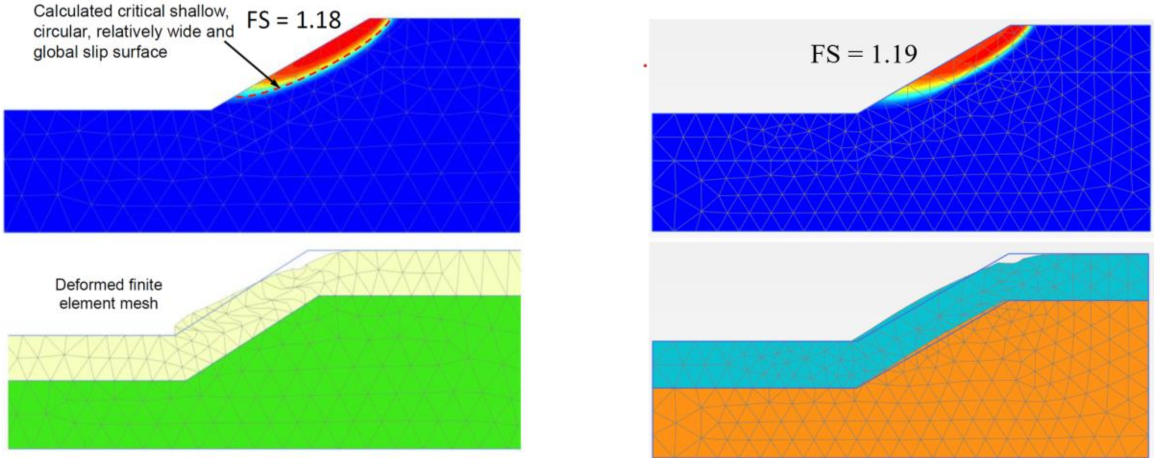
Parameters	Weaker Soil	Stronger Soil
Unit Weight, γ (pcf)	130	130
Cohesion, C (psf)	20	100
Friction Angle, φ (^{o})	29	35

Table 16- Anchor properties of the verification model

Elastic Modulus (psi)	29E+6
Tensile Strength (psi)	2.57E+5
Diameter (inch)	0.14
Maximum Tensile Load for Steel Rod (lb. per anchor)	8075
Allowable Pullout Resistance (lb. per anchor)	800

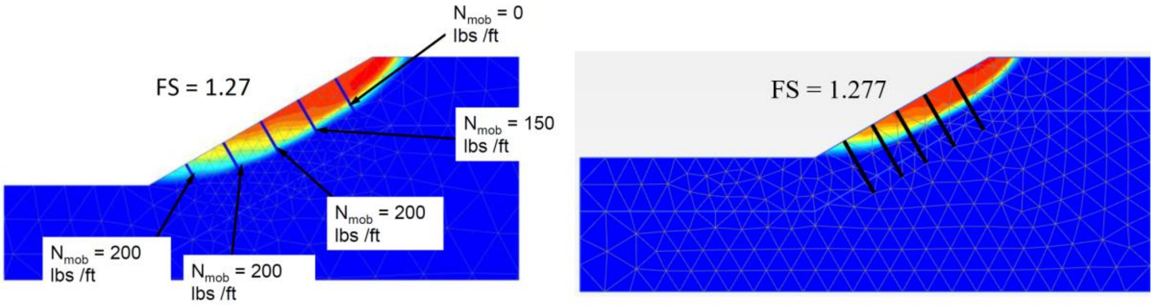
Results

The outcomes of our analysis are meticulously presented in Figure 37 and Figure 38, depicting the performance of the model both without and with the incorporation of anchors, respectively. Notably, the comparison between the results of this study and the model proposed by Ebrahimi et al. reveals a remarkable similarity. This alignment in results underscores the robustness and reliability of our model, affirming its coherence with established research and strengthening the validity of our findings. The congruence observed between the two models further reinforces the efficacy of the anchor-reinforced vegetation system in enhancing slope stability, affirming its potential as a viable and effective solution for soil slopes with similar characteristics.



A **B**

Figure 37- Slope stability analysis results for the verification model – the model without anchor. A) Ebrahimi et al. (2017) B) This study



A **B**

Figure 38- Slope stability analysis results for the verification model – the model with anchor. A) Ebrahimi et al. (2017) B) This study

