Numerical Investigation on the Effects of Nailing Parameters on Soil Nailed Inclined Face

Abdurehman Hange Tufa

A Thesis Submitted to The Department of Civil Engineering, School of Civil Engineering and Architecture.

Presented in Partial Fulfillment of The Requirement for The Degree of Master's In Civil Engineering
(Specialization in Geotechnical Engineering)

Office of Graduate Studies
Adama Science and Technology University

November,2024
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DECLARATION

I hereby declare that this Master Thesis entitled **“Numerical Investigation on the Effects of Nailing Parameters on Soil Nailed Inclined Face”** is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Abdurehman Hange Tufa		
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **"Numerical Investigation on the Effects of Nailing Parameters on Soil Nailed Inclined Face"** prepared under my guidance by **Abdurehman Hange** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Geotechnical engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Argaw Ashaw (PHD)	____________________	_______________
Advisor	Signature	Date

APPROVAL SHEET

I, the advisor of the thesis **"Numerical Investigation on the Effects of Nailing Parameters on Soil Nailed Inclined Face"** and developed by **Abdurehman Hange,** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Argaw Ashaw (PHD)	________________	____________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Abdurehman Hange** have read and evaluated the thesis entitled **"Numerical Investigation on the Effects of Nailing Parameters on Soil Nailed Inclined Face"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Geotechnical Engineering.

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ABSTRACT

The stability of nailed slopes is depending upon the mechanism by which resisting tensile forces, induced by the nails, are transferred into the ground via friction or adhesion mobilized at the interface. Despite the widespread use of soil nailing, there is a lack of comprehensive understanding of the effects of nailing parameters on the behavior of the structures. The present investigation aimed to explore the impact of various nailing parameters, including length, inclination, diameter, and spacing of the nails, on the performance of soil-nailed inclined face utilizing numerical analysis with PLAXIS software. This investigation employed finite element analysis to replicate the behavior of soil-nailed face under static loading conditions while varying the nailing parameters. A total of five distinct models were developed for each parameter to examine the influence of each soil nail parameter on an inclined face by systematically adjusting their values. One model was constructed based on the parameter values recommended by the Federal Highway Administration, while the remaining four models were developed through increments and decrements of the recommended values. In total, 22 models were developed and analyzed. The factor of safety was computed both before and after the construction of the soil nail within the model, to ensuring the stability of the soil nailing and safeguarding the model's integrity. This study determined that the factor of safety computed from the model developed using the recommended parameters values was 1.694. The calculated value for a nail length of 1.5m was 1.435; this value increased to 1.567, 1.694, 1.725, and 1.743 for nail lengths of 2.5m, 3.5m, 5.25m, and 7m, respectively. The remaining parameters were analyzed in a similar fashion; generally, as the length of the nail increased, the factor of safety also exhibited an increase; however, beyond a certain point, approximately 3.5m, the rate of increment began to decline. A similar trend was observed for diameter; moreover, as the spacing of the nails increased, the factor of safety correspondingly decreased. However, beyond a certain point, around 1.5 meters, the rate of increment began to diminish. This suggests that decreasing the space between nails less than 1.5m might not significantly increase stability and could be less cost-effective. Similarly, as the angle of nail inclination increased to 15 degrees, the factor of safety also exhibited an increase, yet the factor of safety began to decline when the angle of inclination was further increased. This study contributed to the advancement of numerical modeling techniques for geotechnical engineering applications and established a foundation for future experimental investigations to substantiate the numerical findings.

Key words: *3D PLAXIS, Soil Nailing, Finite Element, Nailing Parameters, Factor of safety.*

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ABBREVIATION AND SYMBOLS

C	Cohesion
CBR	California bearing ratio
E	Elastic Modules
ESM	Effective Stress Method
FEA	Finite Element Analysis
FEM	Finite Element Model
FHWA	Federal Highway Administration
FOS	Factor of Safety
g	Acceleration due to gravity ratio
GFS	Global factors of safety
H	Height of wall
HS	Horizontal Spacing
Ko	at rest coefficient of lateral resistance
LL	Liquid limit
MCM	Mohr Coulomb Model
MDD	Maximum dry density
NPC	Nail Pullout Capacity
OMC	Optimum Moisture content
PI	Plastic Index
PL	Plastic Limit
PLAXIS	Plane strain and axial symmetry
SSR	Shear Strength Reduction
VS	Vertical Spacing
w	Moisture Content
ɤ	Bulk unit weight
ν	Poisons ratio
ɤ-sat	Saturated unit weight
ɤd	Dry Unit Weight
Φ	Angle of Internal Friction
Ψ	Dilatancy Angle
3D	Three Dimensions

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Soil nailing constitutes a method of augmenting the stability of pre-existing soil by the strategic insertion of steel rods, referred to as nails, into the substrate at specified intervals throughout the vertical construction framework. The utilization of soil nailing has been thoroughly documented as a highly effective technique for the stabilization of slopes, thereby safeguarding the structural integrity and optimal functionality of the supported structures (BVS and VM, 2015).

Soil nailing has been utilized across a diverse array of applications, including but not limited to railway and highway construction, mining activities, as well as urban development projects. This methodology demonstrates significant advantages in environments characterized by limited spatial availability or difficult accessibility, wherein traditional retaining wall construction techniques may be unfeasible (Sheikhbahaei, 2009).

The effectiveness of soil-nailed faces is influenced by numerous variables, such as nail length, spacing, inclination, and diameter. The optimal design of soil-nailed systems is dependent upon the prevailing geotechnical conditions and loading circumstances (Nowroozi1 et al., 2021). Sophisticated numerical modeling techniques have been widely employed within the domain of geotechnical engineering to simulate the behavior of soil structures under varying loading conditions and to analyze the impact of different parameters on their operational performance (Shahir and Delfan, 2021).

FEA represents one of the principal numerical techniques utilized for this specific purpose. FEA enables a comprehensive investigation of the mechanical responses displayed by soil structures, providing essential insights into the stress distributions, deformation patterns, and potential failure mechanisms of the structures when subjected to various loading scenarios. A meticulous analysis of the effects of nailing parameters on inclined surfaces that have been reinforced with soil nails is critical for advancing the understanding of the structural behavior and enhancing the related design approaches (Shahir and Delfan, 2021).

The exigency for the development of highways and railways is experiencing a significant escalation in Ethiopia, primarily aimed at facilitating connectivity between various development hubs and the ports of adjacent nations.

Nevertheless, the inherent challenges posed by the geographical terrain necessitate that the establishment of such infrastructures, particularly highways and railways, involves the excavation of slopes and the erection of embankments. This situation causes issues related to slope instability, particularly when exposed to external destabilizing factors such as precipitation and seismic activities. The failure of these roadside slopes is currently an issue in Ethiopia causing considerable damage to the construction. According to prior case studies, the failure of these slopes can be attributed to the inadequacy of design of embankments, cut slopes, and support structures by considering all expected destabilizing agents (P.B. Shinde and Gaikwad, 2022).

Numerous investigations have utilized FEA to elucidate the behavior of soil-nailed faces; however, the preponderance of these studies has transpired beyond the geographical confines of Ethiopia, culminating in a dearth of pertinent literature relevant to the study region, particularly concerning the assessment of the impacts of spacing, length, diameter, and inclination on inclined soil-nailed faces. The objective of this research initiative is to rectify this deficiency by methodically evaluating the influences of nail length, spacing, inclination, and diameter on the behavior of inclined soil-nailed faces subjected to static loading conditions. The results of this study are expected to provide substantial benefits to geotechnical engineers in the formulation of economically feasible and safe soil-nailed structures, guided by various nailing parameters. Moreover, this investigation is designed to advance the development of numerical modeling techniques applicable to geotechnical engineering and to establish a foundational framework for future experimental studies, thereby enabling the corroboration of the numerical results.

1.2. Statements of the Problem

In geotechnical engineering, soil nailing is a commonly used technique for slope stabilization, excavation support, and retaining wall construction (Tang and Jiang, 2015). To strengthen the soil and give it stability against outside loads, the method entails driving steel bars or nails into the ground (Shiu and Chang, 2005). However, a number of variables, such as how the nails are designed and installed, affect how well soil-nailed structures work (Tang and Jiang, 2015).

In addition, soil nailing has become a very common technique for strengthening soil structures. Three f components of the construction process are typically the excavation of the soil mass, the laying of nails, and the application of shotcrete to stabilize the facing (Sheikhbahaei, 2009).

Furthermore, a number of factors, including nail length, spacing, inclination, diameter, and others, affect how well soil-nailed inclined face work. There are different of researchers, whose are reports, the effect of nailing parameter on soil nailed inclined face. For instance, Mosser, (2016) was reported that the increasing of distance between the nails is causes decreases of FOS. When the length of nails was increased, the FS values of soil nail inclined face models were increased (Jaya and Annie, 2011). With the decrease in the vertical spacing of the nail, FOS is found to increase (Elahi *et al.*, 2022), in the same way, when inclination equals 25^0, the FOS is close to 0, this indicates that soil nails (modeled as geogrid) at such large inclinations do not provide any appreciable stabilizing effect (Pham *et al*., 2020).

Numerous researchers have investigated the behavior of soil-nailed face under static loading conditions and nailing settings using finite element analysis. The majority of these studies, however, have concentrated on particular facets of soil nailing design, such as how nail inclination or spacing affects the walls' ability to support weight, and the researchers have neglected to provide the proper value of the parameters at the suggested safety factor. Comprehending the impact of these variables on the safety factor of the slope is essential to get a cost-effective and secure design.

In order to fill this gap, this study used numerical modelling techniques to compare recommended parameter values with FHWA, either raising or decreasing the value on soil-nailed inclined face. The study examined the impacts of nail length, spacing, inclination, and diameter on soil-nailed inclined face. The study was used FEA to simulate the behavior of soil nailed inclined face under static loading conditions and varying nailing parameters the study's findings provide light on the best way to construct and design soil-nailed face depending on various nailing parameters and static loading scenarios.

1.3. Research Questions

1. How do different nailing parameters, such as spacing, length, inclination, and diameter, affect the stability of soil-nailed inclined face?
2. What is the factor of safety before and after the application of soil nailing in ensuring the stability of soil-nailed inclined face?
3. What are the optimal values for nail spacing, length, diameter, and inclination based on numerical simulations for enhancing the stability of soil-nailed inclined face?

1.4. Research Objectives

1.4.1. General objective

The general objective of this study is to investigate the effect of nailing parameters on the behavior of a soil nailed inclined face using numerical analysis with PLAXIS software.

1.4.2. Specific objectives

The specific objectives of this study were to;

- To examine the impact of various nailing parameters, such as spacing, length, inclination, and diameter, on the performance of a soil-nailed inclined face.
- To determine the factor of safety before and after soil nailing for the stability of soil-nailed systems.
- To normalize optimized guidelines for nail spacing, length, diameter, and inclination for soil-nailed inclined face based on numerical simulations.

1.5. Significance of the study

The proposed investigation seeks to explain the influence of nailing parameters on the mechanics of a soil-nailed inclined face through numerical analysis utilizing PLAXIS software. This study is anticipated to yield significant insights relevant to the design and construction of soil-nailed structures, thereby enhancing their efficiency under static loading scenarios. In addition to advancing the comprehension of soil-nailed inclined face, this investigation also contributes to the improvement of numerical modeling methodologies applicable to geotechnical engineering contexts.

The FEA model formulated in the present study can be employed for subsequent inquiries into various types of soil-nailed structures and their respective loading conditions. Furthermore, this study establishes a foundational framework for future experimental research aimed at supporting the numerical findings and augmenting the precision of soil nailing design approaches.

1.6. Scope of the study

This study included the development of three-dimensional computer models in addition to a thorough evaluation of previous research. These models were built using the PLAXIS 3D software, which integrated the elastic-plastic model for soil nail performance and the Mohr-Coulomb model for soil model. The study looked at how different nailing parameters; such as length, spacing, diameter, and inclination affect the system's overall stability.

To ascertain the type of soil and other nailing parameters factors, further data was gathered. Ultimately, the impact of each parameter within the developed model was analyzed under static loading conditions, and the resulting data were employed to evaluate the factor of safety.

1.7. Limitation of study.

The limitations of this study include Model Simplifications: The PLAXIS 3D model may simplify complex soil behavior, such as anisotropy or non-linear stress-strain relationships, which could affect the accuracy of the factor of safety results. Loading Conditions: The model may not account for all potential loading scenarios, such as seismic activity, excavation-induced stresses, or changes in groundwater levels, which could significantly alter the factor of safety.

1.8. Organization of the study.

The investigation conducted for this thesis has been systematically structured into six distinct chapters.

Chapter l: Introduction. This chapter offers a comprehensive overview of the research undertaken in this thesis, highlighting the significance of investigating slope stability, outlining the objectives, defining the scope of the study, and presenting the overall structure of the thesis.

Chapter 2: Literature Review. This chapter examines critical issues pertinent to the analysis of slope stability and various methods of slope reinforcement that have been widely implemented across numerous countries. The selection of materials to be included in Chapter 2 is intentional, with a pronounced emphasis on understanding the stability of reinforced slopes and the accompanying analytical investigations. Furthermore, soil nailing, encompassing its components, construction techniques, advantages, disadvantages, and the applicability of soil nailing, alongside the diverse analytical methods employed for slope stability assessment and various slope reinforcement techniques, are critically reviewed as the principal elements of the literature review.

Chapter 3: Methodology. This chapter delineates the specific research methodologies employed to fulfill the aims outlined in this investigation

Chapter 4: This chapter pertains to material modeling and elaborates on the specifics and methodologies employed in the parametric analysis of soil-nailed inclined face.

Chapter 5 offers a comparative analysis between the methodologies and the outcomes derived from the two preceding chapters.

Chapter 6 summarizes the key conclusions drawn from this thesis, accompanied by recommendations pertinent to the objectives and methodologies employed in this research. Lastly, this document includes a compilation of references, which encompasses the relevant citations and appendices.

CHAPTER TWO

REVIEW OF RELATED LITERATURES

2.1. Introduction

The main objective of this thesis is to develop a predictive model for effect of different nailing parameter on soil nailed inclined face. Hence, it is necessary to review the fundamental principles of nailing parameter in detail. In this chapter a detailed literature review is carried out to identify the relationship between different nailing parameter. Basic concepts of soil nailing and different nailing parameter are reviewed in detail. The approaches that have been attempted to predict nailing parameters are presented with summary of the literature review.

2.2. Ground Improvement Technique

Soil is characterized as a naturally occurring assemblage of mineral particles, which may or may not incorporate organic components, that can be isolated through mild mechanical processes such as agitation in aqueous environments (Mueller et al., 2010). For a civil engineer, the designation ‘soil’ pertains to the loose, unconsolidated inorganic substances situated on the earth's crust, resulting from the weathering and fragmentation of rocks, overlaying a more consolidated geological substrate, irrespective of the presence of organic material. In the field of engineering, soils are regarded as encompassing all organic and inorganic terrestrial materials found within the stratum that lies above the bedrock. These materials are typically heterogeneous porous substances whose engineering properties are significantly influenced by fluctuations in moisture content and density (Waller and Yitayew, 2016).

The composition of soil comprises three distinct phases: the solid phase, the liquid phase, and the gas phase. The liquid and gas phases are often subject to rapid alterations due to variations in the natural environment, whereas the solid phase tends to exhibit stability. To comprehensively assess the intricate behaviors exhibited by soil, a thorough geotechnical investigation is imperative. A site investigation of some form is invariably necessary for the establishment of any engineering or construction project (Muthuk Kumaran, 2012).

Ground improvement is a process of modifying the properties of soil or rock to improve their engineering performance, such as increasing their bearing capacity, reducing settlement, improving stability, or controlling seepage. It involves various techniques and methods that aim to improve the soil's strength, stiffness, and other properties to meet the requirements of a particular construction project (Phear and Harris, 2008).

Ground improvement techniques can be broadly classified into two categories: soil replacement and soil modification. Soil replacement involves removing the existing soil and replacing it with a more suitable material, such as sand or gravel. This technique is typically used when the existing soil is too weak or compressible to support the proposed structure. Soil modification, on the other hand, involves altering the properties of the existing soil to make it more suitable for construction. This can be achieved through various methods, such as compaction, vibro-compaction, dynamic compaction, grouting, and soil stabilization. These techniques aim to increase the soil's density, reduce its compressibility, or improve its shear strength (Muthuk kumaran, 2012).

Ground improvement is commonly used in various construction projects, such as building foundations, embankments, highways, airports, and tunnels. It is an essential process to ensure the safety and long-term stability of the constructed structures by providing a stable and reliable foundation (Tarawneh and Al Ajmi, 2020).

2.3. Soil Nailing

Soil nailing represents a cost-efficient, straightforward construction methodology that is widely implemented globally to bolster the stability of retaining walls, slopes, and excavations; it is frequently employed for both temporary and permanent earth retention (Garzón-Rocaa et al., 2019). This structural element imparts load to the underlying soil in the context of excavation reinforcement, a process referred to as reinforcement. The implementation of soil nailing is typically warranted when the ground exhibits an inclination ranging from 10 to 20 degrees relative to a horizontal plane, thereby experiencing tensile stress. Tensile stress was applied to the soil nails in response to investigations concerning the deformation of the retained material throughout the procedure (Mohamed et al., 2023). The application of soil nailing is aimed at stabilizing pre-existing slopes, where top-bottom construction offers distinct advantages in comparison to conventional retaining wall systems (P.B. Shinde and Gaikwad, 2022).

The reinforcement technique is regarded as particularly beneficial and economically viable for soils that possess the ability to maintain stability (stand up time) within excavation depths of 1 to 2m for durations ranging from 1 to 2 days. The process of soil nailing for slopes or excavations necessitates the execution of various tests and continuous monitoring at multiple stages of construction, encompassing pre-construction, during construction, and performance monitoring (Nowroozi1 et al., 2021).

Soil nails exhibit a high ratio of circumference to cross-sectional area, thereby fundamentally depending on frictional resistance for effective load transfer. Soil nailing increases the tensile strength and shear strength from friction at the contact surface of the soil and nails. Soil nailed face offer flexibility, speed and ease of execution, and are more cost-effective under certain conditions than other stabilization systems. The main components of a nailing system include the site soil, tensile nails, and retaining structural elements (Nowroozi1 *et al*., 2021).

2.3.1. Types of soil nailing methods employed in the field

Soil nailing constitutes a technique for the reinforcement of soil wherein the reinforcement elements are embedded within the slope face, thereby forming a mass of stabilized ground comprised of either natural soil or pre-existing fill material. The predominant orientation for the installation of soil nails is at a sub-horizontal inclination (Garzón-Rocaa et al., 2019). The composition of soil nails typically involves metallic or polymeric substances, and these may be incorporated into a pre-drilled borehole followed by grouting, executed simultaneously during the drilling process, or inserted through a displacement methodology.

Grouted nail: The grout can be injected shortly after the nail bar has been positioned within the pre-drilled borehole. Nail bars are affixed to the surface of the excavation through a facing system, which can vary in dimensions from 15 to 46 mm and are placed in pre-drilled cavities that range in diameter from 10 to 15 cm, with vertical and horizontal spacings that fluctuate according to the specific type of terrain (0.25 – 1 nail per square meter of wall). The process of hardening, typically involving cementation, occurs under atmospheric pressure (gravity force) or at reduced pressures (Garzón-Rocaa et al., 2019).

Driven nail: These are slender diameter elements (ranging from 14 to 45 mm) that are embedded into the ground with minimal spacing (between 0.5 and 4 nails per square meter of wall) utilizing a vibro-hammer (either pneumatic or hydraulic); steel nails exhibiting ductile behavior are preferred to mitigate the risk of brittle fracture mechanisms. This particular method of installation is characterized by its rapid execution and cost-effectiveness, although it is constrained by the maximum allowable length of the nails and their limited efficacy in heterogeneous soil conditions (Garzón-Rocaa et al., 2019).

Self-drilling soil nail: Hollow bars are penetrated into the slope surface, with grout being injected concurrently during the drilling operation. This method confers enhanced corrosion resistance to the nails in comparison to driven nails (Ansari et al., 2021).

Jet-grouted soil nail: This technique employs jets to facilitate the formation of apertures on the surface of the slope. Subsequently, steel rods are inserted into these apertures and secured with a grout composed of concrete. This approach offers substantial protection against corrosion for the steel rods (Ansari et al., 2021).

Launched soil nail: This technique involves the propulsion of nails into the soil through a singular application utilizing a compressed air mechanism. Consequently, the installation process of soil nails is expedited; however, the penetration of excessively lengthy rods poses challenges (Ansari et al., 2021).

2.3.2. Application of Soil Nailing

Soil improvement is a versatile technique that can be applied in various situations to enhance the stability and strength of soil structures. One of the primary applications of this technique is the stabilization of existing retaining walls, which may have been weakened due to soil erosion or other factors (Fu, 2015).

Similarly, soil improvement can also be used to stabilize existing slopes that are prone to instability. This includes natural slopes, where soil nailing can be used to reinforce the soil and prevent landslides. Railway embankments, highway embankments, and cuttings are other examples where soil improvement can be applied to enhance their stability and prevent soil erosion. Lastly, embankment dams can also benefit from soil improvement techniques to strengthen their foundations and prevent water seepage. Overall, soil improvement is a valuable technique that can be used in a variety of situations to enhance the stability and durability of soil structures (Phear and Harris, 2008; Zhou *et al*., 2013).