Appendix II – IH-20 Slope Failure Planes

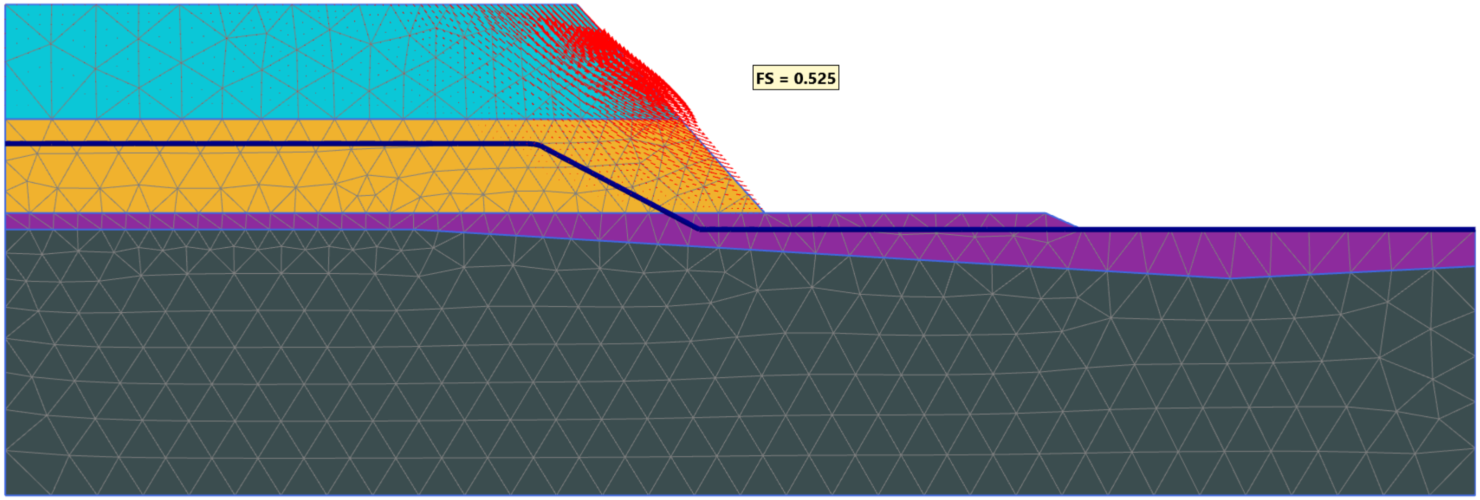


Figure 39- The slope's failure surface before stabilization (Effective Stress Analysis).

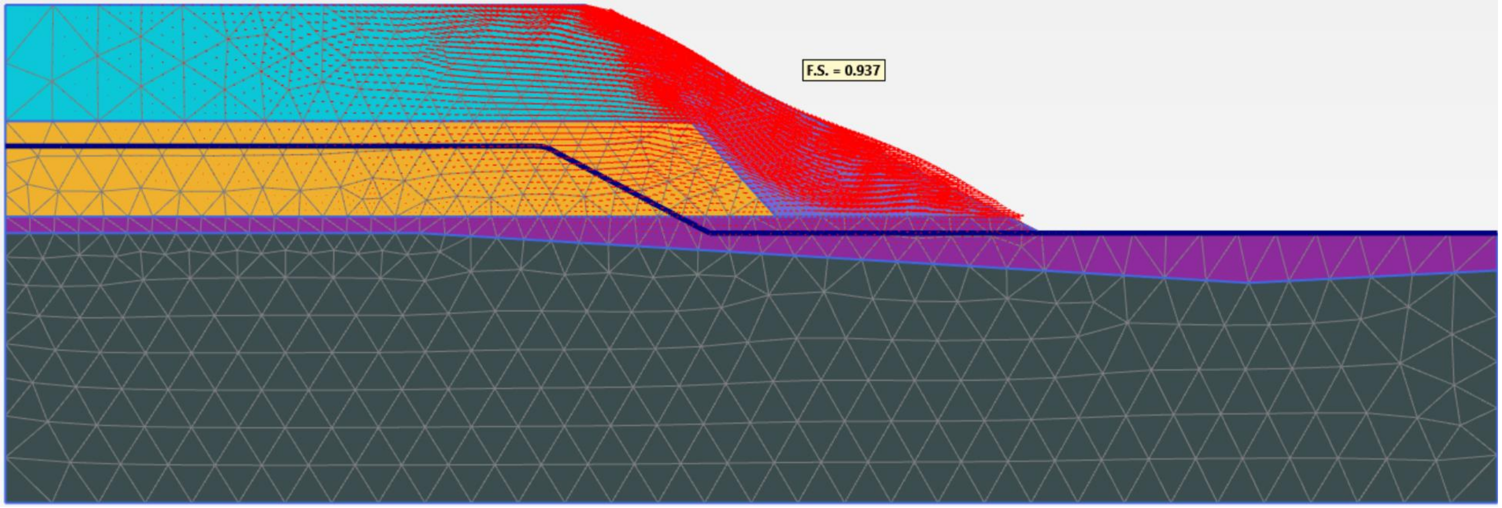


Figure 40- The slope's failure surface after fill construction (fill's S_u = 250 psf) (Total Stress Analysis).

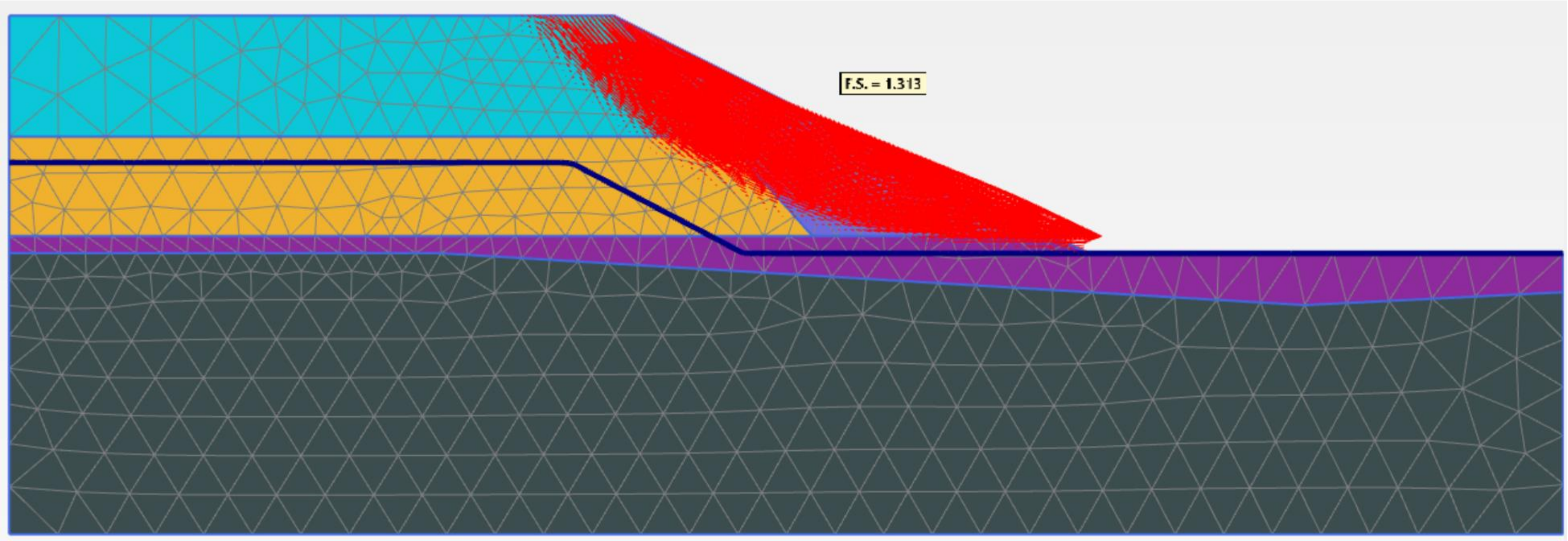


Figure 41- The slope's failure surface after fill construction (fill's S_u = 500 psf) (Total Stress Analysis).