2.3.3. Advantages of Soil Nailing

Soil nailing offers several advantages that have facilitated the proliferation of this technique across various nations. Economic assessments of select projects have led to the inference that soil nailing is unequivocally a cost-effective method when juxtaposed with a tieback wall. Accelerated construction rates can be attained if appropriate drilling apparatus is utilized. In the context of rigid facings, the application of shotcrete readily accommodates an inclined surface, thereby enhancing overall stability. The backward inclination of the facing further mitigates shotcrete losses attributable to rebound. Empirical observations of actual nailed structures have revealed that horizontal deformation at the apex of the wall varies from 0.1 to 0.3% of the wall's height for well-engineered walls (Garzón-Rocaa et al., 2019; Taule, 2019).

Soil nailing may be executed utilizing standard drilling and grouting apparatus. Consequently, this methodology is particularly advantageous in locations characterized by challenging access and restricted spatial limitations. In heterogeneous geological conditions where boulders or hard strata may be encountered amidst softer layers, soil nailing is typically more viable than alternative methodologies, such as soldier piles. Nailed soil retaining structures exhibit greater flexibility compared to traditional cast-in-place reinforced concrete retaining structures (Garzón-Rocaa et al., 2019).

As a result, these structures possess the ability to adapt to deformations of the surrounding terrain and can endure more substantial total and differential settlements. This property of soil nailing can facilitate cost-effective support for excavations on precarious slopes. In the event that a single nail experiences overstress for any reason, it does not precipitate the failure of the entire wall system. Instead, it reallocates the overstress to the adjacent nails. The implementation of a flexible facing system enables the construction of green walls (Taule, 2019).

2.3.4. Limitations of Soil Nailing

Soil nailing is a useful technique for stabilizing soil structures, but it has certain limitations that must be considered. Firstly, it cannot be used in every location, as the soil and rock conditions may not be suitable for this method (Taule, 2019). Secondly, the installation of soil nails requires experienced labor, which can increase the cost of the project. Thirdly, areas with high levels of water are not compatible with soil nailing, as it can lead to corrosion and reduced effectiveness. Additionally, gravel and sand may not be compatible with this method, as they can cause the soil nails to loosen over time. Furthermore, the metal nails used in this technique can corrode and weaken over time, reducing their effectiveness. Lastly, soil nailing may not be the best option for permanent adjustments, as it may require ongoing maintenance and monitoring to ensure its stability (Taule, 2019).

2.3.5. Factor Affecting Soil Nailing

The behavior of nailed face is affected by parameters such as soil resistance, type of nail, wall execution stages, and geometric characteristics. There exists a multitude of factors that influence the feasibility and stability of soil nailing, which encompasses: External stability: The potential for bearing failure, classified as an external failure mode, necessitates evaluation when constructing the inclined face of a soil nail within a fine-grained, soft soil matrix (Nowroozi et al., 2021).

Internal stability: In a manner akin to external failure modes, it is imperative to assess internal failure mechanisms, which may manifest as: nail-soil pull-out failure, bar-grout pull-out failure, nail tensile failure, or nail bending/shear failure. A detailed examination of these four categories of internal failure is provided in the FHWA report, which serves as a thorough reference. Favorable ground conditions: The assessment of facing failure modes constitutes another critical factor that warrants examination within a soil-nailed system, and this can be discerned across four distinct scenarios (Nowroozi et al., 2021).

2.3.6. Design of soil Nail

Before undertaking any of the procedures delineated, the soil nail engineer is required to: ascertain the project prerequisites, encompassing construction limitations (e.g., topography, site accessibility, right-of-way, utilities, neighboring edifices). Assess aesthetic considerations and performance standards (e.g., deformation, stability, longevity). Upon finalizing the design, the design engineer formulates specifications for the inclined face of the soil nail. The sequential generalized methodology for the design of the inclined face of soil nails has been elucidated as follows (Wu, 2015). The five major steps and their sub steps in this design method are outlined in Table 2.1. In the remainder of this chapter, each of these steps is presented.

The design of a soil-nailed face in accordance with the FHWA procedure: To achieve the design of a soil-nailed face, one may adhere to the sequential generalized protocol established by the FHWA (Wu, 2015).

Table 2.1: Design Steps for Soil nail inclined face (FHWA, 2003).

Step 1. Initial soil nail wall design considerations	A. Wall layout (e.g., wall height, wall length, face batter) B. Soil nail vertical and horizontal spacing C. Soil nail pattern on wall face (e.g., square, staggered, other irregular patterns) D. Soil nail inclination E. Soil nail length and distribution F. Soil nail material type (e.g., selection of steel bar grade) G. Selection of relevant ground properties for design (e.g., soil shear strength; location of groundwater table, etc.) H. Other initial considerations

Step 2. Preliminary design using simplified charts	These charts are used to preliminarily evaluate nail length and maximum nail force.
Step 3. Final design	A. External Failure Modes 1) Global stability 2) Sliding stability 3) Bearing capacity B. Seismic Considerations C. Internal Failure Modes 1) Nail pullout resistance 2) Nail tensile resistance D. Facing Design 1) Nail head load 2) Wall facing type and thickness 3) Facing materials 4) Flexural resistance 5) Facing punching shear resistance 6) Facing head stud resistance 7) Other design facing considerations
Step 4. Estimate maximum wall deformations	
Step 5. Other design considerations	A. Drainage B. Frost protection C. External loads D. Support for facing dead load (e.g., foundation support for precast wall facing)

2.4. The behavior of the soil nail

The performance characteristics of soil nails are profoundly influenced by a multitude of factors, including the installation methodology, soil properties, and nail specifications, among others. It has been documented that an increase in the length of the nails corresponds with a reduction in both horizontal deflection and vertical settlement (Pham et al., 2020). Furthermore, it has been noted that the stabilizing efficacy diminishes with an elevation in the water table within the slope, an increase in the vertical and horizontal spacing of the nails, and a reduction in the length of the nails (Pham et al., 2020).

The inclination and length of the nails are identified as critical parameters that significantly influence the static performance of the soil-nailed interface (Sheikhbahaei, 2009). The interface friction stress associated with soil nails is influenced by the density of the surrounding soil. Specifically, the friction stress exhibits elevated levels when the soil possesses greater density and hardness, which is characterized by pronounced stress concentration; conversely, the friction stress is diminished and exhibits uniformity when the soil is less dense and softer, aligning with established theoretical postulations (Sheikhbahaei, 2009; Wang et al., 2021).

The sequence of prestressing on the internal forces of the soil nail is dictated by the tensioning process. When the anchor is subjected to synchronous tensioning, its capacity to mitigate deformation becomes apparent; at the same time, the upper soil nails are similarly affected. In contrast, when the anchor is tensioned at a later stage, the influence on the lower soil nails becomes significant (Pham et al., 2020).

The distribution of the maximum nail forces in soil-nailed retaining structures displays a systematic pattern that corresponds to the proposed sliding surface; however, in the case of soil nail prestressed anchor composite retaining structures, prestressing alters the distribution of stresses, resulting in a distinct "breakpoint" in the distribution (Wang et al., 2021). The unbonded length, regarded as a principal factor influencing slope stability in dense materials, is primarily represented by variations in the stress distribution of soil nails, while the impact on subsequent rows is negligible in loose fill materials (Wang et al., 2021).

During the phases of construction and subsequent to its finalization, a soil nail inclined surface along with the underlying soil frequently exhibit an outward deformation. The most significant horizontal displacements are observed at the uppermost section of the wall, diminishing progressively as one moves toward the base of the structure. Numerous variables contribute to the horizontal and vertical displacements experienced by a facing in the context of soil nailing. These include the height of the wall, with deformation increasing linearly as the height increases. The geometry of the wall also plays a role, with inclined face producing more deformation than battered walls. The type of soil surrounding the nails is another factor, with softer soil allowing for more deformation. The spacing of the nails and the excavation lift heights also contribute, with larger spacing and thicker lifts generating more deformation (Fan and Luo, 2008; Kosalim and Gunawan, 2023)

The global factor of safety is significant, with smaller FSGs leading to more significant deformation. The ratio of nail length to wall height also affects deformation, with shorter nails producing more horizontal displacement. The inclination of the nail is another factor, with steeper nails leading to more significant horizontal deformation due to less efficient mobilization of tensile loads. Finally, the magnitude of surcharge loading on the wall can increase deformation, particularly with permanent surcharge loading (Kosalim and Gunawan, 2023).

2.5. Modelling the soil behavior by Mohr-Coulomb Model

The MCM constitutes an elastic perfectly plastic framework, effectively integrating Hooke's law with the Coulomb failure criterion. In the context of soil behavior modeling during simulations, the MC model frequently serves as the primary option, unless the problem's conditions are sufficiently explicit to warrant the inclusion of additional parameters for the representation of more sophisticated soil models. Consequently, employing the MCM to delineate soil behavior necessitates a minimal set of parameters relative to alternative soil models, thereby resulting in reduced computational time compared to other methodologies. Nonetheless, the application of the MCM is not without its constraints, which will be elucidated in the subsequent paragraph (PLAXIS 2006).)

Initially, it is imperative to acknowledge that the MCM is characterized as an elastic perfectly plastic construct, signifying that the yield surface remains fixed and is unaffected by any plastic deformations. Additionally, the stiffness inherent in this model is invariant to pressure, failing to accurately represent the actual conditions prevalent in the majority of in-situ soils. Furthermore, the model does not account for the viscous characteristics of soils, which can hold significant relevance in certain soil types, such as soft clays and excavation sites.

With respect to the parameters essential for the MC model, five principal parameters must be accessible for the analytical input, specifically: Young's modulus (E): this parameter signifies the fundamental stiffness modulus of soil within the MC framework. Poisson's ratio (ν): ν is typically utilized within a range of approximately 0.3 to 0.4 under loading conditions, and between 0.15 and 0.25 under unloading conditions. Dilatancy angle (ψ): for soils with clayey characteristics, ψ is generally regarded as zero, whereas for sandy soils it is estimated to be roughly equivalent to "φ - 30°". Shear strength parameters of soil (cohesion and friction angle): these two parameters were elaborated upon in the Section of Chapter 3.

As evidenced by the aforementioned descriptions, the MC model can be effectively characterized by five straightforward data points that are commonly available in nearly all engineering projects as the fundamental prerequisites for design. Consequently, by adopting this model to represent soil behavior, one can conduct analyses with remarkable efficiency, and the overarching patterns of displacements can be derived with relative ease.

2.6. Types and Causes of Slope Failure

Natural and man-made slope failures have resulted in a great deal of death and destruction, as well as economic losses and environmental degradation.

2.6.1 Type of Failure

The characteristics of soil composition, the organization of soil layers, the presence of groundwater, the dynamics of seepage, and the topographical configuration of slopes collectively contribute to the phenomenon of slope failure. Various classifications of slope instability that have been referenced in non-peer-reviewed sources are enumerated below.

Rotational Slide: In instances of rotational failure, the phenomenon transpires through rotational movement along a defined slip surface, resulting in a curvature characterizing the slip surface. The compromised surface exhibits a displacement that is both outward and downward. Typically, three distinct classifications of rotational failure are observed. Base failure: Base failure transpires when there exists a deficient soil layer beneath the toe. Toe Failure: Toe failure represents the predominant mode of failure.

Flow Slide: This phenomenon transpires when both internal and external factors compel a soil mass to exhibit characteristics akin to a viscous fluid, subsequently cascading down even slight inclines and disseminating in various directions. The delineation of the failure surface in flow slides is often ambiguous. Typically, multiple failure surfaces manifest and undergo continual alteration as the flow progresses. Flow slides are capable of occurring in both arid and saturated soil conditions.

Translational Slide: The phenomenon of slope failure occurring along a zone of diminished soil strength is referred to as a translational slide. The mass undergoing sliding may traverse considerable distances prior to reaching a state of repose. Translational slides are frequently observed in coarse-grained materials.

Block or Wedge Slide: The phenomenon of block or wedge slides transpires when a soil mass is fragmented along joints, fissures, and zones of weakness due to forces originating soil masses.

2.6.2 Causes of Slope Failure

Natural phenomena, anthropogenic errors in judgment, and the activities of subterranean fauna are all elements that play a role in the occurrence of slope failures. The subsequent etiologies of slope instability were delineated in specific unpublished manuscripts.

Erosion: Both natural and anthropogenic inclines are perpetually subjected to the erosive forces of hydrological and aeolian agents. The process of erosion modifies the configuration of the slope, culminating in slope destabilization or, more precisely, a landslide event. Watercourses and tributaries incessantly abrade their banks, leading to the erosion of both naturally occurring and artificially constructed slopes.

Rainfall: Extended periods of precipitation lead to the saturation, softening, and erosion of soil profiles. Moisture infiltrates pre-existing fissures, thereby compromising the stability of the subsurface soil strata and precipitating slope instability phenomena, including mudslides.

Earthquakes: Earthquakes generate dynamic forces, notably dynamic shear forces, which diminish the shear strength and rigidity of the soil. Dynamic liquefaction transpires when pore water pressures within saturated coarse-grained soils escalate to a level that corresponds with the overall mean stress, resulting in the soils exhibiting behavior akin to that of viscous fluids. Even coarse-grained soils are incapable of expelling surplus pore water pressures due to the rapidity (a matter of seconds) with which these dynamic forces are manifested.

Geological Features: Unrecognized geological characteristics are responsible for numerous operational failures. A minuscule layer of silt (measuring merely a few millimeters in thickness) situated beneath a substantial accumulation of rigid clay may be readily disregarded during drilling activities, or one might exhibit carelessness in the assessment of borehole logs, only to subsequently realize that the existence of the silt precipitated a disastrous failure.

Translational sliding along weak geological layers is frequently observed in inclined, sedimentary soils. In the assessment of slope stability, it is imperative to incorporate geological variables into the analysis.

External Loading: The imposition of loads on the apex of a slope (the summit of the hill) amplifies the gravitational forces and heightens the susceptibility to slope failure. Conversely, a berm, or a load positioned in proximity to the toe, augments the stability of the slope. In order to remediate problematic slopes, a diverse array of terminologies is frequently employed.

Construction Activities: The removal of lateral resistance during construction activities adjacent to the toe of an extant slope may precipitate failure. Slope failures attributable to construction operations can be categorized into two distinct classifications. The first classification pertains to excavated slopes, while the second pertains to fill slopes.

Rapid Drawdown: The rapid drawdown of reservoirs is feasible. In this context, the lateral forces engendered by the water are eliminated, and the additional pore water pressure has insufficient time to dissipate. Ultimately, if proper drainage measures are not implemented, the slope may experience failure. Furthermore, if the water level of the reservoir is maintained at a low elevation and failure does not manifest under undrained conditions, the infiltration of groundwater occurs, resulting in supplementary seepage forces that may lead to failure.

2.7. Shear Strength Reduction Method

For numerous years, practitioners in the field of design have employed the SSR methodology to assess the stability of slopes. The SSR technique represents a pragmatic and efficacious approach for evaluating the stability of soil slopes, encompassing both unreinforced and reinforced variants, and was predominantly utilized in the majority of the modeling endeavors undertaken in this study (Stauffer, 2015).

The SSR methodology is executed by systematically augmenting or diminishing the strength of a soil slope until the condition of equilibrium/non-equilibrium is achieved. At this critical juncture, a FOS is determined, as elucidated below, through the application of Equations 2.1 to 2.4. This methodology presupposes the behavior of elasto-plastic materials.

The FOS, expressed using the Mohr-Coulomb yield criterion as presented in Equation 2.1, can be expressed as (Stauffer, 2015).

$$\frac{\tau}{\mathrm{FOS}} = \frac{\mathrm{C}}{\mathrm{FOS}} + \frac{\tan\phi}{\mathrm{FOS}} \quad \text{……………………………….2.1}$$

This expression can also be written as:

$$\frac{\tau}{\mathrm{FOS}} = c* + \tan\phi* \quad \text{…………..…..……………….2.2}$$

where,

$$c* = \frac{\mathrm{C}}{\mathrm{FOS}} \quad \text{..…..……………………………2.3}$$

and,

$$\phi* = arctan\,\frac{\tan\phi}{\mathrm{FOS}} \quad \text{……….…..………………………2.4}$$

Using these equations, and the following steps, a FOS can easily be obtained (Stauffer, 2015):

Step 1. Develop a finite element model of the chosen slope and allocate the corresponding mechanical strength and deformation characteristics of the soil materials. Execute the computational analysis of the model and document the overall deformation of the slope.

Step 2(Assuming the slope exhibits stability…) By employing Equations 2.3 and 2.4, augment the FOS value to facilitate the assignment of diminished soil strength characteristics to the FE model, and subsequently re-evaluate the model.

Step 3. Repeat Step 2 until the FE model does not obtain a converged solution. (The FOS value obtained that is just above the non-converged solution is recorded as the slopes.

(It is noteworthy that in instances where the slope is initially characterized by instability, the FOS is reduced in Steps 2 and 3, whereby the soil strength properties are enhanced until the FE solution achieves convergence (Stauffer, 2015).

2.8. The effect of different nailing parameters on soil nail

NPC constitutes a significant element in the evaluation and formulation of nailed facades, which is derived by considering the dimensions of the nail (specifically, its diameter and length) as well as the adhesive strength (bond resistance) (Moayed and Mortezaee, 2018). It can be asserted with confidence that there exists a positive correlation between NPC and the enhancement of bond strength. Consequently, any variable that facilitates an augmentation in bond strength will similarly lead to an increase in NPC as well (Moayed and Mortezaee, 2018).

Height: Height denotes the vertical measurement from the base to the apex of a construction or element. It constitutes a critical variable in the engineering of foundations, retaining structures, and embankments. The height of these constructs can influence their overall stability and the load-bearing capacity of the underlying soil (FHWA, 2015).

Lengths: Extended nail lengths are necessitated in scenarios involving weak soils; where deep-seated critical slip surfaces are present; when substantial surcharge loads are applied behind the structure; and in cases where an ascending backslope is situated behind the wall. For the purpose of formulating a preliminary cross-section for analytical evaluation, the length of the soil nail can be approximated to be around 0.7H. Should it be concluded, based on meticulously selected parameters and a suitable stability assessment, that nail lengths must exceed approximately 1.2H, this finding may indicate that the ground conditions are unfavorable for the implementation of soil nails on an inclined face (FHWA, 2015).

Conversely, nail lengths that are shorter than 0.5H are unlikely to meet the requirements for sliding stability, and lengths below approximately 0.6H are infrequently encountered (FHWA, 2015).

Spacing: Spacing is defined as the interval existing between proximate structures or components within a soil system. This parameter holds significant importance in the engineering of retaining walls, sheet piles, and various other geotechnical constructs. The specific spacing employed is contingent upon the type of soil and the angle of the facing. The arrangement of these structures possesses the capacity to influence both their stability and the overarching stability of the soil system (Shahir and Delfan, 2021). Soil nails are positioned in a systematic grid formation. As indicated by the Federal Highway Administration, the horizontal nail spacing, denoted as SH, frequently aligns with the vertical nail spacing, represented as SV (FHWA, 2015).

The spacing of nails in both orientations typically varies from 4 to 6 ft (1.22 to 1.83 m), and in certain instances may extend to 6.5 ft (1.98 m), with a common selection of 5 ft (1.52 m). The spacing must be evaluated to ensure that the product of SH and SV remains below approximately 36 to 42 ft (10.98 to 12.81 m). The initial row of nails ought not to be installed at a depth exceeding approximately 2 to 3.5 ft (0.61 to 1.06 m) from the superior edge of the wall, in order to mitigate the risk of instability in the upper excavation lift and to alleviate cantilever effects on the temporary facing (FHWA, 2015), The lowest row of nails should be positioned approximately 2 to 3 ft (0.61 to 0.915 m) above the excavation's base. Furthermore, a minimum soil nail spacing of around 3.5 ft (1.06 m) must be stipulated to reduce the likelihood of drilling into previously installed nails due to deviations during drilling.

Additionally, closely spaced nails may induce stress overlap in load transfer, analogous to the behavior observed in closely spaced piles (FHWA, 2015).

Pattern: The utilization of varying nail length configurations along the vertical extent of the wall has a significant impact on the efficacy of the soil-nailed face; thus, implementing either decreasing or increasing length arrangements along the wall height influences the lateral earth pressures exerted behind the wall facing (Sheikhbahaei, 2009). Soil nails are positioned on the excavation face in "square" or, more frequently, "staggered" patterns. The configuration of nails on the excavation face may become irregular in areas where spatial constraints are present. This configuration facilitates the straightforward construction of vertical joints in shotcrete and simplifies the installation of precast concrete panels (if utilized). Drain strips maintain equidistance from the nails within this arrangement (Sheikhbahaei, 2009).

A staggered arrangement yields more uniform distributions of earth pressures, enhances soil arching effects, and offers slightly greater resistance in comparison to a square configuration (FHWA, 2015).

Diameters: The term diameter pertains to the measurement of the width or thickness of a structural element within a soil system. This parameter is crucial in the engineering design of piles, drilled shafts, and various other types of deep foundations. The dimensions of these constructs can significantly influence their load-bearing capacity as well as their interaction with the adjacent soil matrix. High-yield deformed steel bars with diameters of 25 mm, 32 mm, and 40 mm are frequently employed as reinforcement in soil-nailing applications; however, bars with smaller diameters should be utilized judiciously, especially in the context of extended soil nails, due to their propensity to exhibit excessive bending during installation (Group, 2008).

Inclinations: The concept of inclination denotes the angle at which a structural element is positioned relative to the horizontal plane. This characteristic is a significant factor in the design considerations of slopes, retaining walls, and other geotechnical constructs. The angle of inclination of these structures can considerably impact their stability and the overall integrity of the soil system (Alsubal et al., 2017). Moreover, the reinforcing efficacy of soil nails may be influenced by the angle of inclination at which these nails are installed. The orientation of soil nails is contingent upon the angle of the slope (Dewedree and Jusoh, 2017).

Furthermore, the inclination of nails for a steep slope ought to be less than that of soil nails for a gentle slope. An increase in their inclination would lead to a reduction in the reinforcing force within the nails, consequently diminishing the stabilizing effect (Pham et al., 2020). Standard nail inclinations are typically set at 60°, 50°, and 40° relative to the horizontal plane, corresponding to slopes with steepness angles of 30°, 45°, and 60°, respectively (Dewedree and Jusoh, 2017). Soil nails are generally installed at an angle ranging from 10° to 20° from the horizontal, with a predominant inclination of 15° (FHWA, 2015).

Project specific conditions may necessitate the installation of nails at angles steeper than 15°. When utilities or subterranean structures are in close proximity, the inclination of the nails must be adjusted around these utilities or structures. The existence of utilities predominantly affects only the uppermost rows of nails, as these utilities are typically located at shallow depths. Nails should be avoided above utilities to prevent future excavations for maintenance from compromising wall stability (FHWA, 2015).

2.9. Finite element model of a soil nail

A multitude of computational software applications have been created for the assessment and design of soil nail inclined faces. The model of a soil nail inclined face is approached as a plane strain issue, with long-term behavior being emulated under drained analysis conditions, and the finite element mesh is generated using 15-noded triangular elements of suitable density (Singh and Babu 2010).

Furthermore, various general slope stability software has incorporated the functionality to simulate different forms of soil reinforcement, which include the employment of soil nails and ground anchors (BVS and VM, 2015).

Despite the fact that soil nails can be integrated into most prevalent general slope stability software, the design process for soil nail inclined faces, particularly concerning nail lengths, is not as straightforward within these programs compared to those specifically tailored for soil nail applications.

2.10. Description and Implementations of PLAXIS 3D

The FEA was conducted with the objective of elucidating the basic mechanisms present within the excavated slope and then validating the behavior of the reinforced soil mass concerning slope displacements and ground settlements. Numerical modeling was executed using the computational program “PLAXIS” to replicate the sequence of excavation (Ghareh, 2015).

PLAXIS 3D is a three-dimensional FEM software designed specifically for the analysis of three-dimensional issues pertaining to deformation and stability within the domain of geotechnical engineering, encompassing excavations, foundations, embankments, and tunnels (Ghareh, 2015). This software is capable of providing both two-dimensional and three-dimensional analyses for such structural types, and notably, it accommodates both basic soil models, such as Mohr-Coulomb, as well as sophisticated constitutive soil models for simulating the nonlinear, time-dependent behavior of soils. According to its manual, several significant attributes of PLAXIS can be concisely summarized as follows (Bonnier, 2006).

Graphical representation of geometrical models: the incorporation of soil strata, loads, construction phases, water table levels, among other factors, can be achieved through user-friendly drawing methodologies, resulting in precise and comprehensive modeling of actual scenarios (Ghareh, 2015).

Higher-order elements: in addition to the six-node triangular elements, PLAXIS also includes fifteen-node cubic strain triangular elements to facilitate the simulation of more precise failure mechanisms.

Beams: This feature makes it simple to represent bending elements in PLAXIS, which is particularly helpful for simulating projects including tunnel linings or retaining walls. Interface: this feature allows for the modelling and addition of the soil-structure interaction to the problem. For the purposes of this study, this is particularly crucial because precise modelling of the interaction between soil and reinforcing materials is one of the most crucial aspects of a slope reinforcement problem (Bonnier, 2006).

Anchors and Geotextiles: The PLAXIS software encompasses self-defined elements for anchors and geotextiles, which facilitate the expedited modeling of these components. Different soil models: As previously articulated, PLAXIS provides an extensive array of soil models, including but not limited to Mohr-Coulomb, Cam-Clay (Soft Soil model), and Hardening Soil, as referenced by Bonnier (2006).

Pore pressure conditions: PLAXIS is capable of simulating both steady-state and excess pore water pressure, thereby serving as an effective tool for approximating drained and undrained scenarios. Automatic mesh generation: An automatic finite element mesh is generated based on the specified input geometry. Staged construction: This characteristic holds substantial significance for the project, as the authentic modeling of slope reinforcement initiatives necessitates a precise representation of construction phases. Factor of safety: The computation of the FOS within PLAXIS is predicated upon its soil mechanics definition, which is deemed more suitable for addressing geotechnical challenges, as noted by Bonnier (2006).

2.11. Phi – C Reduction Method

A slope failure transpires when the shear strength of its material along the sliding surface is inadequate to counteract the existing shear stresses. In the computational modeling of soil nail inclined faces utilizing a FEM, the FOS was ascertained through the Phi – C reduction technique. This methodology entails the progressive and simultaneous decrement of the strength parameters “tanφ” and “cohesion C” of the soil until the structural failure is realized. The occurrence of failure is signified when the FEM fails to converge toward a solution, implies that equilibrium is no longer achievable. The pivotal threshold at which failure transpires is regarded as the FOS (Jaya and Annie, 2011).

2.12. Factor of safety

Engineering design frequently uses the FOS, which is a measure of a structure or system's safety margin, to make sure the system or structure can sustain the anticipated loads and forces without failing. Slopes, embankments, and retaining walls are commonly evaluated for stability using the FOS (Jaya and Annie, 2011). The FOS is determined in slope stability studies by comparing the soil's shear strength to the shear stress exerted on the slope. Laboratory or field tests are used to evaluate the soil's shear strength, and the weight of the soil plus any additional loads, like water or structures, are used to compute the shear stress acting on the slope (Pham et al., 2020).

The FOS is typically expressed as a ratio, with values greater than 1 indicating that the structure or system is safe and can withstand the expected loads and forces. The minimum FOS 1.5 can be considered as a preliminary guide for design of optimal and safe soil nailed on face (Shahir and Delfan, 2021). Overall, the factor of safety is an important parameter in engineering design that helps ensure the safety and reliability of structures and systems in above soil applications. The change of soil-nail angle is not sensitive to the safety factor, while the change of soil-nail horizontal spacing, soil-nail diameter and soil-nail length are sensitive (Tang and Jiang, 2015).

There are different researchers which are reports the effect of nailing parameters using factor of safety. The conclusion of their report is summarized on table 2.2.

Table 2.2: Summery of different researcher report on the effect of soil parameters

Parameters	Their conclusion	Reference
Length	✓ At 6mm diameter, when the length of nails was increased from 0.5 m to 0.6 m, the FS values of soil nail wall models were increased by 7.34%.	(Jaya and Annie, 2011)
	✓ The length of the nail exerts a considerable influence on the ultimate pullout capacity, as an augmentation in length results in enhanced skin resistance being activated along the length of the nail	(Won et al., 2023)
	✓ FS escalates markedly with an increase in the ratio of L/H up to 0.9; however, beyond this threshold, the extension of nail length results in a mere increase in FS by a range of 1.7–4.3%.	(Elahi et al., 2022)

Diameter	✓ Increasing of the nailing diameter facilitates an expanded surface area conducive to load transfer, thereby engendering a linear enhancement in the pullout force, observed with a diameter increment from 105 mm to 203 mm, culminating in a mean amplification factor of 1.9.	(Won et al., 2023)
Spacing	✓ With the reduction in the vertical separation of the nails, it is observed that the FS increases, with the peak FS occurring at a vertical spacing of 1.25 m. ✓ While diminished vertical spacing enhances the FS of slopes, the variation in FS between the spacings of 1.25 m and 2.0 m ranges from 9% to 17%.	(Elahi et al., 2022)
	✓ The FS exhibits a decline with an increase in the horizontal spacing of the soil nails, demonstrating an initially steep slope which subsequently levels off. This curve can be utilized effectively to conclude that the optimal range for soil-nail horizontal spacing lies between 1 m and 2 m.	(Tang and Jiang, 2015)
Inclination	✓ When α equals 25^0, the FOS approaches 0. This suggests that soil nails, which are represented as geogrids, at such significant angles of inclination do not yield any meaningful stabilizing effect. effect.	(Pham et al., 2020)
	✓ For a horizontal backslope, the ideal nail inclinations for β values of 45◦, 60◦, 75◦, and 90◦ are determined to be 25◦, 20◦, 10–15◦, and 0◦, respectively. Furthermore, the significance of selecting an optimal nail inclination is elucidated through the examination of failure surfaces derived from finite element analysis.	(Elahi et al., 2022)

2.13. Research Gap

The performance of soil-nailed on face is influenced by various parameters and range of studies has explored the impact of various parameters such as nail length, spacing, inclination and diameter on the stability of soil-nailed slopes. length of nail significantly influence stability, and as the length of nail increase factor of safety increase (Won *et al.*, (2023). further demonstrated the increasing of vertical and horizontal space make decrease of factor of safety Elahi *et al.*, (2022. The role of inclination and the soil nails at large inclinations do not provide any appreciable stabilizing effect (Pham *et al*., 2020). As the increasing the nailing diameter provides a larger surface area for the load transfer (Won *et al*., (2023). These findings collectively underscore the complex interplay of nail parameters in determining the stability of nailed face, however they do not mention the appropriate value of nail parameter to develop safe nail inclined face at recommended factor of safety.

CHAPTER THREE

METHODOLOGY OF THE STUDY

In this chapter, detailed explanation is presented about the methodologies which include the materials, methods and procedures required to conduct the research.

3.1. Study Area

The study was undertaken at the Adama-Awash expressway development initiative. The Adama-Awash Expressway serves as a critical transportation artery in Ethiopia, facilitating connectivity between the urban centers of Adama and Awash. The initiative encompasses the establishment of 60 kilometers of a newly constructed 126-kilometer four-lane expressway extending from Adama to Awash, the design of a one-stop border post, various road sections, policy reforms, sector enhancements within the Djibouti transport industry, and capacity development initiatives. The expressway traverses the southern export-import corridor via the Dewele/Galile border point, which provides a route to the sea that is 120 kilometers shorter than the existing northern alternative that routes through the Galafi border point.

The Adama–Awash Expressway is characterized by various climatic factors, including temperature and precipitation. The temperature within the study area is subject to fluctuations based on seasonal variations and diurnal cycles. During the arid season, which conventionally spans from November to February, daytime temperatures may ascend to 30°C (86°F) while nocturnal temperatures may descend to approximately 10°C (50°F). Conversely, in the pluvial season, occurring from June to September, temperatures are predominantly lower, exhibiting a range of 20°C (68°F) to 25°C (77°F) during the day and declining to about 15°C (59°F) at night. Precipitation in the study area also exhibits variability contingent upon both seasonal and geographical contexts. The central highlands of Ethiopia are the recipients of the highest rainfall, averaging between 1,200 and 2,500 mm (47 to 98 inches) annually. In stark contrast, the low-lying regions adjacent to the Adama-Awash Expressway experience significantly reduced precipitation, averaging between 200 and 600 mm (8 to 24 inches) per year.

The study area pertinent to this expressway encompasses the entire expanse of the roadway, inclusive of its junctions with other principal roads and highways. This study area will integrate an analysis of the terrain's topography as well as the various soil types present in the vicinity. Furthermore, the implications of soil nailing on the expressway must be duly considered within the study area.

The requisite data and methodologies employed for modeling techniques were collated to forecast the construction dynamics of the Adama-Awash Expressway. This information could subsequently be utilized to mitigate any adverse effects and to ascertain the safety of the expressway. The subsequent figure 3.1 illustrates the cut section of the study area.

Figure 3.1: Study Area

3.2. Study design

In order to achieve the aims of this research, the study utilized secondary data for collection and constructed a model in alignment with the research objectives. An extensive literature review was undertaken to compile relevant information regarding soil nailing techniques, fundamental design principles, and prior investigations concerning the influence of nailing parameters on soil-nailed structures.

A finite element model representing a soil-nailed inclined face was established utilizing PLAXIS 3D software. Numerical simulations of the inclined face of the soil nail were executed employing the elastic-plastic model. In this investigation, a 15-node triangular element and plane strain configuration were utilized for modeling, thereby enabling accurate predictions of failure load and safety factors. Ultimately, a comparative analysis was conducted between the numerical results derived from the study and the experimental results documented in the extant literature, with the aim of validating the finite element model. The present study was conducted following the sequence outlined in next section.

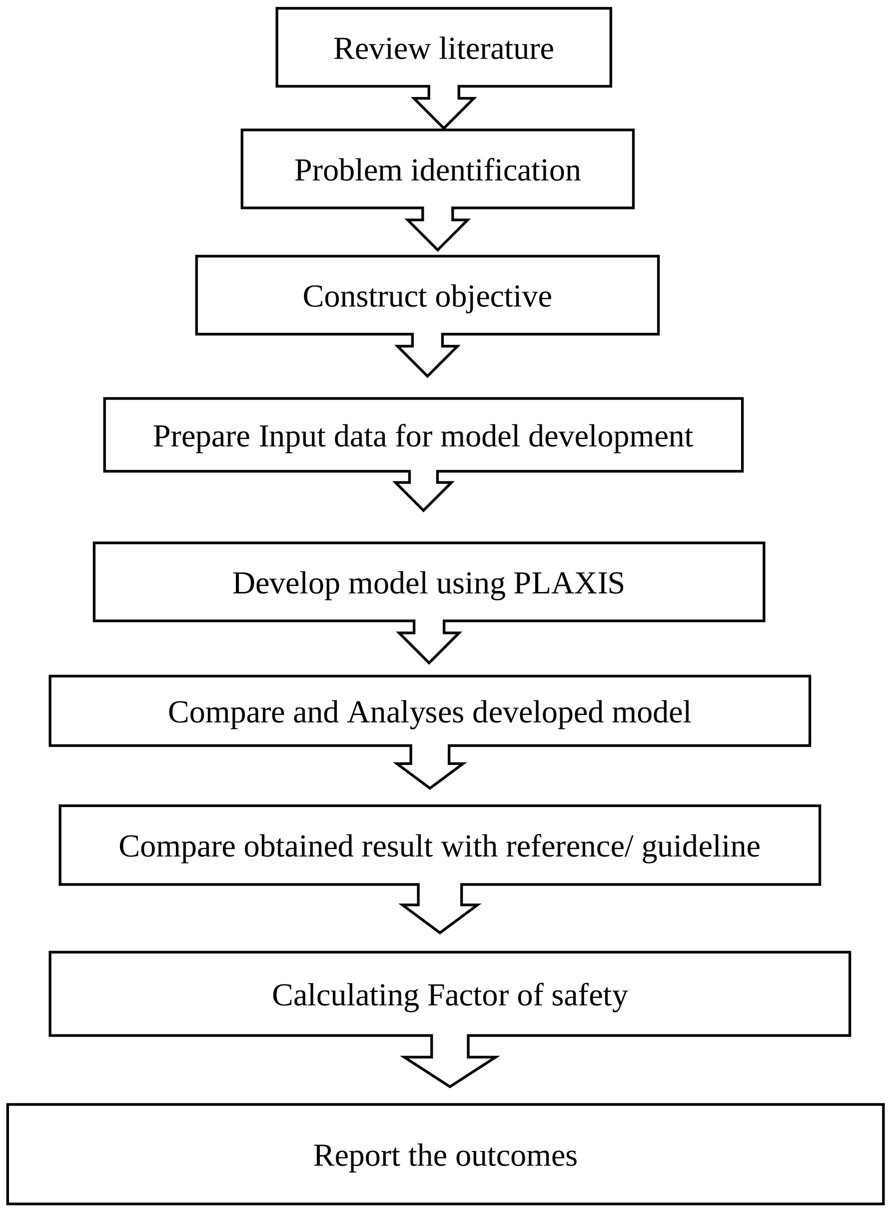

Figure 3.2: Sequence of research

3.3. Finite element analysis using PLAXIS 3D

A comprehensive series parametric studies via numerical analysis was conducted to examine the effect of nail spacing, diameter, inclination and nail length on the development of soil stability improvement of soil nail. For the numerical performance, the three-dimensional PLAXIS was used for this study, the Moher coulomb model was used to model the soil, and the nail was performed considering the elastic plastic model.

The elastic-plastic model encompasses various parameters, namely the Young's modulus, Poisson's ratio, and the shear strength parameters, which include cohesion and the angle of internal friction. The predominant clay soil classification and the drained soil condition were employed to facilitate the finite element analysis simulation.

The investigation performed a total of 22 analyses concerning various parameters such as wall nail diameter, nail length, nail inclination, and nail spacing. The vertical extent of the soil beneath and the horizontal dimension of the soil from the excavation depth must be sufficiently adequate to prevent any influence on the lateral displacement of the soil. The parameters of depth, length, and width are described through the application of sensitivity analysis. A soil depth of 9 meters was established, comprising a 3-meter floor layer and a 6-meter height of soil layer, with the frontal section of the wall constructed at a slope of 45 degrees; additionally, the dimensions of width and length were designated as 10 meters and 20 meters, respectively, for the modeling construction.

3.3.1. Secondary Data Collection for Basic parameters

Data was collected to get the soil stiffness, nail, and grout characteristics from a variety of sources, including research, correlations, and institutions which needed for the numerical analysis. Data was collected from Adama-Awash project provided by institutions. The data was varied depending on the soil type. Most borrow is major clay soil. The average values for CBR, PI, MDD, and OMC were computed through established correlations to derive the subsequent parameters: Young's modulus, Poisson's ratio, internal friction angle, cohesiveness, dilatancy angle, and unit weight for both saturated and unsaturated conditions; refer to Appendix A, with each model parameter shown in Table 4.1.

3.3.2. Output model (Mesh configuration)

Based on the established fixed parameters utilized and the various values considered within the parametric analysis, the deformed configuration of the soil nails was discerned in the resultant model. Following the creation of the model in PLAXIS, in order to implement the finite element method, the geometry was subdivided into smaller components, a process referred to as mesh generation; the resultant smaller meshes are interconnected by nodes. Ultimately, the mesh generation for all analyses was successfully finalized.

3.3.3. Calculation of FOS

FOS represents a metric employed to evaluate the stability condition of soil nailing systems. In the numerical modeling of soil nail installations on an inclined surface utilizing a finite element methodology, the safety factor for the simulations was derived through the application of the strength reduction technique, specifically the phi-reduction method implemented in PLAXIS 3D, which systematically diminishes the soil shear strength parameters through iterative processes until the soil mass fails.

$$\sum Msf = \frac{Cinput}{Creduced} = \frac{tan\varphi\ input}{\tan\varphi\ reduced} \quad \text{Eq 3.1}$$

(Mosser, 2016; PLAXIS 3D-Reference Manual, 2022).

where C-reduce and φ-reduce are the reduced value of cohesion and friction angle at failure (kPa), whereas C-input and φ-input are the input value of cohesion and the angle of internal friction of the soil-nail interface.

3.4. Data Analysis

The gathered data was arranged, and the PLAXIS software results were examined as a safety factor in order to ascertain the impact of the parameter on soil nail. Ultimately, a table and graphs displaying the achieved result were shown.

3.5. Validation of Numerical Model

To validate the findings of this study, the outcomes of numerical simulations were compared with estimates from established engineering approaches, including FHWA guidelines, and recommendations for optimizing the design and construction of soil-nailed buildings.

CHAPTER FOUR
NUMERICAL MODELING

4.1. Introduction

Finite Element Analysis is a numerical method used to solve engineering and mathematical physics issues. The resultant solution is articulated in a piecewise manner through the utilization of specified basis functions within the context of FEM discretization. In the framework of FEM, a solution is approximated through the integration of interrelated sub-regions or elements, as opposed to relying on a grid composed of hexahedral cells or discrete nodes. Generally, these elements are represented as fundamental geometrical shapes (Safuan et al., 2013).

When employing the Finite Element Method to assess slope stability, two principal methodologies are identified. The initial approach involves increasing the gravitational loading on the soil element, whereas the alternative method involves diminishing the strength properties of the soil mass, commonly designated as the Shear Strength Reduction (SSR) technique. The SSR technique was used in this work with the help of PLAXIS 3D, a robust FEM-based software. The slope materials were believed to have elasto-plastic behavior in the SSR approach. The SSR is based on the gradual lowering of soil strength parameters until slope failure occurs (Mahmud Sazzad et al., 2015). The processes for modeling and analyzing slopes in FEM (PLAXIS 3D) are given in this section.

4.2 Formulation of Finite Element Method

The process of partitioning a continuum into discrete segments or elements for the purpose of clarifying the functions of individual components, and subsequently combining them to describe the overall behavior of the continuum, is referred to as finite element modeling. In the context of deformation analysis, each element comprises a set of nodes, and each node possesses several degrees of freedom that correspond to various displacement components (Mekonnen, n.d.)

The initial stage in the FEM involves the description of the problem domain, which includes the characterization of the geometric model, the material model, and the boundary conditions Subsequently, the domain is subject to discretization into a series of continuum elements, thereby facilitating the formation of a mesh that interlinks nodes for the transmission of forces and displacements. The software Plaxis 3D was employed to execute the discretization of soil profiles utilizing triangular planar elements. The stiffness matrices of the elements are formulated once the problem domain has been clearly defined and discretized into FE.

$$[K]\{d\} = \{f\} \qquad 4.1$$

$$K = \int B^T D^e B dV \qquad 4.2$$

Where K represents the stiffness, matrix associated with an element, d denotes a vector comprising an unknown degree of freedom, and f signifies the resultant vector of nodal forces pertinent to the element. The stiffness matrix of an elastic element can also be characterized as a function of the strain interpolation matrix (B) and the elastic material matrix (D^e).