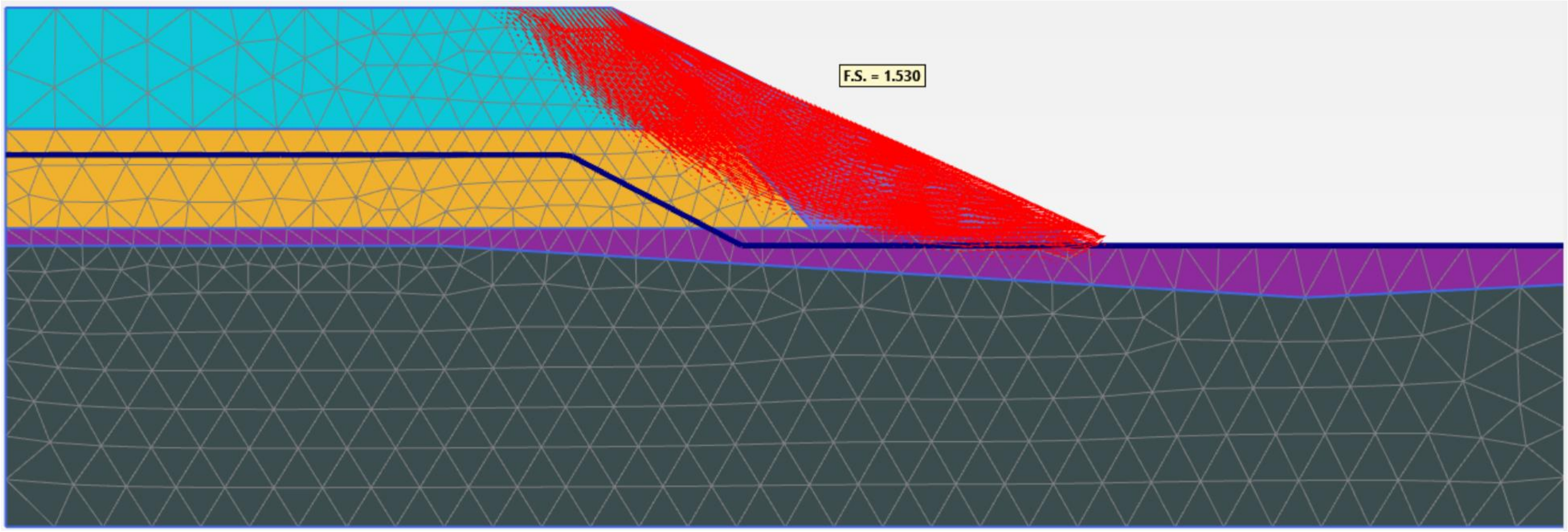


Figure 42- The slope's failure surface after fill construction (fill's S_u = 750 psf) (Total Stress Analysis).

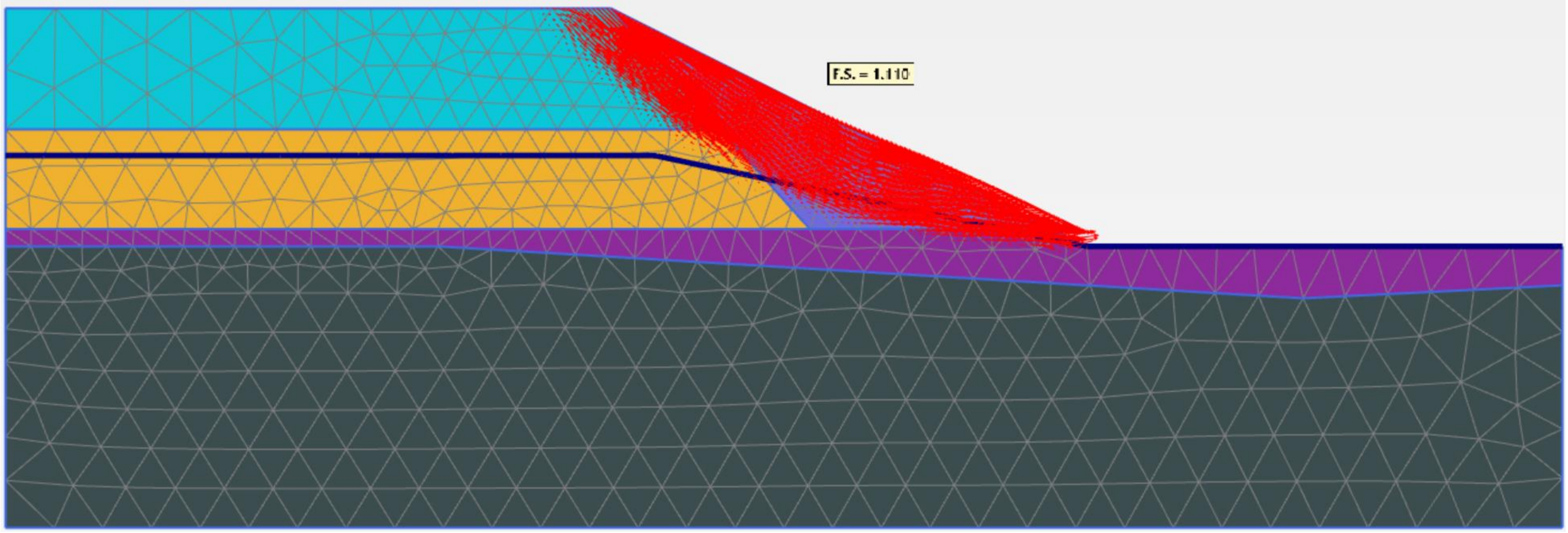


Figure 43- The slope's failure surface after fill construction and water table rise (fill's S_u = 350 psf) (Total Stress Analysis).

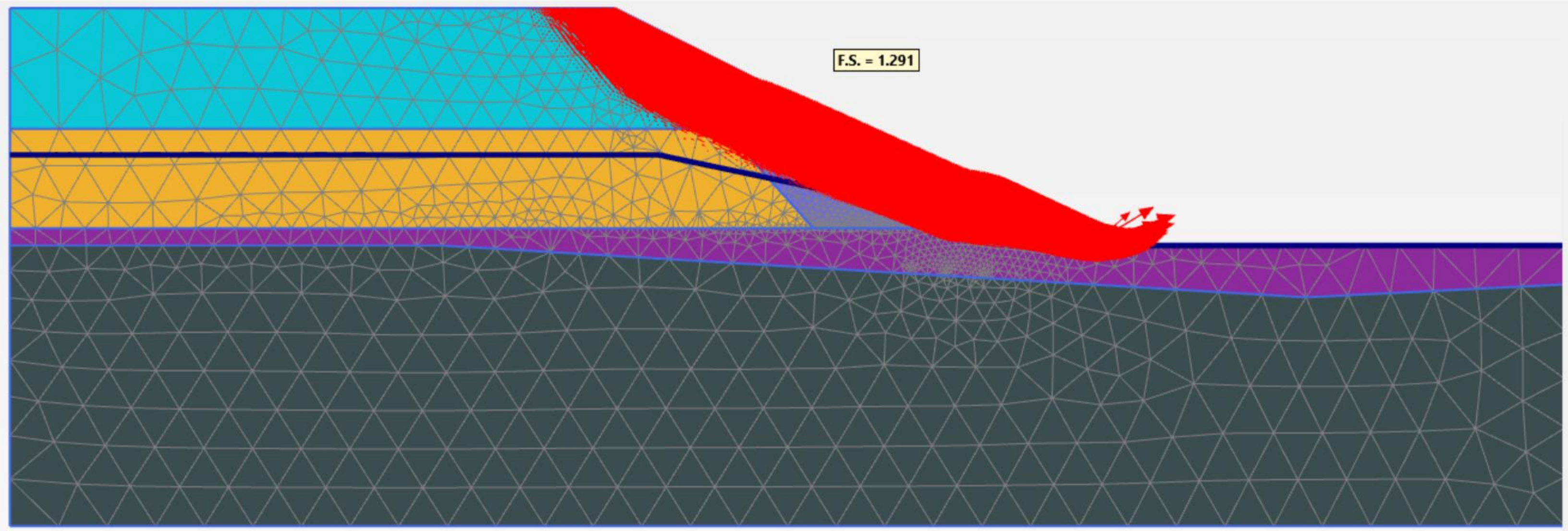


Figure 44- The slope's failure surface after fill construction (Effective Stress Analysis).

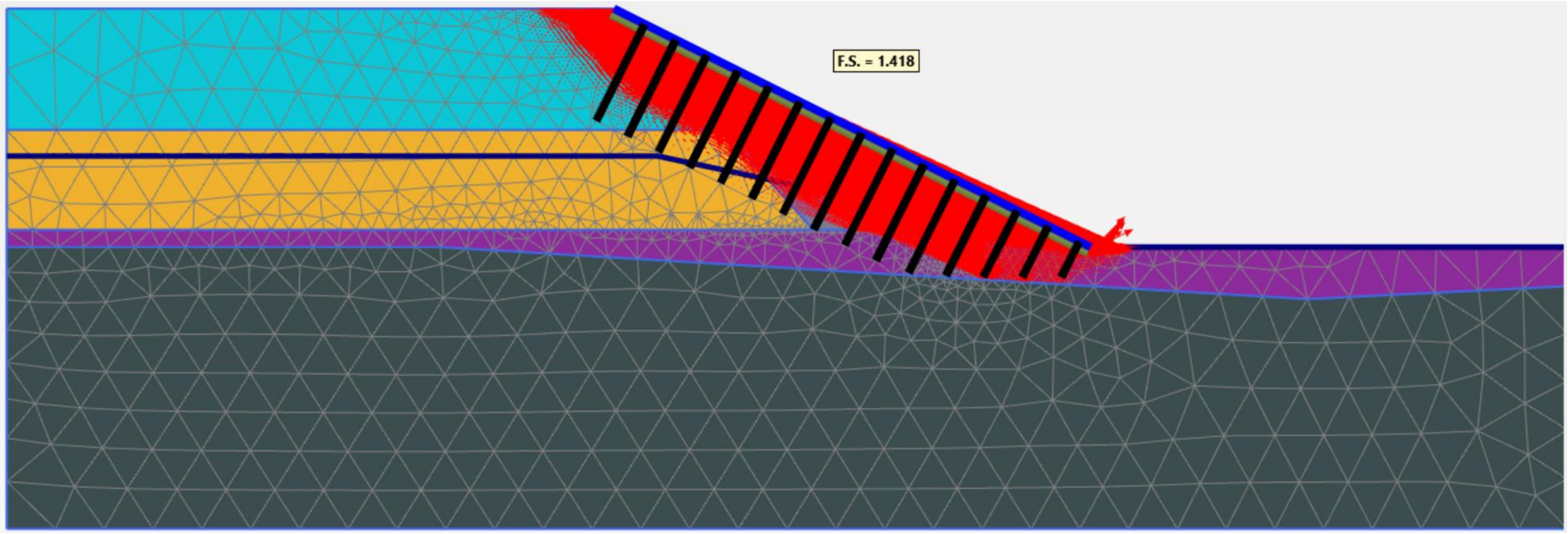


Figure 45- The slope's failure surface after fill, ACB, and anchor (Effective Stress Analysis) (12.5 ft anchors, 4 ft spacing, and 3900 lbs pullout capacity).