4.3. Modeling with PLAXIS 3D

4.3.1. Geometric modeling

Before generating a finite element mesh, the full geometry model was completed. This signifies that the geometry model's boundary conditions and model parameters were entered and applied first (Plaxis-3D - Version 8, 2013). Because there is a uniform cross section and corresponding stress state and loading scheme over a specified length perpendicular to the cross section (z-direction), a plain strain model was utilized for the analysis. In the z-direction, displacements and strain are assumed to be zero. Normal strains in the z-direction, on the other hand, are fully considered (Plaxis 3D v8, 2013).

The study paper conducted by developing 22 total model. About 21 model analyses the various nailing length, nail inclination, nail diameter and nail spacing, and the remain one model was developed without any nailing. In each model, a soil depth of 9m was established, comprising a 3m floor layer and a 6m height of soil layer, with the frontal section of the wall constructed at a slope of 45 degrees; additionally, the dimensions of width and length were designated as 10m and 20m, respectively, for the modeling construction. The geometric model structure of a layered soil and the location of the retaining wall is shown in Figure 4.1.

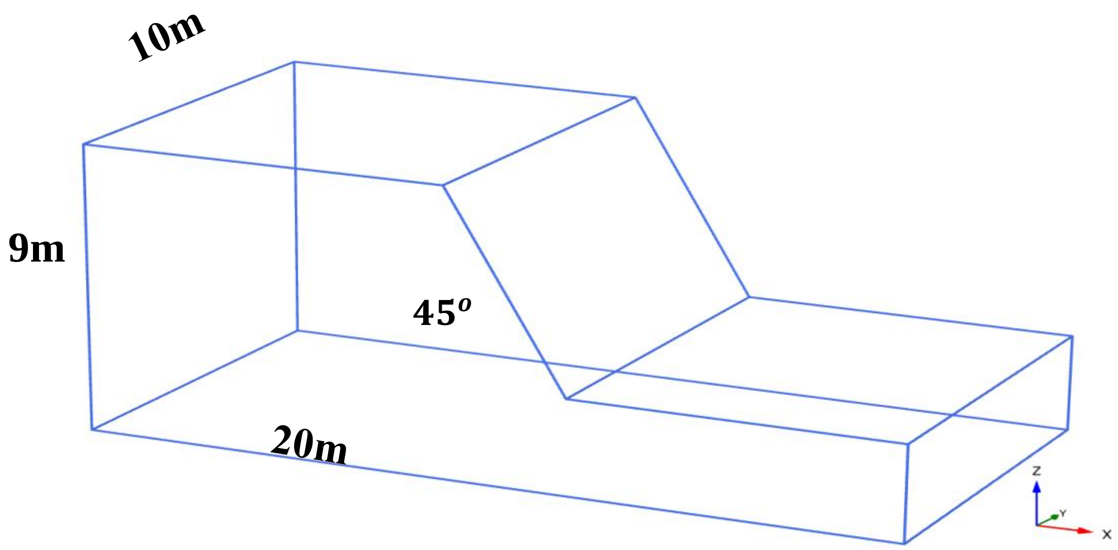

Figure 4.1: Geometric model

4.3.2. Material modeling

The influence of various nailing parameters, including spacing, lengths, diameter, and inclination on the behavior of the soil nail inclined face, was rigorously examined. The Mohr-Coulomb soil model served as the foundational framework for this investigation. Within this research, two distinct data types were employed for model development, each of which delineates a summary of the characteristics attributed to the models. The first data type comprises fixed parameters that remain constant throughout this study across all models, with the input data for this category derived from secondary sources, as illustrated in Appendix A. Conversely, the second data type encompasses varying values considered in the parametric analysis, where the input data for these parameters was informed by the FHWA manual and relevant literature; the values were altered to assess the impact of these parameters.

For the purpose of predicting the influence of nailing parameters, five distinct models were constructed for each parameter under investigation. The fundamental characteristics of soil nails, encompassing the soil model, Elasticity Modulus of nails, Cohesion, Friction angle, and Geometrical properties, remained consistent across all scenarios (Shahir and Delfan, 2021). In accordance with the specifications set forth by the FHWA, the diameter of the drilled borehole is stipulated to fall within the range of 100mm to 200mm, and in this study, a diameter of 150 mm was employed. Given the relatively small diameter of the nail bar, Elastic modules were assumed to be 22 MPa. The subsequent table 4.1 delineates the values of the soil parameters utilized in this analysis.

Table 4.1: Input data for Model properties in PLAXIS

Types of data	Model properties	Unit	Value
Fixed parameters for all models	Height nailed wall	m	6
	Soil nail pattern	-	Square
	Soil nailing model	-	Elastic plastic
	Soil model	-	Mohr coulomb
	Elasticity Modulus of nails	GPa	200
	Elasticity Modules of grout	GPa	22
	Grout diameter for nails	mm	150
	Poison’s Ratio	-	0.375
	Cohesion of soil	KPa	18.5
	Frictional angle	(°)	24.96
	Dilatancy angle	(°)	0
	Young Modules of soil	MPa	8.6
	Soil density	KN/m^3	15.6

	Saturated unit weight	KN/m^2	18.89
	Unsaturated unit weight	KN/m^2	18.83
	coefficient of horizontal soil stress	-	0.59

The value recommended by FHWA for length, space, diameter and inclination was used as standard for model and each value was changed to compare effect of each parameter on soil nailing. For example, as (FHWA, 2015) illustrated that, Soil nails are installed at 10° to 20° of nail inclination from the horizontal, and most commonly at 15°. To evaluated the effect of inclination on soil nailing, five model was developed in this study at different soil nailing inclination value. One model was enveloped at value of 15° as standard inclination for nailing. The remain four model was developed at inclination value of 5°, 10°, 20° and 25°, the effect of this changed value was compared with standard model and the result was analyses further. In the same ways, the value of length, space, and diameter was changed based on FHWA reference. The input data of inclination, spacing, diameter and length for this study are summarized on the following Tables.

Table 4.2: Nailing parameters with different Nail length and the same other parameters (standard)

Independent variable	Inclination (^{o})	15				
	Space (m)	1.5				
	Diameter (mm)	16				
Dependent variable/parameter	Length (m)	1.5	2.5	3.5	5.25	7

Table 4.3**:** Nailing parameters with different Nail Inclination and the same other parameters (standard)

Independent variable	Length (m)	3.5				
	Space (m)	1.5				
	Diameter (mm)	16				
Dependent variable/parameter	Inclination (^{o})	5	10	15	20	25

Table 4.4: Nailing parameters with different Nail Diameters and the same other parameters (standard)

Independent variable	Length (m)	3.5
	Inclination	15

	Space (m)	1.5				
Dependent variable/parameter	Diameter (mm)	10	14	16	20	22

Table 4.5: Nailing parameters with different Nail Spacing (SH = SV) and the same other parameters (standard)

Independent variable	Length (m)	3.5				
	Inclination (^{o})	15				
	Diameter (mm)	16				
Dependent variable/parameter	Space (m)	1	1.25	1.5	1.75	2

4.3.3. Boundary Condition

Boundary conditions can influence the simulation results. Therefore, the boundary conditions used for this study are similar three-dimensional models, as shown in Figures 4.2. Completely fixed boundaries were used for all three side back, side and bottom. There were restraints ("Free") on the top, front and sloped Face of the models.

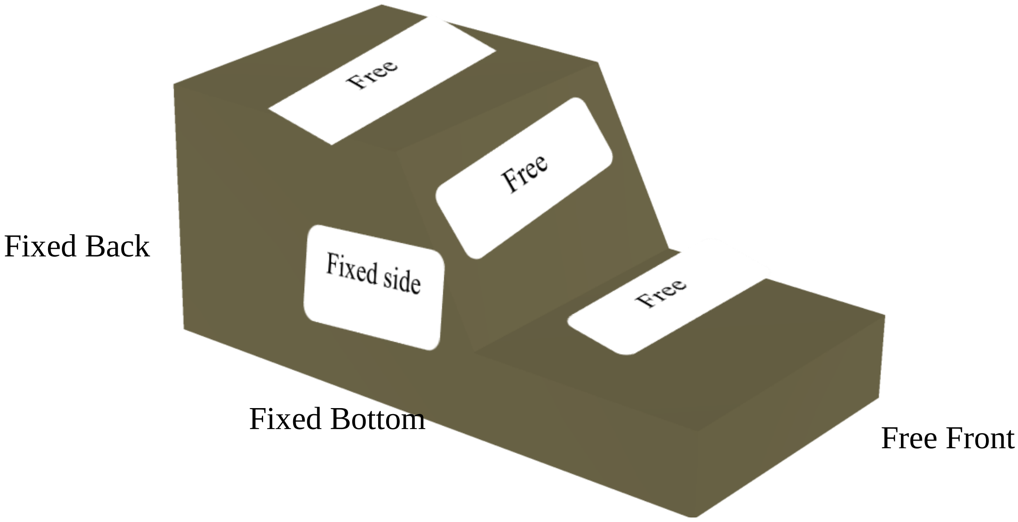

Figure 4.2: Boundary condition of model

4.3.4. Model before Nailing

Model of inclined face was developed before nailing. This model was developed from soil parameter without any nail. The purpose of this model was to analyses the soil parameter on factor of safety and to compare with a model that was developed with nailing. Figure 4.3 shows modeling without nailing.

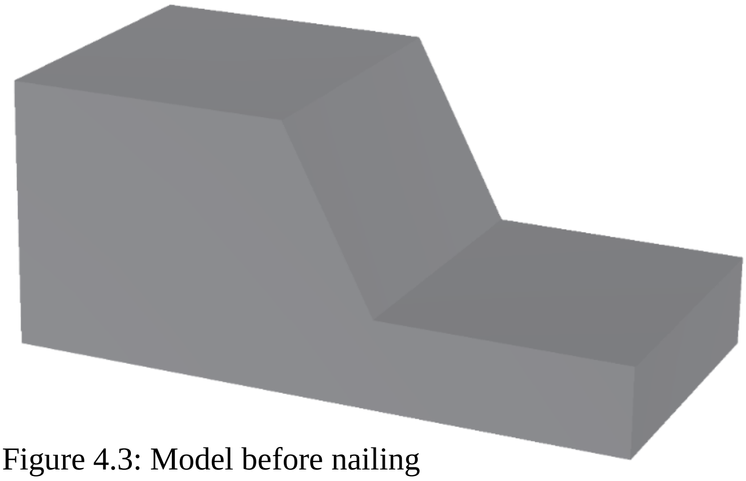

Figure 4.3: Model before nailing

4.3.5. Model after nailing (Nail Constructions)

In this section, two distinct types of models were formulated. The initial type was the model constructed utilizing the parameters suggested by the FWHA, which is regarded as the standard model. The subsequent type of model was developed with various parameters, either increasing or decreasing from the standards, to assess the impact of these parameters. The following sub section shows each model.

4.3.6. Standard model

The standard model was developed as explained on methodology. For instance, figure 4.4 was shows the model developed to test the effect of length at 3.5m, 15^0 of nail inclination, 16mm of nail diameter and 1.5m of nailing space (either horizontal or vertical) and this model was developed with 28 nails.

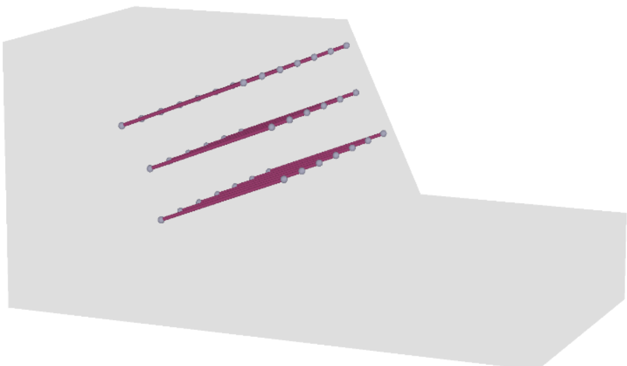

Figure 4.4: Model of Standard parameters (3.5m length,15^0 of Inclination,16mm diameter and 1.5m spacing) with nail

4.3.7. Model with nail of different parameters

The model developed in this study was developed from nail of different parameters. Due to variation of nail parameters, the geometer of developed model was filled with different number of nailing. As the length of nail increases, it was passed to out of inclined soil face. For instance, figure 4.7 was shows the model developed to test the effect of length at 1.5m, 5^0 of nail inclination, 10mm of nail diameter and 1.25m of nailing space. This model requires 40 nails, this because the amount of space between two nail and the degree (inclination) of nailing was forms more space for nailing, because of this the number of nailing increased. The model developed from 7m, 5.25m, 3.5m,2.5m and 1.5m of nail length are shown in below section respectively. The remain models was developed and analyzed in the same way.

Figure 4.5: Model with 7m nail length,1.5m spacing, 15° Inclination and 16mm diameter

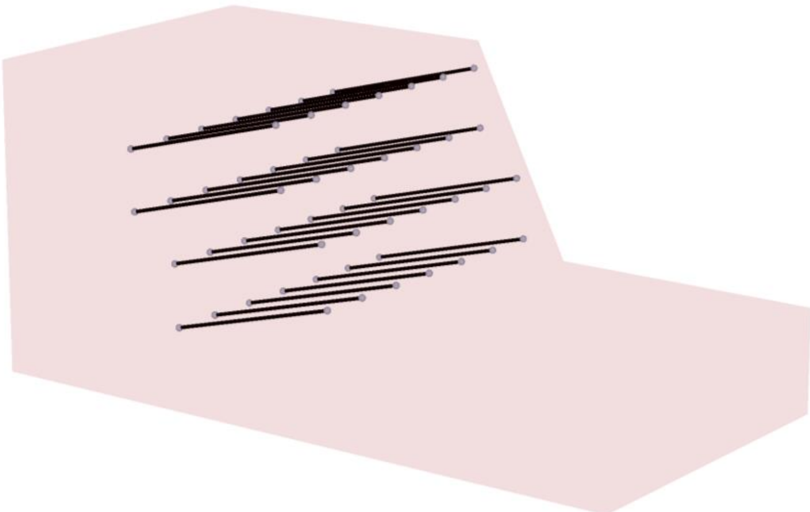

Figure 4.6: Model with 5.25m nail length,1.5m spacing, 15° Inclination and 16mm diameter

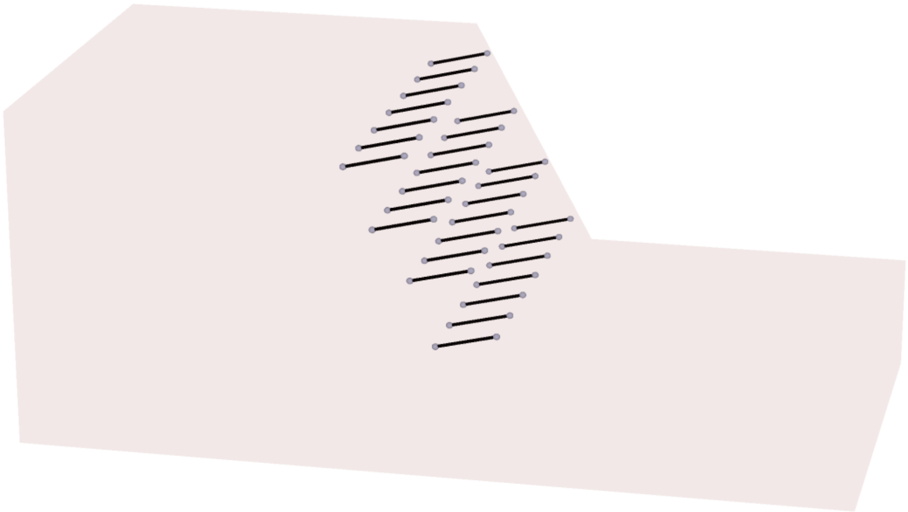

Figure 4.7: Model with 1.5m nail length,1.5m spacing, 15° Inclination and 16mm diameter

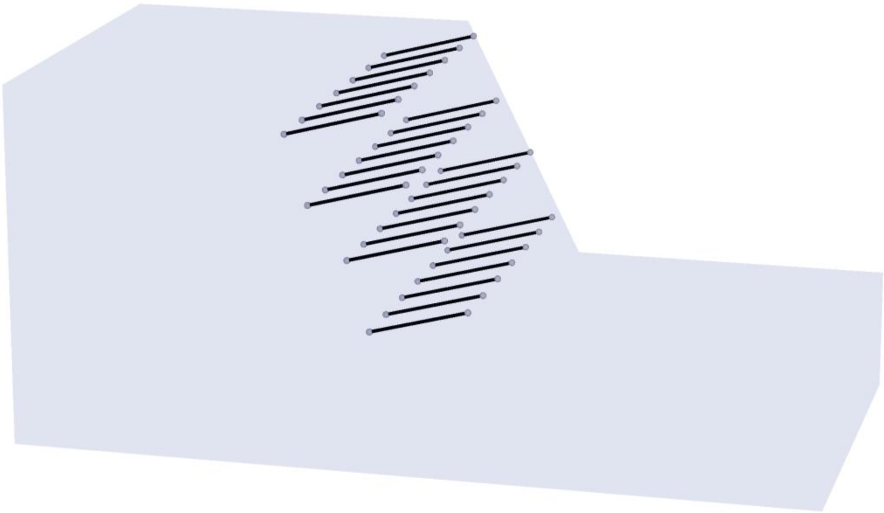

Figure 4.8: Model with 2.5m of nail length,1.5m spacing, 15° Inclination and 16mm diameter

The summery of studied model that are developed with different parameter and with different number of nailing was shown on the following Tables.

Table 4.6: number of nails with different nail length and the same other nailing parameters

<table>
<tr><td rowspan="3">Independent variable</td><td>Inclination</td><td colspan="5">15</td></tr>
<tr><td>Space</td><td colspan="5">1.5</td></tr>
<tr><td>Diameter</td><td colspan="5">16</td></tr>
<tr><td>Dependent variable/parameter</td><td>Length</td><td>1.5</td><td>2.5</td><td>3.5</td><td>5.25</td><td>7</td></tr>
<tr><td colspan="2">NO of nail</td><td>28</td><td>28</td><td>28</td><td>28</td><td>21</td></tr>
</table>

Table 4.7: number of nails needed for models with different nail inclination and the same other nailing parameters

Independent variable	Length	3.5				
	Space	1.5				
	Diameter	16				
Dependent variable/parameter	Inclination	5	10	15	20	25
NO of nail		28	28	28	28	28

Table 4.8: number of nails needed for models with different diameter of nail and the same other nailing parameters

Independent variable	Length	3.5				
	Inclination	15				
	Space	1.5				
Dependent variable/parameter	Diameter(mm)	10	14	16	20	22
NO of nail		28	28	28	28	28

Table 4.9: number of nails needed for models with different nail spacing and the same other nailing parameters

Independent variable	Length	3.5				
	Inclination	15				
	Diameter	16				
Dependent variable/parameter	Space	1	1.25	1.5	1.75	2
NO of nail		60	40	28	24	15

4.4 Mesh Generation

The concluding phase in the assessment of the behavior of soil-nailed inclined faces necessitated the rigorous examination of the results obtained from the analysis performed in PLAXIS, which was executed through the implementation of the output models. In this study, a 15-node triangular element was utilized for the purpose of modeling, thereby enabling the precise forecasting of failure loads and safety factors. Ultimately, the creation of the mesh for all 22 model analyses was successfully accomplished. A representative mesh for a nail length of 3.5m, a nail inclination of 15°, a nail diameter of 16mm, and a nail spacing of 1.25m is illustrated in Figure 4.9.

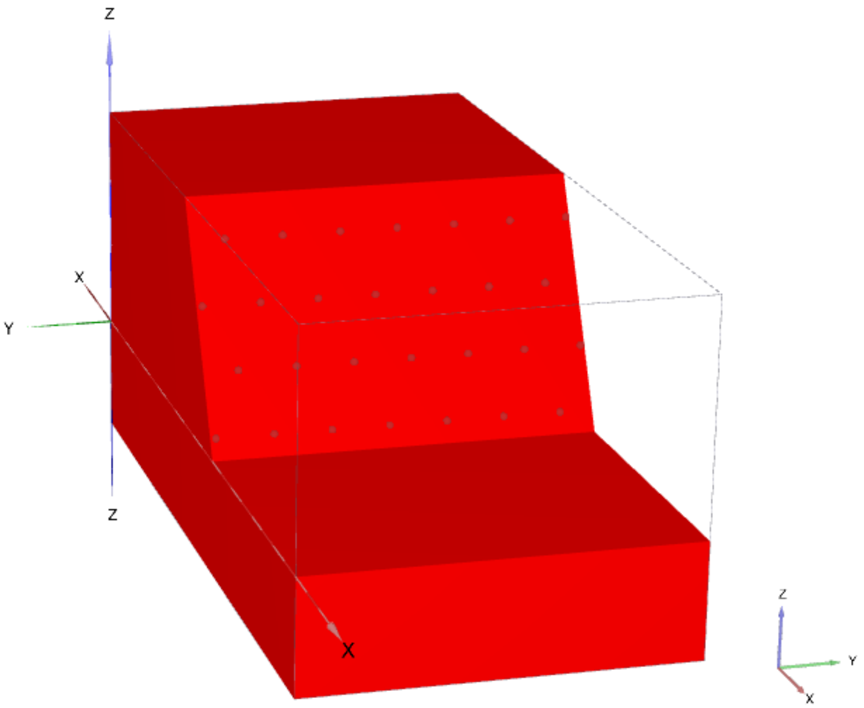

Figure 4.9: Mesh of developed model

4.5. Output

The next Figures 4.10 show one of deformed mesh and extreme horizontal displacement mesh at the end of calculation phases for 6m wall height with 15° nail inclination and 1.25 nail spacing.