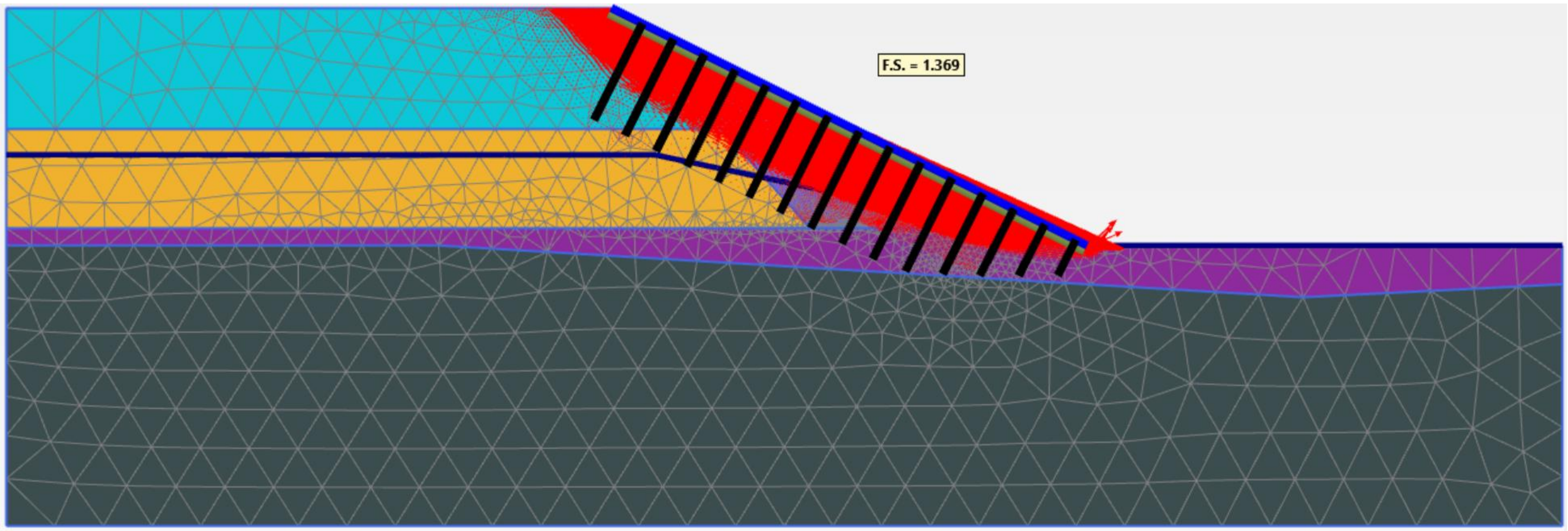


Figure 46- The slope's failure surface - 12.5 ft anchors, 4 ft spacing, and 1950 lbs pullout capacity.

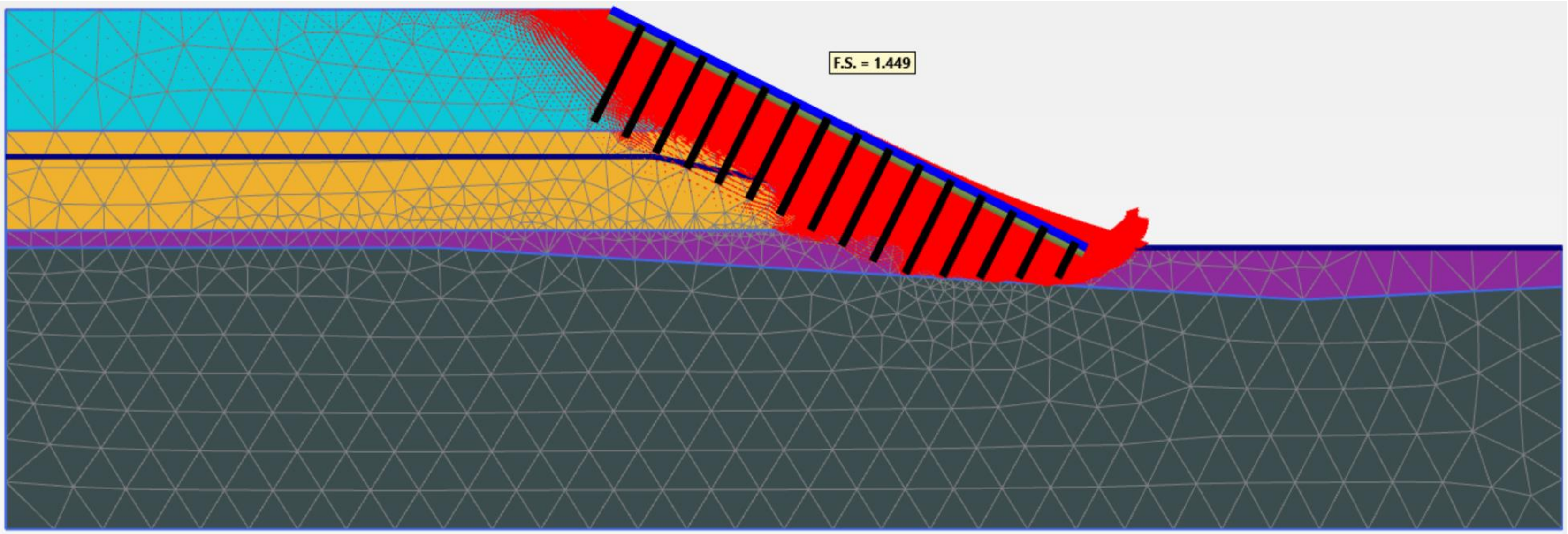


Figure 47- The slope's failure surface - 12.5 ft anchors, 4 ft spacing, and 7800 lbs pullout capacity.

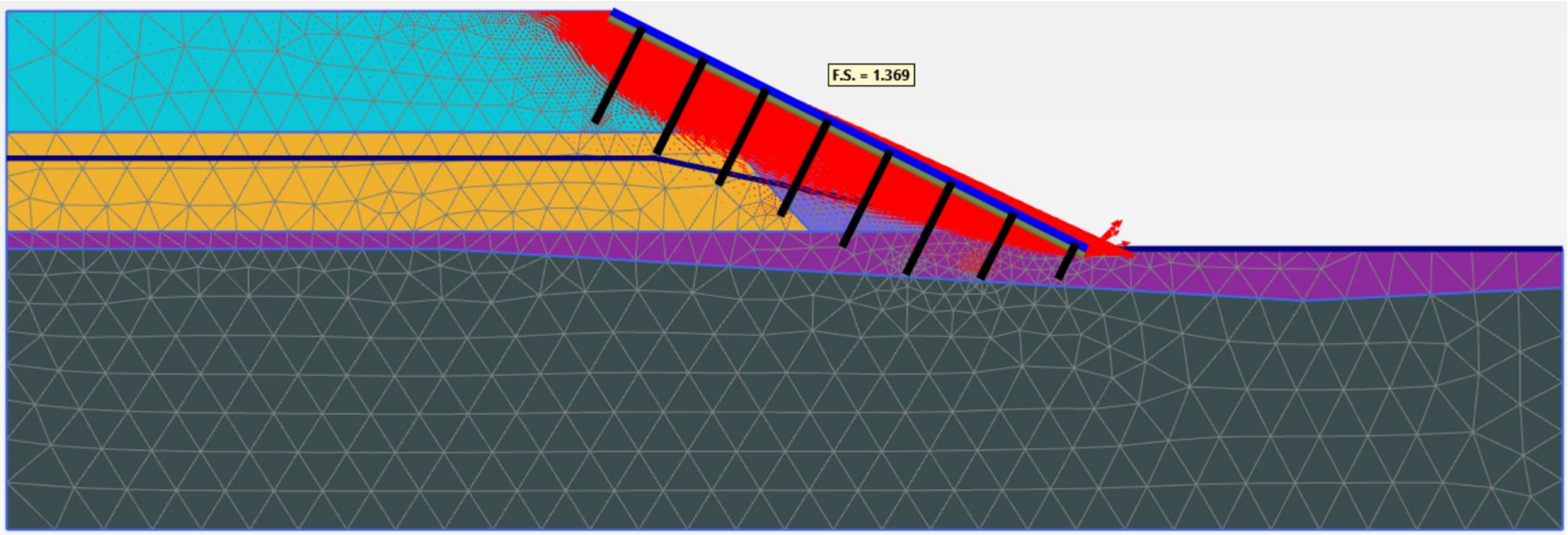


Figure 48- The slope's failure surface – 12.5 ft anchors, 8 ft spacing, and 3900 lbs pullout capacity.