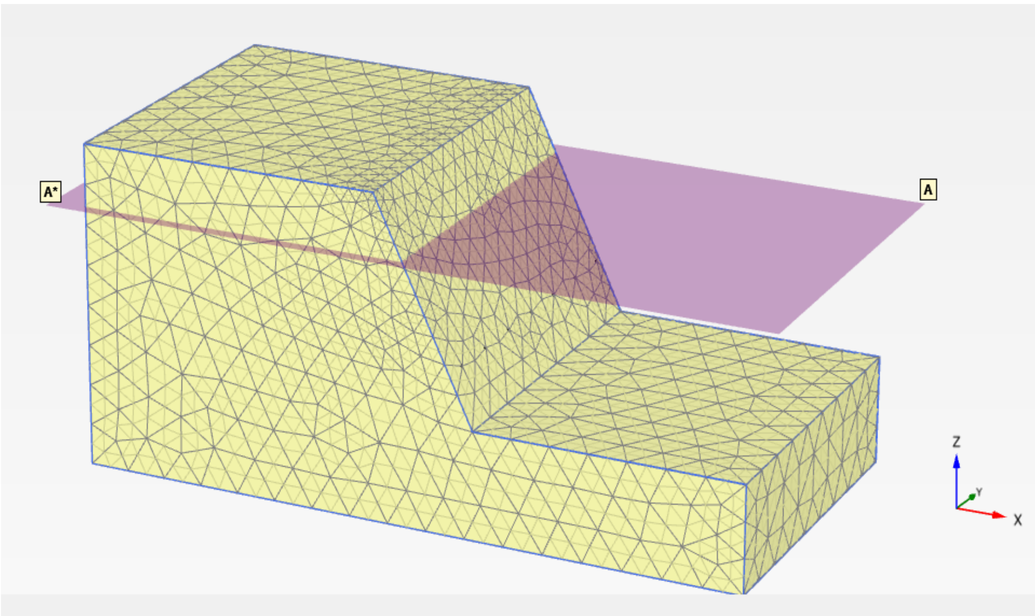

Figure 4.10: Extreme horizontal displacement mesh

CHAPTER FIVE

RESULT AND DISCUSSION

5.1. Introduction

The efficacy of the nailed slope has undergone rigorous numerical examination to elucidate the diverse parameters associated with the nails and the interactions occurring between the soil and the nails under conditions of static loading. This section provides an analytical overview and deliberation concerning a thorough synthesis of the findings obtained from the parametric investigations executed in all prior sections as well as in the dedicated study chapter. Utilizing the PLAXIS 3D software, the results of the stability analysis concerning soil-nailed slopes have been simulated, with a particular focus on the effects of nail length, nail inclination, nail diameter, and nail spacing on the performance of the soil-nailed slopes.

In the present study, a comprehensive total of 22 unique models were meticulously constructed utilizing PLAXIS 3D software to evaluate the implications of the specified parameters. Among these models, one was designed without the incorporation of a nail, whereas an additional model was created with a nail in accordance with the prescribed parameter values. The remaining 20 models were developed based on varying configurations of the nail parameters. The FOS for each model was systematically calculated through the phi-c reduction technique within the PLAXIS 3D software. The software utilizes the subsequent formula to ascertain the factor of safety.

$$\sum \mathrm{Msf} = \frac{\mathrm{Cinput}}{\mathrm{Creduced}} = \frac{\tan\varphi \text{ input}}{\tan \varphi \text{ reduced}}$$ (PLAXIS 3D-Reference Manual, 2022)

The results of numerical simulation results are compared with estimates from widely used engineering methods such as FHWA.

5.2. Model before nailing

As delineated in chapter 3, the primary objective of this model was to analyze the soil parameters affecting the factor of safety and to draw comparisons with a model that was formulated utilizing soil nailing techniques. The investigation revealed that the slope devoid of soil nailing exhibited a factor of safety of 0.97, which is considerably below the recommended threshold. This finding suggests that the slope, in its current condition, is characterized by instability and is incapable of safely accommodating anticipated loads. Consequently, the implementation of soil nailing is imperative to guarantee both the stability and safety of the structure.

5.3. Standard model

The standard model that was developed to evaluate the influence of length at 3.5m, an inclination of 15° for the nails, a diameter of 16mm for the nails, and a spacing of 1.5m for nailing. This model mandates the incorporation of 28 nails, and the FOS pertinent to this investigation was computed. The derived FOS for the established standard model was determined to be 1.694; this figure denotes that the implemented project employing this specific nailing technique would be deemed secure, as a minimum FOS of 1.5 can be regarded as a foundational reference for the design of optimal and secure soil nailing on the surface (Shahir and Delfan, 2021). Consequently, the FOS linked to this model implies that the structural framework or system is stable and proficient in withstanding the expected loads and forces.

5.4. Effect of studied parameter on nailing

Upon the establishment of an appropriate model, an investigation was conducted into the impacts of length, spacing, inclination, and diameter of fully characterized slopes. In order to evaluate the influence of these parameters on soil nailing, a total of 21 distinct models were formulated to ascertain the effects of length, spacing, inclination, and diameter, each varying in their respective values, and the implications of each model were systematically analyzed in terms of FOS.

All model is developed and analyzed in the same way and the analyzed result of each studied model are summarized on figure (graph) that was shows the calculated value of FOS. The graph was used to clarify easily the effect of all studied parameter on soil nail. The summery of effect of studied parameter on soil nail are explained on the following section separately.

5.4.1. Effect of length on soil nailing.

Figure 5.1 is showing the model was constructed utilizing a consistent spatial shape of 1.5m, a 15° inclination, and a 16mm nail diameter, while with varying nail lengths. The model derived from a nail length of 1.5m yielded a total of 28 nails and a FOS measuring 1.435; conversely, the model established with a 2.5m nail length similarly resulted in 28 nails but achieved a higher FOS at 1.567. The remaining models with differing length parameters were subjected to analogous analyses, and a summary of each model's findings is presented in Figure 4.5.

Generally, an increase in the length of the soil nails resulted in a corresponding decrease in the quantity of nails employed. The research indicated that an augmentation in the length of soil nails typically enhanced the FOS.

Nevertheless, after reaching a specific threshold, approximately 3.5m, the rate of improvement began to decline. This implies that extending the nails significantly beyond 3.5m may not yield substantial enhancements in stability and could potentially be less economically viable. Consequently, for the purposes of achieving optimal safety and operational efficiency, it is recommended to evaluate the utilization of a nail length of around 3.5m or shorter.

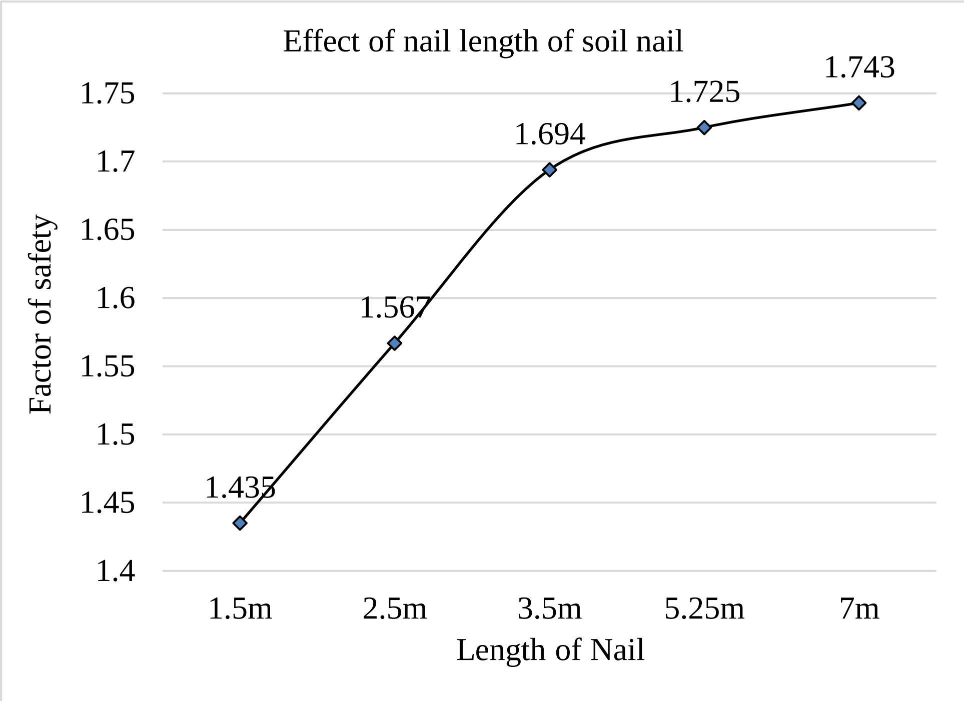

Figure 5.1: Effect of Nail length on the Factors of safety

FHWA was illustrated that the soil nail length can be estimated to be approximately 0.7H, where H is the wall height. This study was examined to test which nail length value was full filled the above statement. It was tasted as 0.7 x 6m = 4.2m, so the nail length which records good factor of safety is approximately the closer value of recommended value by (FHWA)2015.

The Federal Highway Administration demonstrated that the length of soil nails can be estimated to be roughly 0.7 times the height of the wall (H). This investigation was conducted to evaluate which specific nail length corresponds to the above-mentioned statement. It was calculated as 0.7 multiplied by 6 meters, resulting in 4.2 meters; therefore, the nail length that achieves an optimal factor of safety approximates the value recommended by the (FHWA) (2015

In the same report, nail lengths greater than about 1.2H (7.2m according to this study) may suggest that ground conditions are not favorable for soil nail inclined face.

As well as the nail lengths less than 0.5H (3m according to this study) not likely satisfy sliding stability requirements, and nail lengths less than approximately 0.6H (3.6m according to this study) are rare (FHWA, 2015). Depending on the FHWA and analyzed result, the current study revealed that the soil nail constructed with nail length of 3.5m is favorable and economical for soil nail inclined face.

The analysis elucidates a direct association between the length of nails and the factor of safety. Extended nail lengths significantly enhance the overall stability of the slope, as they afford increased resistance to potential modes of failure. Nevertheless, an excessive extension of nail length may also incur elevated construction expenses and may not be requisite in all circumstances, especially for slopes characterized by relatively shallow depths. Ultimately, the length of the nails is integral to the transfer of load from the soil mass to the reinforcement components. As the length of the nails increases, the zone of load distribution expands, thereby facilitating a more efficacious load transfer mechanism.

5.4.2. Effect of inclination on soil nailing.

The numerical model suggests that an augmentation in the inclination angle generally improves the safety factor. This occurrence transpires because inclined nails proficiently disseminate the load over a more extensive surface area, thus alleviating the localized stress concentrations at specific sites. Nevertheless, it is imperative to recognize that excessively high inclination angles may pose practical difficulties and could induce complications throughout the installation procedure.

The reinforcing efficacy of soil nails can be significantly influenced by their angle of inclination. Figure 5.2 presents the examined model, which was constructed with uniform dimensions of 1.5m in width, a length of 3.5m, and a diameter of 16mm, albeit with varying angles of inclination. The angle of these structural components possesses the capacity to affect not only their individual stability but also the overall stability of the surrounding soil matrix (Alsubal et al., 2017). The model developed using a 5^0-inclination resulted in a total of 28 nails and a safety factor of 1.143, while the model predicated on a 10^0 inclination produced the same number of nails but achieved a higher safety factor of 1.459.59.

The remain model of different inclination parameter was also analyzed in the same ways and the Appendix B was shows the summery of model generated from the same parameters but with differing inclinations.

When the nail inclined it, cover free space in bottom and upper, due to this, the number of nailing was decreased. As the inclination of nail was increased from 5^0 to 15^0, the factor of safety also increases; however, as inclination increase above standard (15^0) value the factor of safety decrease. the rising of inclination would make the reinforcing force in the nails decrease and reduce the stabilizing effect, and the soil nails at large inclinations do not provide any appreciable stabilizing effect (Pham *et al*., 2020).

Soil nails wall are installed at 10^0 to 20^0 degrees from the horizontal, and most commonly at 15^0, and the Nails should not be installed above utilities because future excavations for maintenance likely disturb the wall stability (FHWA, 2015). This study was also showing that, nail inclination at 15^0 was safe for soil nail construction.

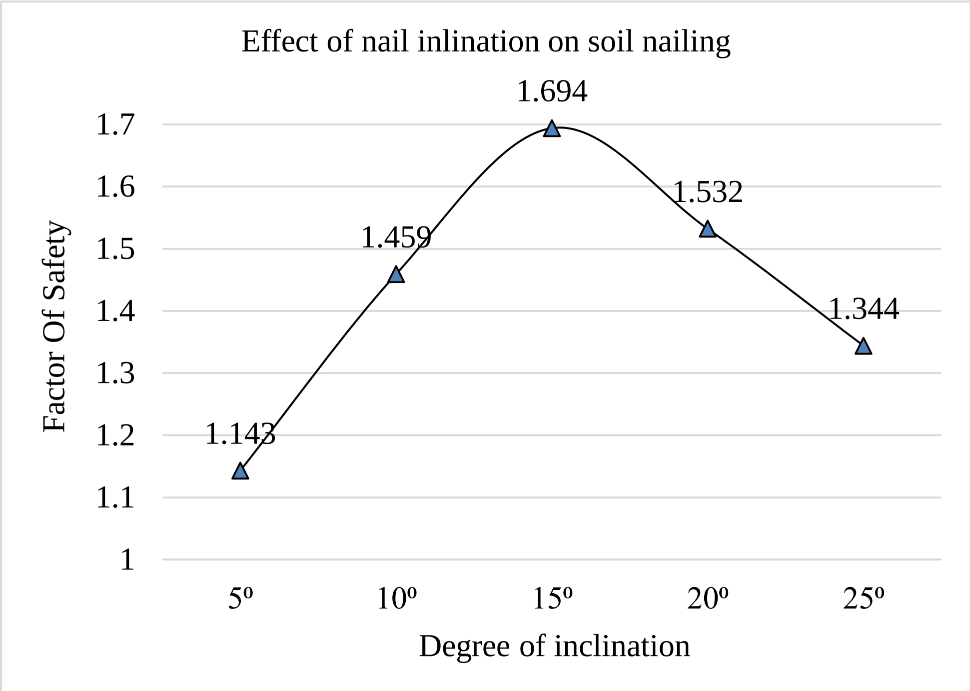

Figure 5.2: Effect of Inclination of nail on the Factors of safety

5.4.3. Effect of diameter on soil nailing.

Diameter signifies the extent or thickness of a structure or element within a soil system; the augmentation of the factor of safety with increased nail diameters highlights the significance of nail diameter in enhancing the stability of soil slopes. An increased nail diameter further contributes to stability by augmenting the shear strength and load-bearing capacity of the nailing apparatus. Nevertheless, excessively large diameters may result in escalated construction expenses and potential challenges during the installation process.

Figure 5.5 illustrates the analysis of a model created using identical parameters of 1.5m spacing, 3.5m nail length, and 15° of inclination, though with varying diameter values. The model derived from a nail diameter of 10mm yielded a factor of safety of 1.454, while the model established from a 14mm nail diameter resulted in a factor of safety of 1.472.

The study revealed that although increasing the diameter of soil nails typically led to an improvement in the factor of safety, the requisite number of nails diminished. However, the rate of improvement in stability began to decrease when the diameter exceeded 16 millimeters. This indicates that employing nails with a diameter exceeding 16 millimeters may not substantially enhance safety and could potentially be less economically viable Consequently, for the purpose of maximizing safety and operational efficiency, it is advisable to consider a nail diameter of around 16 millimeters or less.

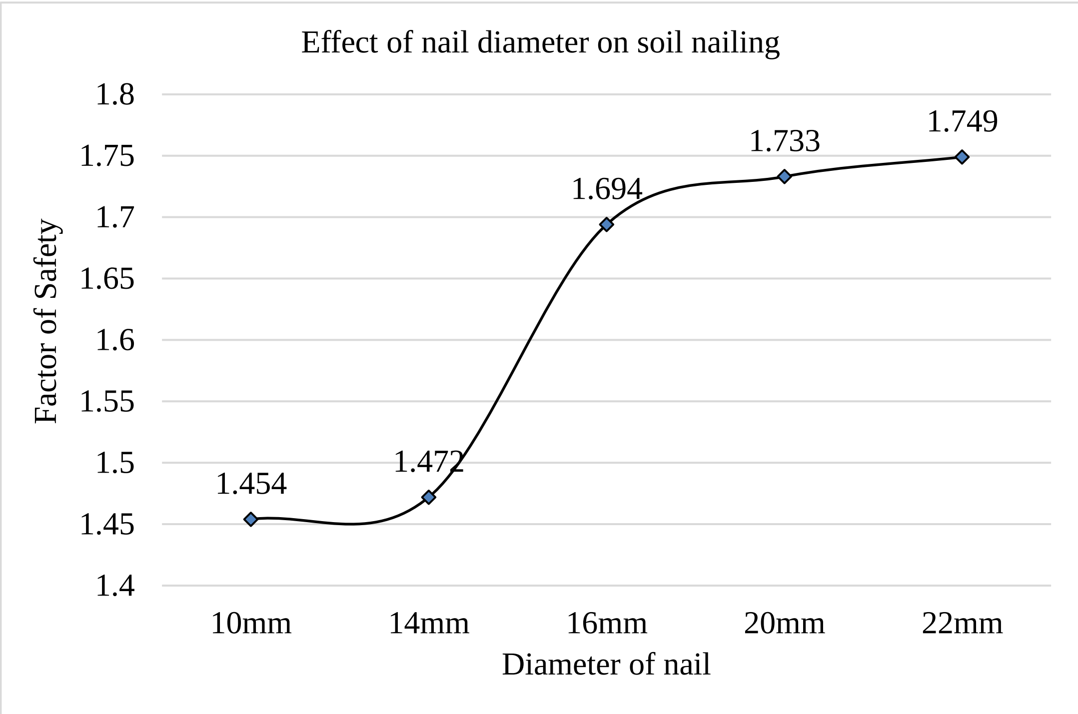

Figure 5.3: Effect of Nail diameter on the Factors of safety

This investigation primarily concluded that soil nails fabricated with diameters of 16mm or greater exhibit superior quality, whereas those constructed from diameters measuring less than 16mm necessitate careful consideration. Furthermore, it was reported that high-yield deformed steel bars with diameters of 25mm, 32mm, and 40mm are frequently utilized as reinforcement for soil nails; however, bars with smaller diameters should be employed with caution, particularly when dealing with elongated soil nails, as they are prone to excessive bending during the installation process (Group, 2008).

Diameter is an important parameter in the design of piles, drilled shafts, and other deep foundations. The diameter can affect their load-bearing capacity and their interaction with the surrounding soil. The diameter of the nails affects their strength and load-carrying capacity (Group, 2008).

Nails with a larger diameter possess the capacity to endure elevated tensile forces and offer enhanced resistance to bending. Nevertheless, an increase in diameter concurrently results in augmented construction expenses and may present difficulties during installation, particularly in adverse soil conditions.

Numerical analyses reveal a significant positive correlation between the diameter of the nail and the FOS; however, this influence may not be as substantial as that associated with nail length. In the context of most practical applications, augmenting nail diameter past a specific threshold is unlikely to yield considerable enhancements in slope stability (Group, 2008).

5.4.4. Effect of space on soil nailing.

In this study the space between two nails toward horizontal is identical to space of nail toward vertical (SH = SV reduced spacing is imperative for optimal reinforcement efficacy. An augmented spacing may result in inadequate coverage of potential failure surfaces, thereby diminishing the overall stability of the system. The models developed in this investigation elucidated that an increase in the space between two nails correlates with a decrease in the number of nails employed and a concomitant reduction in the factor of safety. The requisite number of nails for a spacing of 1m is 60, for 1.25m is 40, and similarly, the necessary numbers for spacings of 1.5m, 1.75m, and 2m are 28, 24, and 15, respectively. This finding indicates that as the inter-nail spacing expands, the quantity of nails necessary for a defined area decreases. Furthermore, this study also assesses that, as illustrated in Figure 5.4, an increase in the spacing between two nails results in a decrease in the factor of safety of the model. This finding suggests that the number of nails and the factor of safety are directly proportional, implying that an increase in the number of nails in soil nailing concurrently leads to an increase in the FOS of that soil nailing.

The investigation revealed that the reduction of the interval between two soil nails resulted in an enhancement of the safety factor. Specifically, when the spacing is 1.5m, the safety factor is calculated to be 1.694, whereas for spacings of 2m, 1.75m, 1.25m, and 1.0m, the corresponding safety factors are 1.477, 1.511, 1.782, and 1.801, respectively.

In general terms, the study elucidates that a decrease in the distance between nails typically leads to an improvement in the safety factor. Nonetheless, beyond a particular threshold, approximately 1.5m, the rate of increase in safety factor begins to decline. This indicates that a reduction in the spacing between nails to less than 1.5m may not yield a significant enhancement in stability and could potentially be less economical. Consequently, for the purposes of achieving optimal safety and operational efficiency, it is recommended to maintain a spacing between nails at 1.5m or less.

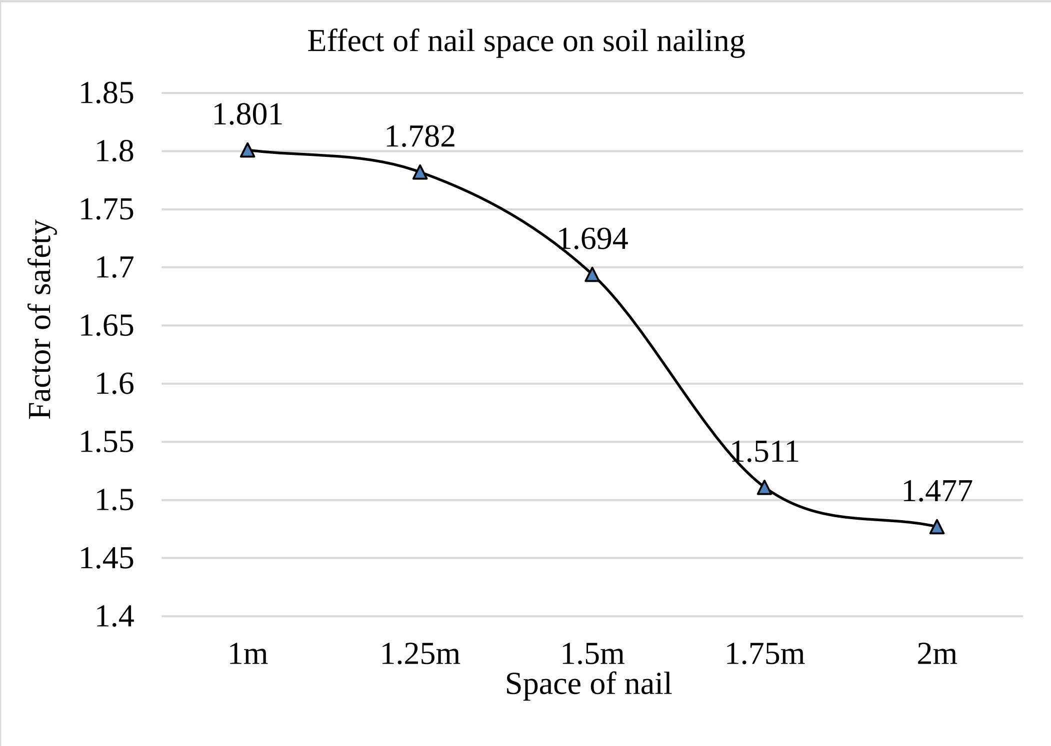

Figure 5.4: Effect of nailing space on the Factors of safety

In addition, as the inter-nail spacing diminished from 2m to 1m, the safety factor experienced an augmentation; however, the Federal Highway Administration indicated that a minimum soil nail spacing of approximately 1.06m should be established to mitigate the likelihood of inadvertently drilling into previously installed nails as a result of drilling inaccuracies. Furthermore, the close proximity of nails may lead to a phenomenon of stress overlap during load transfer, akin to the behavior observed in closely arranged piles (FHWA, 2015). The specific spacing of these structural elements is contingent upon the soil classification and the inclination of the facing. The arrangement of these structures can significantly influence their stability as well as the overall integrity of the soil system (Shahir and Delfan, 2021).

According to FHWA (2015), the horizontal nail spacing, denoted as SH, is frequently equivalent to the vertical nail spacing, denoted as SV; the nail spacing in both dimensions typically spans from 1.22 to 1.83m and may occasionally extend to 1.98m, with a common selection being 1.52m.

5.5. Model Validation

The impact of nail parameters on soil nailing was examined utilizing Plaxis-3D, and the findings of (Tang & Jiang, 2015) were employed for the validation of the present study in conjunction with other pertinent research regarding the influence of nail length on the stability of soil nails. Figure 5.5 illustrates a comparison of the effect of nail parameters on soil nailing through finite difference analysis alongside other referenced finite element analyses. The factor of safety exhibits an increase correlating with the augmentation of nail length, revealing a nearly identical pattern. (Tang & Jiang, 2015) indicated that as the value of Length escalates, the Factor of Safety concurrently rises. Variations in soil type and input parameters result in differing factors of safety; nevertheless, the software demonstrates a consistent pattern regarding the effects of length.

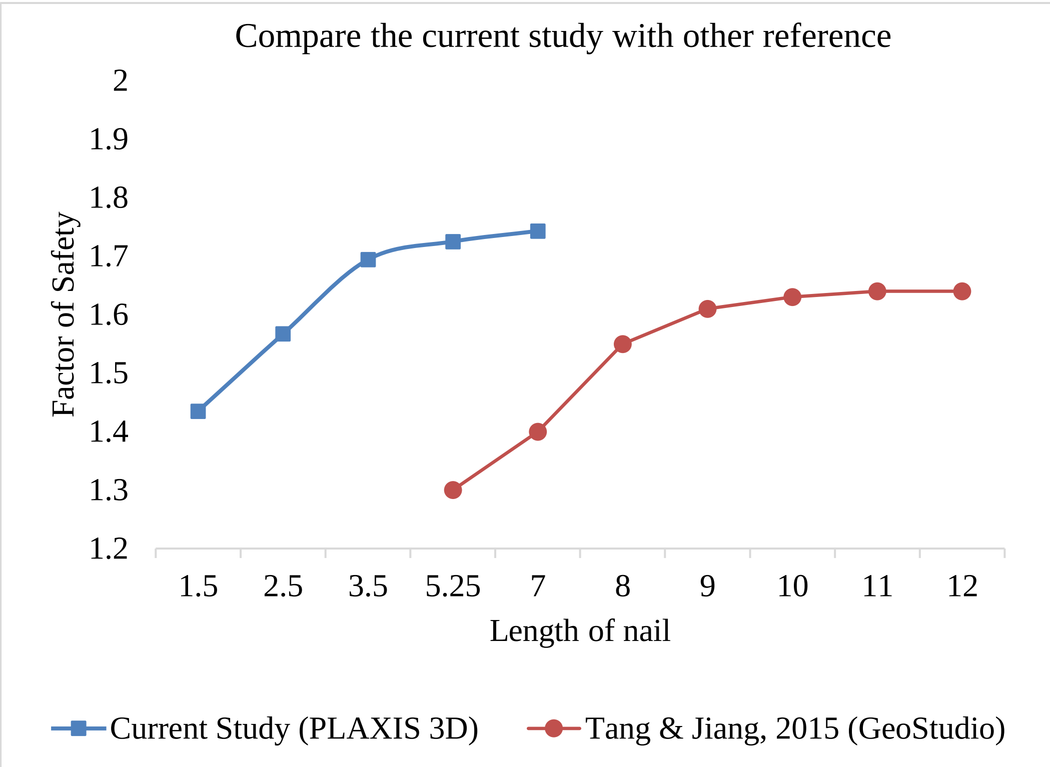

Figure 5.5**:** Effect of nail length on the soil nailing (Tang & Jiang, 2015)

CHAPTER SIX

CONCLUSION AND RECOMMANDATIONS

6.1. CONCULUSION

This study was carried out on Adama-Awash Express way for 25+300 cut-section of slope stability. The objective of the stability analysis was to determines a clear relationship between various parameters of soil nails specifically length, inclination, diameter, and spacing with the factor of safety. and Compare the factor of safety before nailing and after nailing. The soil parameters for the analysis were derived from secondary data gathered from Adama -awash project. Then, using the finite element approach, the stability was evaluated in drained state with static loading condition (PLAXIS 3D). All finite element analyses used the elastoplastic Mohr-Coulomb material model. The following conclusions are made:

- The positive correlation between nail length and the factor of safety suggests that increased nail lengths enhance the efficacy in counteracting failure mechanisms. AS the length of soil nails increases the factor of safety also increase This This phenomenon can be attributed in improving overall slope stability.

- The results demonstrate that nail inclination exerts a significant impact on the factor of safety, with an optimal angle of up to 15°. Beyond this edge, the factor of safety begins to decrease, suggesting that excessive inclination may lead to reduced effectiveness in resisting lateral forces.

- The increase in factor of safety with larger nail diameters underscores the role of nail diameter to improve soil slope stability. A larger nail diameter also enhances stability by increasing the shear strength and load-carrying capacity of the nailing system. However, excessive diameters can lead to higher construction costs and potential difficulties in installation.

- The negative relationship between nail spacing and the factor of safety suggests that a reduced spacing is essential for optimal reinforcement efficacy. Augmented spacing may result in inadequate coverage of the potential failure plane, thereby compromising the overall stability of the system. While closer spacing facilitates superior load distribution, it may also present economic inefficiencies.

These conclusions delineate the imperative for meticulous evaluation of nail design parameters within geotechnical contexts that involve soil nails. Through the optimization of these variables, practitioners in the engineering field can augment the safety and efficacy of soil nail systems across diverse construction and remediation endeavors. Consequently, the Factor of Safety (FOS) associated with this model signifies that the structure or system is deemed secure and capable of enduring anticipated loads and forces; thus, this particular type of construction is considered safe within the specified study area.

6.2. RECOMMANDATIONS

A comprehensive parametric investigation was undertaken to assess the impact of nailing parameters on the efficacy of a soil-nailed inclined face through numerical analysis conducted with PLAXIS software. In addition to the boundaries delineated by this thesis and the conclusions and findings derived from the diverse analyses executed as an integral component of the research endeavor, the subsequent points may be contemplated for prospective practice and research:

1. Investigation of the impact of environmental determinants, including weathering processes, variations in groundwater levels, and freeze-thaw cycles, on the enduring performance of soil nailing systems may facilitate the advancement of more resilient and sustainable engineering solutions.

SPECIAL ACKNOWLEDGEMENT

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R/28124/15

Adama, Ethiopia

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APPENDIX

Appendix A: Input data calculation

Table A.1: Secondary data taken from Adama Awash project from borrow area at 25+200-25+400 based on AASHTO classifications

Location	Pit no.	LL	PL	PI	MDD	OMC	CBR	Group Classification	Soil Classification	Bulk Density
A	P-1	31.3	20.5	10.8	1.791	18.4	8.8	A-6(4)	Clay soil	2.1
	P-2	32.9	24.4	8.5	1.643	23.4	9.5	A-4(5)	Silty soil	2.04
	P-3	44.7	29	15.7	1.497	24.8	9	A-6(4)	Clay soil	1.87
	P-4	42.2	28.1	14.1	1.481	24.9	6.8	A-7(6)	Clay soil	1.85
B	P-1	35.7	20.4	15.3	1.607	18.4	15.3	A-6(4)	Clay soil	1.9
	P-2	36.8	20.7	16.1	1.63	18.4	12	A-6(5)	Clay soil	1.93
	P-3	35.5	20.4	15.1	1.595	19.9	12	A-6(4)	Clay soil	1.91
C	P-1	33.1	24.2	8.9	1.507	20.7	11.5	A-6(4)	Clay soil	1.82
	P-2	28.6	18.9	9.7	1.641	17.5	17.5	A-6(5)	Clay soil	1.93
	P-3	35.6	22	13.6	1.58	21.7	12.5	A-6(11)	Clay soil	1.92
	P-4	34.5	23.3	11.2	1.595	21.6	18	A-6(5)	Clay soil	1.94
D	P-1	38.8	23.9	14.8	1.676	21.2	9.5	A-6(7)	Clay soil	2.03
	P-2	53.7	33	20.6	1.496	22	6.1	A-7(5)	Clay soil	1.83
	P-3	46.3	29.5	16.8	1.557	20.6	7.4	A-7(6)	Clay soil	1.88
Average		35.31	22.55	13.66	1.59	20.96	11.14			1.92

A.1. Saturated and Unsaturated Unit Weight Determination

The general properties required for simulating the soil material as per the Mohr-Coulomb model mainly include: bulk unit weight (ɤ-bulk, KN/m^3), saturated unit weight (ɤ-sat, KN/m^3), the at-rest coefficient of horizontal soil stress (Ko) etc. The bulk unit weight (ɤ-balk KN/m^3) of the cohesive soil has been calculated by using the index property correlation recommended by Carter and Bentley (2016).

$$\gamma bulk = pbulk * g \quad \ldots\ldots \text{E.q. A.1}$$

$ɤbulk = pbulk * g$ = 1.92 ∗ 9.81) = 18.83KN/m^3

where: $ɤs - saturated\ unit\ weghit$

$ɤd - dry\ nit\ weghit\ and$

$w -\ moisture\ content$ and

$ɤb - buik\ unit\ weghit$

The saturated unit weight (ɤ-sat, KN/m^3) and dry unit weight of the cohesive soil has been calculated (Eq. A.2) by using the index property correlation recommended by Carter and Bentley (2016).

$ɤsat = ɤ\,(1 + w)$ ……………………………………………………………$E.q.$ A.2

$ɤd = \ \ldots \rho * g \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots$……$E.q$ A.3

$ɤd = \ \ldots \rho\ * g$ = 1.59 ∗ 9.81 = 15.6KN/m^3

$ɤsat = ɤ\,(1 + w)$ = 15.6(1 + 20.96) = 18.89KN/m^3.

The at-rest coefficient of horizontal soil stress (Ko) is determined us following:

$ko = 1 - sin\ \phi \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots E.q.$ A.4

ko = 1 − sin (24.96) = 0.59

A.2. Strength Characteristics

The strength characteristics required for simulating the soil material as per Mohr Coulomb model mainly includes effective cohesion (c‛‛, KN/m^2), effective angle of internal friction (ϕ), initial angle of dilatancy (φ) and etc. Gibson (1953), as indicated in Eq. A.5 has established a relationship between effective shear strength (internal friction angle) and plasticity index for remolded clays.

$\phi = 0.085PI^{1.4} - 0.75PI + 31.9$ ………………………………………………….… …………Eq A.5

By taking PI average value PI=13.66. So,

$\phi = 0.085 * 13.66^{1.4} - 0.75 * 13.66 + 31.9 = 24.96$

The effective cohesion value (c‛‛) had taken as c=18.5Kpa. (Budhu, 2000).

A.3 Stiffness Characteristic

The elastic deformation parameters of the soil material required as per Mohr Coulomb model includes: Young's modulus (E) and Poisson's ratio (ν). The stiffness parameter (Young's modules) has been correlated with CBR value based on the poison's ratio (after Elsa Eka Putri et. al, 2012)

$E = 863.82 * \text{CBR}\ (Kpa)$ $\quad\quad @v = 0$………………Eq A.6

$E = 840.53 * \text{CBR}\ (Kpa)$ $@v = 0.3$……………...Eq A.7

$E = 751 * \text{CBR}\ (Kpa)$ $@v = 0.4$………………Eq A.8

For silty clay types of soil Poisson's ratio is between 0.35 and 0.4 so, the researcher taken average of them. $v = 0.375$. In addition, by using interpolation, the researcher find coefficients of CBR as follows on table A.2

Table A.2: Relation between of Poisons ratio and coefficient of CBR

poisons ratio(v)	coefficient of CBR
0.3	840.53
0.375	X
0.4	751.0

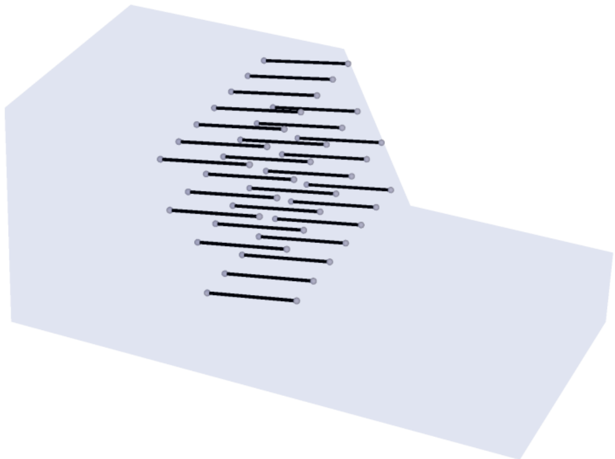
X =773.38 Coefficient of CBR.

Therefor $E = 773.38 * \text{CBR}\ (Kpa)$…………………………………………...Eq A.10

$E = 773.38 * 11.14(Kpa) = 8615.5Kpa = 8.6Mpa = 8.6e\text{^}6pa$

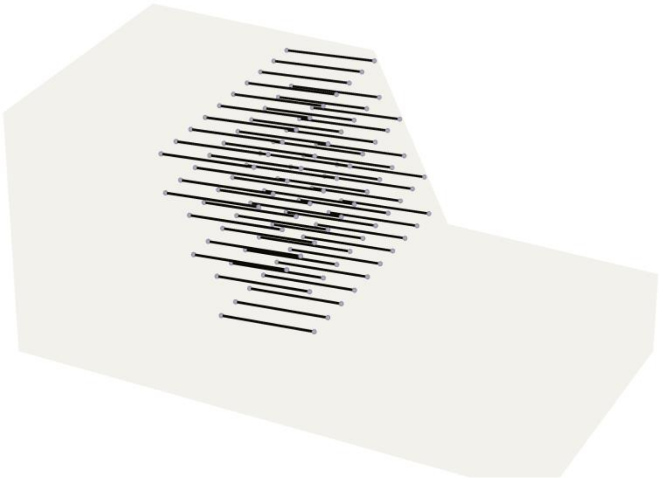
The soil parameters are calculated using the above equation and the model parameter are presented in Table 4.1 These properties have been used in FEA.

Appendix B: Model developed for this study

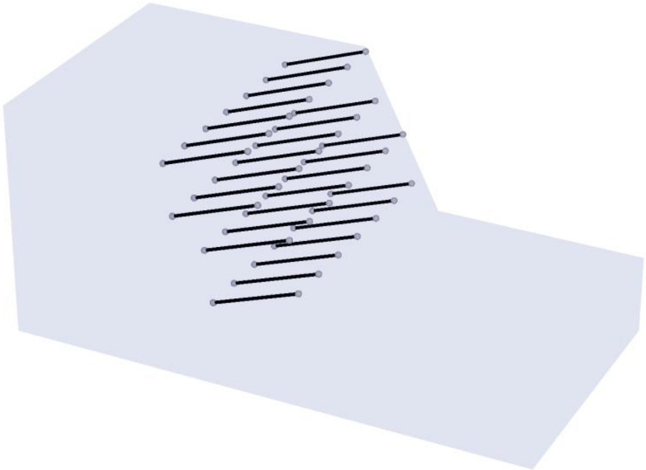


Model developed with nail of 3.5m length, 10 inclination, 1.5m space and 16mm of diameter.

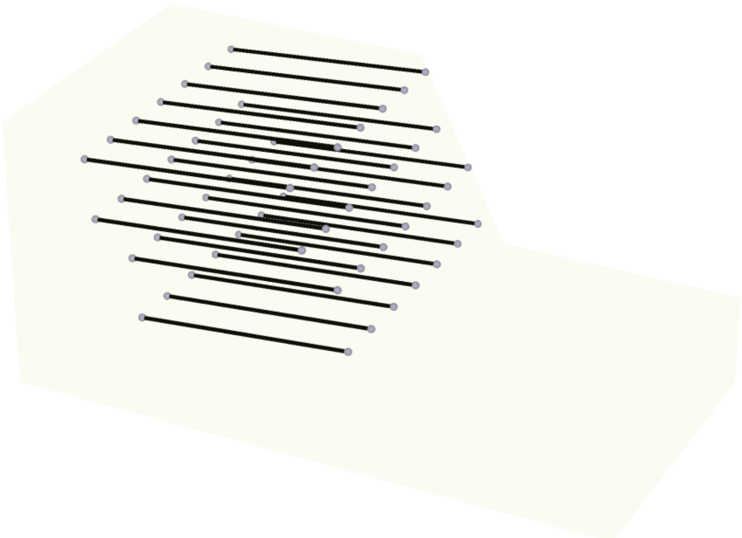
Model developed with nail of 3.5m length, 15 inclination, 1.75m space and 16mm of diameter.



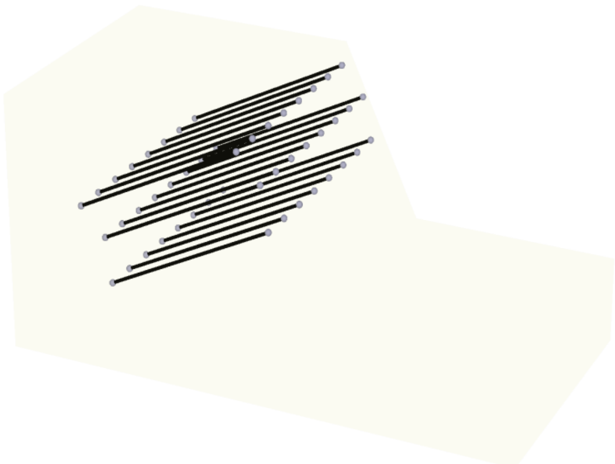
Model developed with nail of 3.5m length, 15 inclination, 1m space and 16mm of diameter.



Model developed with nail of 3.5m length, 20 inclination, 1.5m space and 16mm of diameter.

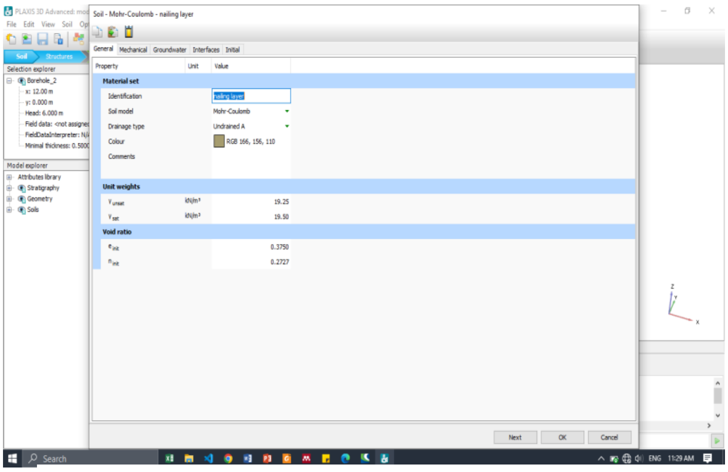


Model developed with nail of 7m length, 10 inclination, 1.5m space and 16mm of diameter.