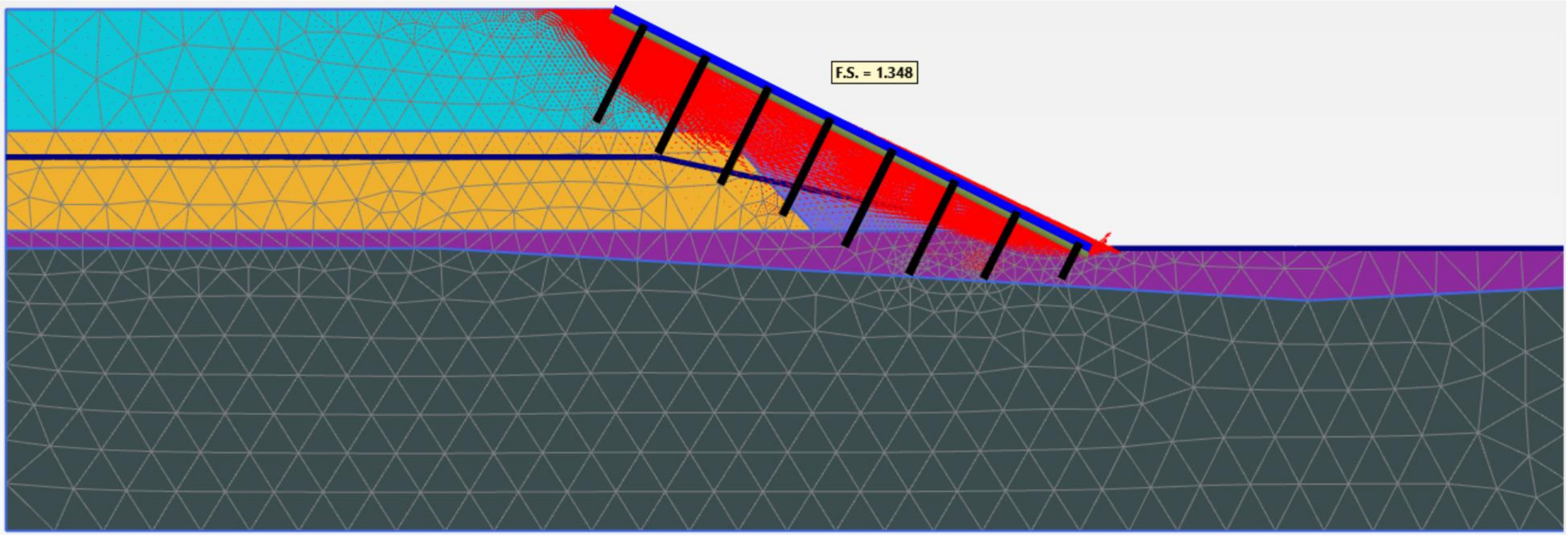


Figure 49- The slope's failure surface – 12.5 ft anchors, 8 ft spacing in both directions, and 3900 lbs pullout capacity.

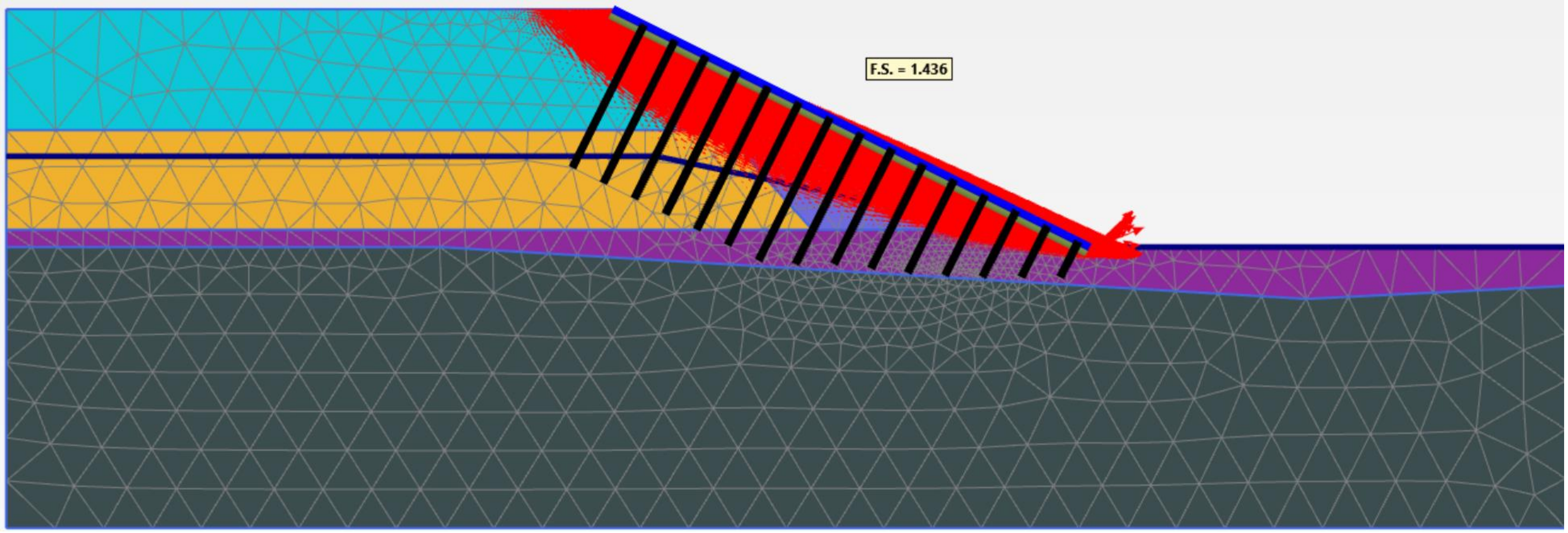


Figure 50- The slope's failure surface – 18.5 ft anchors, 4 ft spacing, and 3900 lbs pullout capacity.