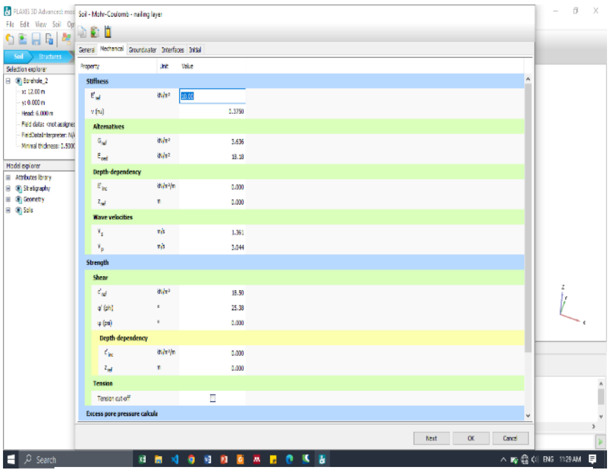


Model developed with nail of 7m length, 25 inclination, 1.25m space and 16mm of

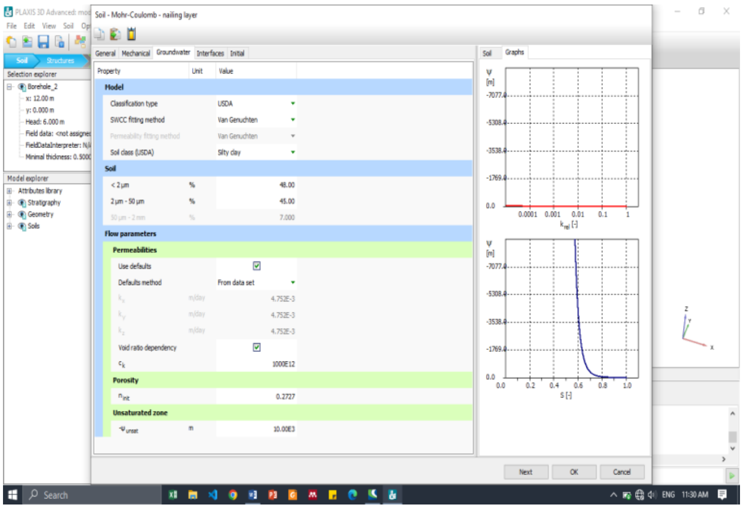
Appendix C: Screenshot captured from software during model development



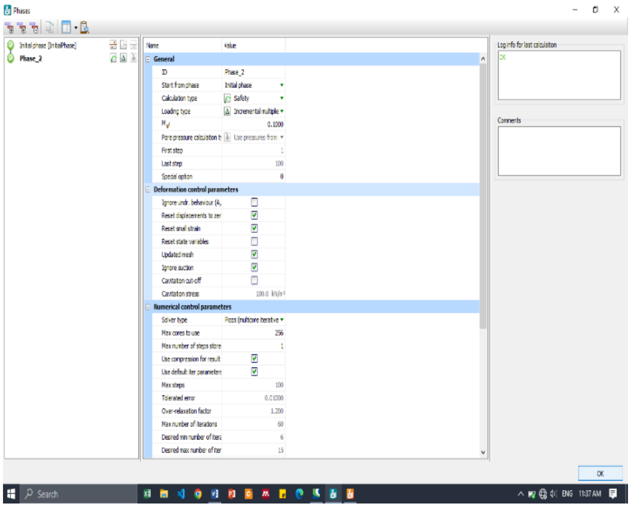
General soil layer naming/ forming



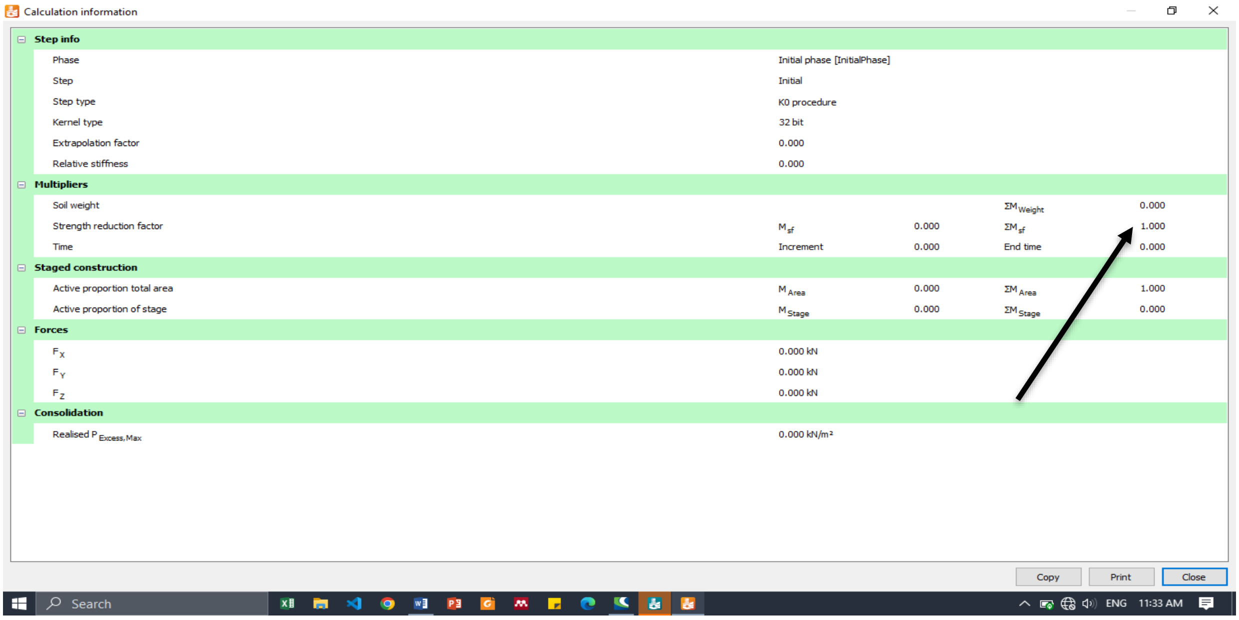
inputting some soil parameter



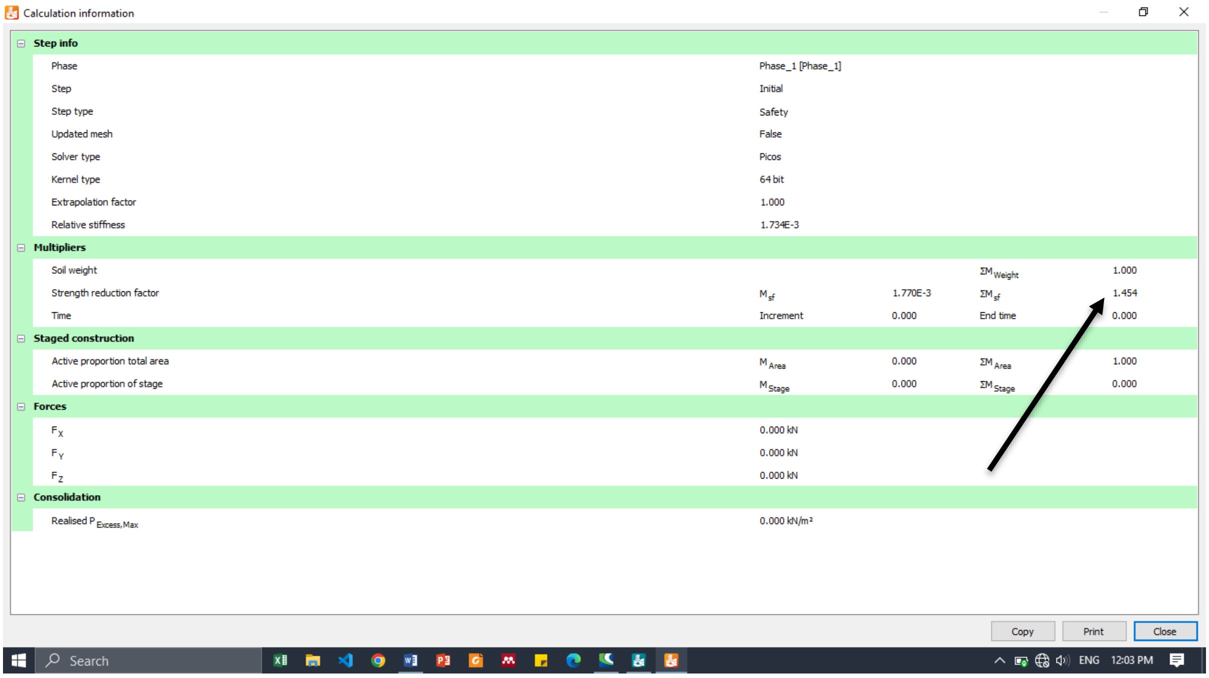
Selecting soil type



inputting calculation type in safety



Observing the calculation result of FOS as ΣM_{Sf} (Model constructed without nail)



Result of model constructed from nail of 3.5m length, 15 inclination, 1.5m space and 10mm of diameter.

Appendix D: Secondary Data taken from studied area

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/331/4017**	LAB REF. NO.	**EDTCP/ADAMA/BA/385**
SOURCE	**Borrow Area No.25+200 A P-1**	SAMPLEING DATE	**2/10/2023**
SAMPLING LOCATION	**Km.25+200**		
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Silty Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.791	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	18.4	%			YES	NO
		MDD at 95%	1.701	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	8.8	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	0.81	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	31.3	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	20.5	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	10.8	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -6(4)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			Material Engineer		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

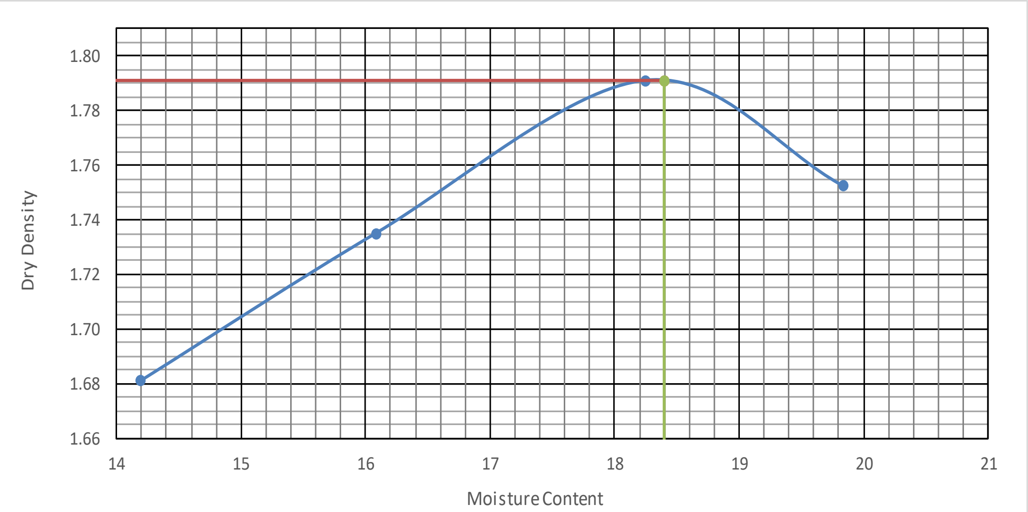
(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

MAXIMUM DRY DENSITY AND MOISTURE CONTENT

(AASTHO T-180) **Format No: 01002/JMC/EHAE/21F/03-R0**

RFI No.	QA-QC/LAB/331/4017	Lab Ref No. :	EDTCP/ADAMA/BA/385
Source :	Borrow Area No.25+200 A P-1	Date of Sampling:	2/10/2023
Location:	Km.25+200	Date of Testing:	1/30/2023
Propose Used	For Earthwork filling	Sampled By:	Jointly
Type of Method:	**A**	Tested By:	Jointly
Material Discription	Yellowish Silty Clay Soil	Depth (M)	1/0/1900

Description	Test I	Test II	Test III	Test IV	Test V		
	Density Determination						
Water Added %	**6%**	**8%**	**10%**	**12%**			
Mass of mould + Wet Soil (g)	10656	10856	11076	11038			
Mass of mould, W5 (g)	6578	6578	6578	6578			
Mass of wet soil, W7=W6-W5 (g)	4078	4278	4498	4460			
Volume of mould, V (cc)	2124	2124	2124	2124			
Bulk density, y_m = [(W7-W6)/V] g/cc	1.920	2.014	2.118	2.100		**NMC**	
	Moisture Content Determination						
Container no	D-12	D-4	D-13	D-20		D-10	
Mass of container + wet soil, W1 (g)	341.60	355.10	339.50	309.80		365.00	
Mass of container + oven dry soil, W2 (g)	302.64	309.80	291.30	263.40		338.90	
Mass of Water (g) W3=W1-W2	38.96	45.30	48.20	46.40		26.10	
Mass of container, W4 (g)	28.30	28.20	27.20	29.50		28.40	
Mass of Dry Soil (g) W5 = W2-W4	274.34	281.60	264.10	233.90		310.50	
Moisture Content (%) W6= W3/W5*100	**14.20**	**16.09**	**18.25**	**19.84**		8.41	
Dry density, $y_d = y_m/(100+W6)*100$ (g/cc)	**1.681**	**1.735**	**1.791**	**1.752**		8.41	



Moisture Density Relationship

X	Y
0	0
18.4	1.791
18.4	1.791

MDD: 1.791 (gm/cc) OMC: 18.4 %

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Engineer

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

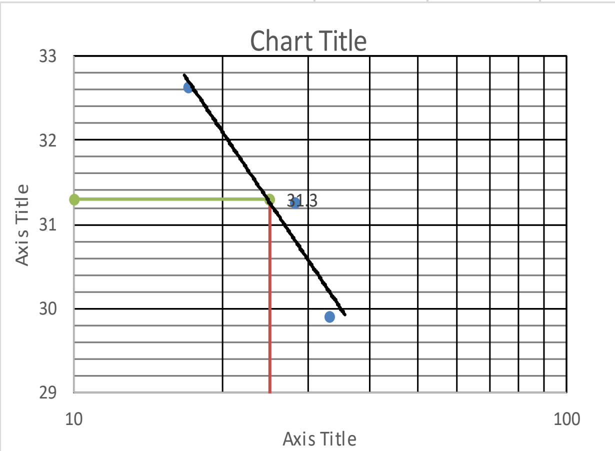
(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

ATTERBERG LIMITS

(AASTHO T-89/90) Format No: 01002/JMC/EHAE/21F/02-R0

RFI No.	QA-QC/LAB/331/4017	Lab Ref No. :	EDTCP/ADAMA/BA/385
Source :	Borrow Area No.25+200 A P-1	Date of Sampling:	2/10/2023
Location:	Km.25+200	Date of Testing:	2/12/2023
Propose Used	For Earthwork filling	Sampled By:	Jointly
Material Discription	Yellowish Silty Clay Soil	Tested By:	Jointly

Description	LIQUID LIMIT				PLASTIC LIMIT		
	Test I	Test II	Test III	Test IV	Test I	Test II	Avg.
No of blows/Penetration (mm)	33	28	17				
Container No	C-5	C-15	C-22		C-23	C-16	
Container + Wet soil, W1 (g)	58.5	61.1	61.6		27.3	26.9	
Container + Dry soil, W2 (g)	50.7	52.6	52.77		26.8	26.5	
Weight of Container (g)	24.6	25.4	25.7		24.3	24.6	20.53
Weight of water, W4= W1-W2 (g)	7.80	8.50	8.83		0.50	0.40	
Weight of oven dry sample, W5=W3 - W1 (g)	26.10	27.20	27.07		2.50	1.90	
Water content percentage, 100x(W4/W5)	29.89	31.25	32.62		20.00	21.05	



Grain Size Analysis			
Total Wt.(gm)			600.0
Sieve size mm	Wt. Ret. (g.)	% Retained	% Passing
2.0	56.6	9.43	90.57
0.425	66.3	11.05	79.52
0.075	116.9	19.48	60.03
Pan	360.2	60.03	0.00

DD-Swell Relation	
0	10
31.3	25
31.3	25

LL	PL	PI	Soil Class
31.30	20.53	10.77	A -6(4)

Comments:-

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Engineer

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC PROJECTS (I) LTD.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

CALIFORNIA BEARING RATIO TEST

(AASHTO T 193)

Format No: 01002/JMC/EHAE/21F/04A-R0

RFI No.	QA-QC/LAB/331/4017	Lab Ref. No.	EDTCP/ADAMA/BA/385
Source :	Borrow Area No.25+200 A P-1	Date of Sampling:	2/10/2023
Location:	Km.25+200	Date of Soaking:	2/13/2023
Propose Used	For Earthwork filling	Date of Testing:	2/17/2023
Material Discription	Yellowish Silty Clay Soil	Depth (m):	1/0/1900

DENSITY DETERMINATION

SOAKING CONDITION	10 Blows		30 Blows		65 Blows	
	Before	**After**	**Before**	**After**	**Before**	**After**
MOLD NUMBER	M-39		M-40		M-51	
WEIGHT OF MOLD	7748	7748	7500	7500	7436	7436
WEIGHT OF SOIL + MOLD	11584	12084	11740	12094	11854	12138
WEIGHT OF SOIL	3836	4336	4240	4594	4418	4702
VOLUME OF MOLD	2124	2124	2124	2124	2124	2124
WET DENSITY OF SOIL	1.81	2.04	2.00	2.16	2.08	2.21
DRY DENSITY OF SOIL	1.52	1.72	1.68	1.82	1.75	1.86

MOISTURE DETERMINATION

CONTAINER NUMBER	D-19	D-3	D-14	D-20	D-10	D-18
WET SOIL + CONTAINER (g)	331.50	340.50	350.70	258.50	338.30	321.90
DRY SOIL + CONTAINER (g)	283.50	291.30	299.30	221.90	288.60	274.60
WEIGHT OF WATER (g)	48.00	49.20	51.40	36.60	49.70	47.30
WEIGHT OF CONTAINER (g)	27.10	28.30	28.50	29.40	28.40	27.00
WEIGHT OF DRY SOIL (g)	256.40	263.00	270.80	192.50	260.20	247.60
MOISTURE CONTENT (%)	18.72	18.71	18.98	19.01	19.10	19.10
AVG. MOISTURE CONTENT (%)	18.71		19.00		19.10	

Ring Factor **0.03081**

PENETRATION TEST DATA

PENETRATION (mm)	Std. Load	Dial reading	Load (kn)	Cor. Load (kn)	Dial reading	Load (kn)	Cor. Load (kn)	Dial reading	Load (kn)	Cor. Load (kn)
0		0.0	0		0.0	0		0.0	0	
0.64		4.0	0.1		5.0	0.2		10.0	0.3	
1.27		7.0	0.2		12.0	0.4		23.0	0.7	
1.96		11.0	0.3		19.0	0.6		35.0	1.1	
2.54	13.54	20.0	0.6	0.6	26.3	0.8	0.9	47.0	1.4	1.5
3.18		23.0	0.7		37.0	1.1		56.0	1.7	
3.81		24.0	0.7		40.0	1.2		67.0	2.1	
4.45		25.0	0.8		45.0	1.4		70.0	2.2	
5.08	20.22	27.0	0.8	0.8	55.0	1.7	1.5	76.0	2.3	2.3
7.62		30.0	0.9		60.0	1.8		87.0	2.7	
10.16		35.0	1.1		65.0	2.0		95.0	2.9	
12.7		45.0	1.4		75.0	2.3		106.0	3.3	

SWELL READING (INITIAL)	4.37	3.01	6.14
SWELL READING (FINAL)	5.00	4.52	6.83
PERCENTAGE SWELL	0.54	1.30	0.59
CBR @ 2.54 mm	4.1	6.6	11.1
CBR @ 5.08 mm	4.0	7.4	11.4

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material	Consultant's Lab Technician	Consultant's Material Engineer

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC PROJECTS (I) LTD.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

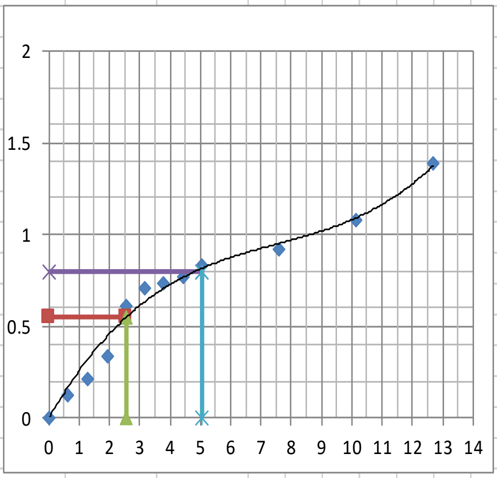
CALIFORNIA BEARING RATIO TEST

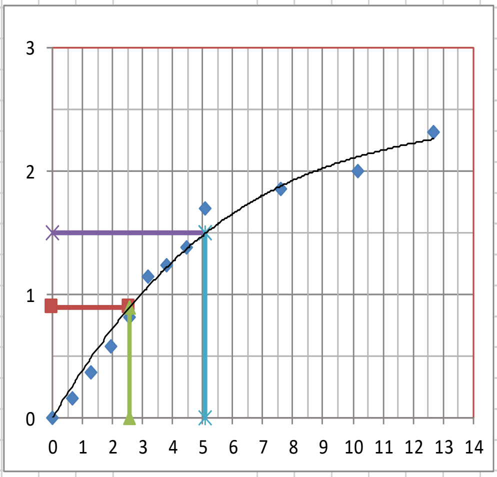
(AASHTO T 193)

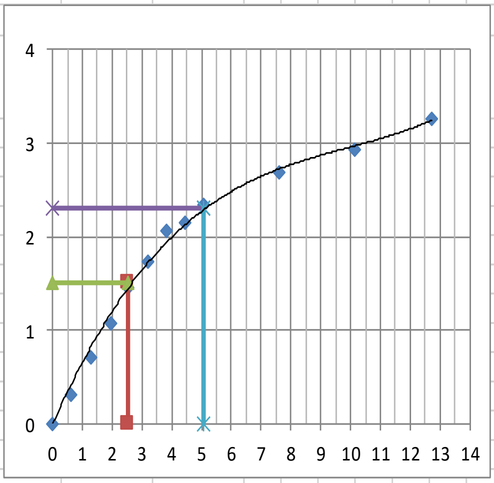
Format No: 01002/JMC/EHAE/21F/04B-R0

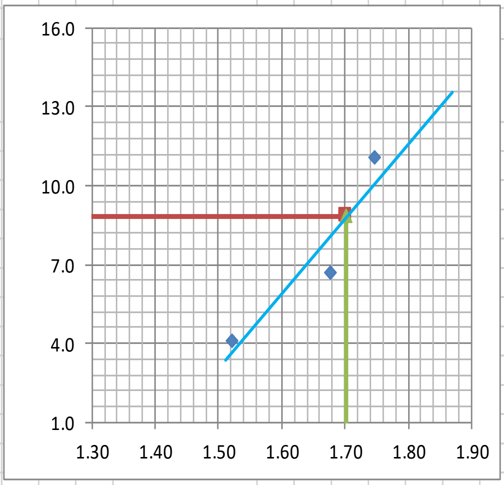
RFI No.	QA-QC/LAB/331/4017	Lab Ref. No.	EDTCP/ADAMA/BA/385
Source :	Borrow Area No.25+200 A P-1	Date of Sampling:	2/10/2023
Location:	Km.25+200	Date of Soaking:	2/13/2023
Propose Used	For Earthwork filling	Date of Testing:	2/17/2023
Material Discription	Yellowish Silty Clay Soil	Depth (m):	1/0/1900

MDD (gm/cc)	1.791	OMC (%)	18.40









10 blows			
0	0	0	0
0.80	5.08	0.55	2.54
0.80	5.08	0.55	2.54
0	0	0	0

30 blows			
0	0	0	0
1.50	5.08	0.90	2.54
1.50	5.08	0.90	2.54
0	0	0	0

60 blows			
0	0	0	0
2.30	5.08	1.50	2.54
2.30	5.08	1.50	2.54
0	0	0	0

CBR-DD Relation	
0	0
8.80	1.701
8.80	1.701

Density @ 95% Compaction (gm/cc)	**1.701**
CBR @ 95% Compaction (%)	**8.8**
Swell @ 95% Compaction (%)	**0.81**

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Enginee

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I. Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/444/4705**	LAB REF. NO.	**EDTCP/ADAMA/BA/478**
SOURCE	**Borrow Area No.25+200 A P-2**	SAMPLEING DATE	**3/27/2023**
SAMPLING LOCATION	**Km.25+200**		
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellow Silty Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.643	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	23.4	%			YES	NO
		MDD at 95%	1.561	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	9.5	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.09	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	32.9	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	24.4	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	8.5	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -4(5)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/348/4201**	LAB REF. NO.	**EDTCP/ADAMA/BA/402**
SOURCE	**Borrow Area No.25+200 A P-3**	SAMPLEING DATE	**2/21/2023**
SAMPLING LOCATION	**Km.25+200**		
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellow Silty Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.497	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	24.8	%			YES	NO
		MDD at 95%	1.422	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	9.0	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.53	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	44.7	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	29.0	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	15.7	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A-7-6(3)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/348/4201**	LAB REF. NO.	**EDTCP/ADAMA/BA/402**
SOURCE	**Borrow Area No.25+200 A P-4**	SAMPLEING DATE	**2/21/2023**
SAMPLING LOCATION	**Km.25+200**		
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellow Silty Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.481	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	24.9	%			YES	NO
		MDD at 95%	1.407	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	6.8	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.29	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	42.2	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	28.1	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	14.1	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -7-6(6)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			Material Engineer		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

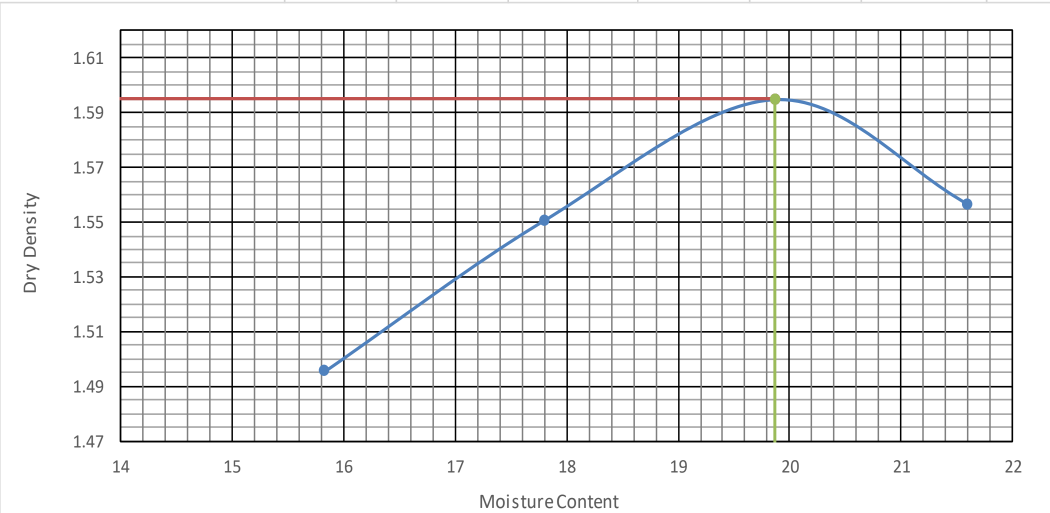
(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

MAXIMUM DRY DENSITY AND MOISTURE CONTENT

(AASTHO T-180) Format No: 01002/JMC/EHAE/21F/03-R0

RFI No.	QA-QC/LAB/137/2072	Lab Ref No. :	EDTCP/ADAMA/BA/195
Source :	Borrow Area No.33 25+250 B P- 1	Date of Sampling:	9/29/2022
Location:	Km.25+250	Date of Testing:	9/30/2022
Propose Used	For Earthwork filling	Sampled By:	Jointly
Type of Method:	A	Tested By:	Jointly
Material Discription	Yellowish Silty Clay Soil	Depth (M)	1/0/1900

Description	Test I	Test II	Test III	Test IV	Test V		
	Density Determination						
Water Added %	**8%**	**10%**	**12%**	**14%**			
Mass of mould + Wet Soil (g)	10160	10360	10540	10500			
Mass of mould, W5 (g)	6480	6480	6480	6480			
Mass of wet soil, W7=W6-W5 (g)	3680	3880	4060	4020			
Volume of mould, V (cc)	2124	2124	2124	2124			
Bulk density, y_m = [(W7-W6)/V] g/cc	1.733	1.827	1.911	1.893		**NMC**	
	Moisture Content Determination						
Container no	A-2	A-10	A-5	A-6		B-10	
Mass of container + wet soil, W1 (g)	387.57	301.84	329.31	376.22		270.52	
Mass of container + oven dry soil, W2 (g)	343.56	263.94	285.18	321.00		254.22	
Mass of Water (g) W3=W1-W2	44.01	37.90	44.13	55.22		16.30	
Mass of container, W4 (g)	65.60	51.04	63.11	65.36		34.11	
Mass of Dry Soil (g) W5 = W2-W4	277.96	212.90	222.07	255.64		220.11	
Moisture Content (%) W6= W3/W5*100	**15.83**	**17.80**	**19.87**	**21.60**		7.41	
Dry density, y_d = y_m/(100+W6)*100 (g/cc)	**1.496**	**1.551**	**1.595**	**1.556**		7.41	



Moisture Density Relationship

X	Y
0	0
19.87	1.595
19.87	1.595

MDD: 1.595 (gm/cc) OMC: 19.9 %

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Engineer

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/137/2072**	LAB REF. NO.	**EDTCP/ADAMA/BA/195**
SOURCE	**Borrow Area No.33 @25+250 B P-2**	SAMPLEING DATE	**9/29/2022**
SAMPLING LOCATION	**Km.25+250**		
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.607	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	18.4	%			YES	NO
		MDD at 95%	1.527	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	15.3	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.18	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	35.7	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	20.4	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	15.3	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -6(4)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

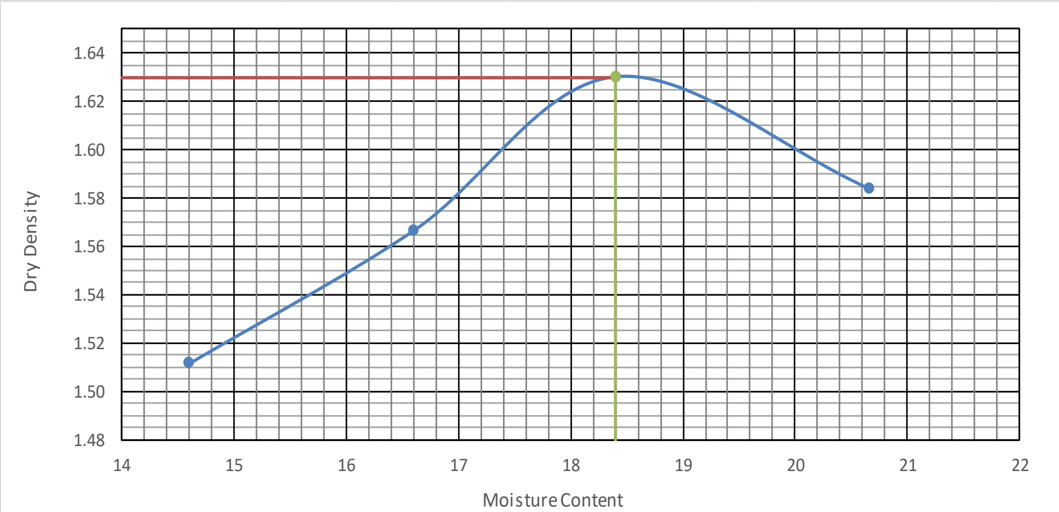
(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

MAXIMUM DRY DENSITY AND MOISTURE CONTENT

(AASTHO T-180) **Format No: 01002/JMC/EHAE/21F/03-R0**

RFI No.	QA-QC/LAB/137/2072	Lab Ref No. :	EDTCP/ADAMA/BA/195
Source :	Borrow Area No.25+250 B P-3	Date of Sampling:	9/29/2022
Location:	Km.25+250	Date of Testing:	9/30/2022
Propose Used	For Earthwork filling	Sampled By:	Jointly
Type of Method:	**A**	Tested By:	Jointly
Material Discription	Yellowish Silty Clay Soil		

Description	Test I	Test II	Test III	Test IV	Test V		
	Density Determination						
Water Added %	**10%**	**12%**	**14%**	**16%**			
Mass of mould + Wet Soil (g)	10160	10360	10580	10540			
Mass of mould, W5 (g)	6480	6480	6480	6480			
Mass of wet soil, W7=W6-W5 (g)	3680	3880	4100	4060			
Volume of mould, V (cc)	2124	2124	2124	2124			
Bulk density, y_m = [(W7-W6)/V] g/cc	1.733	1.827	1.930	1.911		**NMC**	
	Moisture Content Determination						
Container no	B-15	B-5	B-3	B-9		A-7	
Mass of container + wet soil, W1 (g)	276.80	283.40	269.22	291.75		335.10	
Mass of container + oven dry soil, W2 (g)	245.26	247.36	231.73	247.03		323.46	
Mass of Water (g) W3=W1-W2	31.54	36.04	37.49	44.72		11.64	
Mass of container, W4 (g)	29.22	30.24	28.02	30.59		46.40	
Mass of Dry Soil (g) W5 = W2-W4	216.04	217.12	203.71	216.44		277.06	
Moisture Content (%) W6= W3/W5*100	**14.60**	**16.60**	**18.40**	**20.66**		4.20	
Dry density, y_d = y_m/(100+W6)*100 (g/cc)	**1.512**	**1.567**	**1.630**	**1.584**		4.20	



Moisture Density Relationship

X	Y
0	0
18.4	1.63
18.4	1.63

MDD:	1.630 (gm/cc)	OMC:	18.4 %

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Engineer

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/70/717**	LAB REF. NO.	**EDTCP/ADAMA/BA/123**
SOURCE	**Borrow Area No.25+320 C P-1**	SAMPLEING DATE	**10/6/2022**
SAMPLING LOCATION	**Km.25+320**	SAMPLE DEPTH (M)	**0.2 to 2.5 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Silty-Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.507	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	20.7	%			YES	NO
		MDD at 95%	1.432	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	11.5	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	0.62	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	33.1	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	24.2	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	8.9	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -7-5(25)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			Material Engineer		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/70/717**	LAB REF. NO.	**EDTCP/ADAMA/BA/123**
SOURCE	**Borrow Area No.11 @25+320 C P- 2**	SAMPLEING DATE	**10/6/2022**
SAMPLING LOCATION	**Km.25+320**	SAMPLE DEPTH (M)	**0.2 to 2.5 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Silty Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.641	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	17.5	%			YES	NO
		MDD at 95%	1.559	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	17.5	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	0.68	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	28.6	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	18.9	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	9.7	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -4(1)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/94/1071**	LAB REF. NO.	**EDTCP/ADAMA/BA/153**
SOURCE	**Borrow Area No @25+320**	SAMPLEING DATE	**7/15/2022**
SAMPLING LOCATION	**Km.25+320 C P-3**	SAMPLE DEPTH (M)	**0.3 to 3 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Silty Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.580	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	21.7	%			YES	NO
		MDD at 95%	1.501	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	12.5	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.26	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	35.6	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	22.0	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	13.6	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -6(11)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/94/1071**	LAB REF. NO.	**EDTCP/ADAMA/BA/153**
SOURCE	**Borrow Area No. 25+320**	SAMPLEING DATE	**7/15/2022**
SAMPLING LOCATION	**Km.25+320 P- 4**	SAMPLE DEPTH (M)	**0.3 to 3 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Yellowish Silty-clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.595	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	21.6	%			YES	NO
		MDD at 95%	1.515	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	18.0	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.00	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	34.5	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	23.3	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	11.2	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -6(5)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	Date		Signature	Date
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/220/3075**	LAB REF. NO.	**EDTCP/ADAMA/BA/276**
SOURCE	**Borrow Area No.46 @25+400 LHS Pit 1**	SAMPLEING DATE	**12/1/2022**
SAMPLING LOCATION	**Km.25+400**	SAMPLE DEPTH (M)	**0.2 to 4.0 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Brown Silty Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.676	g/cm^3	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	21.2	%			YES	NO
		MDD at 95%	1.592	g/cm^3			YES	NO
2	CBR	CBR at 95% MDD	9.5	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.40	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	38.8	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	23.9	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	14.8	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -6(7)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	**Date**		**Signature**	**Date**
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

Ethiopia - Djibouti Transport Corridor Project Phase I.
Design & Build of Adama - Km 60 Expressway

SOIL TESTING AND APPROVAL RECORD

RFI No.	**QA-QC/LAB/220/3075**	LAB REF. NO.	**EDTCP/ADAMA/BA/276**
SOURCE	**Borrow Area No.46 @25+400 Pit 2**	SAMPLEING DATE	**12/1/2022**
SAMPLING LOCATION	**Km.25+400 LHS**	SAMPLE DEPTH (M)	**0.2 to 4.0 m**
PURPOSED TO USE	**For Earthwork filling**		
MATERIAL DESCRIPTION:	**Brown Clay Soil**		

No.	TEST PERFORMED		TEST RESULTS		TEST METHODS	ACCEPTANCE CRITERIA	APPROVAL STATUS	
1	COMPACTION TEST	MDD at 100%	1.496	g/cm³	AASHTO T-180 Method D/ ASTM D 1557		YES	NO
		OMC	22.0	%			YES	NO
		MDD at 95%	1.421	g/cm³			YES	NO
2	CBR	CBR at 95% MDD	6.1	%	AASHTO 193/ ASTM D 1883	> 5	YES	NO
		SWELL	1.75	%		< 2	YES	NO
3	SOIL PLASTICITY	LIQUID LIMIT (LL)	53.7	%	AASHTO T-89/90/ ASTM D 4318	< 60	YES	NO
		PLASTIC LIMIT (PL)	33.0	%	AASHTO T-89/90/ ASTM D 4318		YES	NO
		PLASTICITY INDEX(PI)	20.6	%	AASHTO T-89/90/ ASTM D 4318	< 30	YES	NO
4	SOIL CARACTER	SOIL CLASSIFICATION	A -7-5(12)		AASHTO M 145		YES	NO
5	ORGANIC CONTENT	SOIL CLASSIFICATION	NA		AASHTO T-267-86	< 3	YES	NO

Note: Attach individual test records and data sheet

Remarks:

Contractor's Representative			Consultant's Representative		
	Signature	**Date**		**Signature**	**Date**
Material Engineer			**Material Engineer**		

CLIENT	CONSULTANT	CONTRACTOR
ETHIOPIAN ROAD AUTHORITY	LEA-LASA-UNICONE	JMC - LRBCL Joint Venture.

ETHIOPIA-DJIBOUTI TRANSPORT CORRIDOR PROJECT

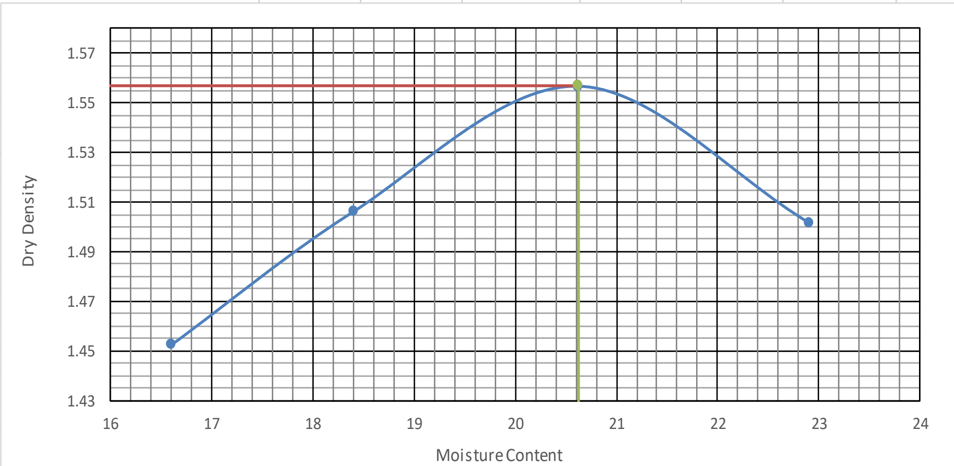
(PHASE-I: DESIGN BUILD OF ADAMA-Km 60 EXPRESSWAY)

MAXIMUM DRY DENSITY AND MOISTURE CONTENT

(AASTHO T-180) **Format No: 01002/JMC/EHAE/21F/03-R0**

RFI No.	QA-QC/LAB/220/3075	Lab Ref No. :	EDTCP/ADAMA/BA/276
Source :	Borrow Area No.46 @25+400 P-3	Date of Sampling:	12/1/2022
Location:	Km.25+400	Date of Testing:	12/2/2022
Propose Used	For Earthwork filling	Sampled By:	Jointly
Type of Method:	**A**	Tested By:	Jointly
Material Discription	Brown Silt-Clay Soil	Depth (M)	0.2 to 4.0 m

Description	Test I	Test II	Test III	Test IV	Test V		
	Density Determination						
Water Added %	**10%**	**12%**	**14%**	**16%**			
Mass of mould + Wet Soil (g)	10178	10368	10568	10500			
Mass of mould, W5 (g)	6580	6580	6580	6580			
Mass of wet soil, W7=W6-W5 (g)	3598	3788	3988	3920			
Volume of mould, V (cc)	2124	2124	2124	2124			
Bulk density, y_m = [(W7-W6)/V] g/cc	1.694	1.783	1.878	1.846		**NMC**	
	Moisture Content Determination						
Container no	D	A-5	A-6	F-3		A-10	
Mass of container + wet soil, W1 (g)	318.90	410.00	286.00	249.90		191.10	
Mass of container + oven dry soil, W2 (g)	283.12	356.09	248.30	208.60		180.30	
Mass of Water (g) W3=W1-W2	35.78	53.91	37.70	41.30		10.80	
Mass of container, W4 (g)	67.60	63.10	65.48	28.30		35.90	
Mass of Dry Soil (g) W5 = W2-W4	215.52	292.99	182.82	180.30		144.40	
Moisture Content (%) W6= W3/W5*100	**16.60**	**18.40**	**20.62**	**22.91**		7.48	
Dry density, $y_d = y_m/(100+W6)*100$ (g/cc)	**1.453**	**1.506**	**1.557**	**1.502**		7.48	



Moisture Density Relationship

X	Y
0	0
20.62	1.557
20.62	1.557

MDD:	1.557 (gm/cc)	OMC:	20.6 %

....	....	....	....
Tested By	Checked By	Verified by	Approved By
Contractor's Lab Technician	Contractor's Material Engineer	Consultant's Lab Technician	Consultant's Material Engineer