TO STUDY THE EFFECT OF SOIL NAILING FOR THE STABILITY OF SLOPES

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
GEOTECHNICAL ENGINEERING

Submitted by:

NISHA JHA
(2K23/GTE/11)

Under the Supervision of

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Shahbad Daulatpur, Main Bawana Road, Delhi-110042

MAY, 2025

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CANDIDATE'S DECLARATION

I, **NISHA JHA,** M. Tech (Geotechnical Engineering) student, having **Roll no: 2K23/GTE/11,** hereby certify that the work which is being presented in the dissertation entitled "**TO STUDY THE EFFECT OF SOIL NAILING FOR THE STABILITY OF SLOPES**" in partial fulfillment of the requirements for the award of the Degree of **Master Of Technology in Geotechnical Engineering**, submitted in the **Department of Civil Engineering , Delhi Technological University**, Delhi Technological University is an authentic record of my work carried out under the supervision of **Prof. ANIL KUMAR SAHU,** Professor, Department of Civil Engineering, Delhi Technological University, Delhi.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other Institute.

(NISHA JHA)

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Prof. ANIL KUMAR SAHU
(SUPERVISOR)

Place: Delhi

Date:

(Signature of External Examiner)

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CERTIFICATE BY THE SUPERVISOR

Certified that **NISHA JHA (2K23/GTE/11)** has carried out his research work presented in this thesis entitled "**TO STUDY THE EFFECT OF SOIL NAILING FOR THE STABILITY OF SLOPES**" for the award of the Degree of **Master of Technology in Geotechnical Engineering** from the Department of Civil Engineering, Delhi Technological University, Delhi, under our supervision. The thesis embodies the results of original work and studies are carried out by the student himself. The contents of the thesis do not form the basis for the award of any degree to the candidate or to anybody else from this or any other University/Institution.

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SUPERVISOR
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ABSTRACT

Slope instability poses significant challenges to infrastructure development and environmental safety, often resulting in catastrophic failures with severe social and economic consequences. Soil nailing has emerged as a useful and cost-effective solution for stabilizing slopes and retaining walls. This technique involves the insertion of reinforcement elements, such as steel bars, into the soil to enhance its shear strength and improve overall stability. Despite its widespread application, understanding the critical factors influencing the performance of soil nailing systems remains an area of ongoing research. This research investigates the effect of soil nailing on slope stability by examining key parameters such as soil properties, including cohesion, angle of internal friction, nail spacing, orientation, length, and material properties. The research employs a combination of analytical simulations using PLAXIS Software and experimental analyses to assess the act of soil-nailing systems under various conditions.

The slope models were developed using the Mohr-Coulomb failure criterion, incorporating calculated soil characteristics. Slope angles of 30°, 45°, and 90° were analyzed with nail inclinations of 0°, 10°, 20°, and 30° with the horizontal plane and nail lengths of 6m, 8m, 10m and 12m to determine the optimum configuration. The Factor of Safety (FOS) was calculated for the slope under both unreinforced and reinforced conditions. Results indicated that FOS decreases with increasing slope and backslope angles but significantly improves with optimized nail orientation and length. A nail inclination of 10° with the horizontal, a nail length of 8 m and a nail diameter of 6mm were found to be the most effective, yielding a maximum FOS of 1.539. The optimum configuration identified through numerical modelling was validated experimentally using a scaled model at a 1:100 ratio. The physical model was made in a tank with dimensions of 40 cm × 15 cm × 20 cm. The backfill material was sourced from the DTU ground, and basic soil properties such as cohesion and angle of internal friction—were determined to ensure accurate input for slope stability analysis. Static loads were applied at the crest of the slope, and deformations were measured using a magnetic dial gauge.

The Factor of Safety (FOS) was calculated using Culmann's method, yielding values of 1.62 for the unreinforced slope and 1.82 for the reinforced slope as the load increased. The failure load was observed to be 4166 N for the unreinforced slope and 5161 N for the reinforced slope, demonstrating the improved load-bearing capacity due to soil nailing. The outcomes of this research provide valuable insights into the efficiency of soil nailing in slope stabilization and contribute to developing more robust design guidelines for geotechnical engineers. This study underscores the potential of combining computational simulations with experimental approaches to achieve a complete understanding of slope performance and reinforcement mechanisms.

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I, **NISHA JHA**, would like to express my gratitude to all those who have given unforgettable contributions to the successful contribution of this thesis.

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Last, but not least, I would like to express my enormous gratitude towards God. I don't think I would have been what I am today if it was not his/her blessing.

NISHA JHA
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LIST OF ABBREVIATIONS

C_u = Coefficient of uniformity

C_c = Coefficient of curvature

D_{10} = Effective particle size (m)

D_{30} = Diameter through which 30 % of the total soil particles is passing

D_{60} = Diameter through which 60 % of the total soil particles is passing

OMC =Optimum moisture content

G = Specific gravity of soil

MDD = Maximum dry density

C = Cohesion

Φ = Angle of internal friction

τ = Shear strength

σ = Normal stress

γb = Bulk Density

γd = Dry Density

I_p = Plasticity Index

W_P = Plastic limit

W_L = Liquid Limit

FOS = Factor of Safety

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The stability of slopes is a critical concern in geotechnical engineering due to its implications for infrastructure safety, environmental sustainability, and disaster mitigation. Slopes, whether natural or man-made, are subject to various destabilizing forces such as gravitational stresses, seepage, and external loads. Unstable slopes pose significant risks, including landslides, road closures, and structural failures, which can lead to catastrophic human and economic losses.

To address these challenges, innovative and efficient stabilization techniques are essential. Among them, soil nailing has appeared as a widely adopted and cost-effective method for reinforcing slopes. This technique comprises the insertion of steel bars (nails) into the soil to provide additional support and resist shear forces. The nails, typically grouted in place, act in conjunction with the soil to create a composite material with enhanced strength and stability.

Over the past few periods, soil nailing has gained recognition for its versatility, ease of installation, and adaptability to diverse site conditions. However, despite its widespread application, there remain significant gaps in understanding the precise mechanisms of soil nailing, its optimal design parameters, and its long-term performance across different environments.

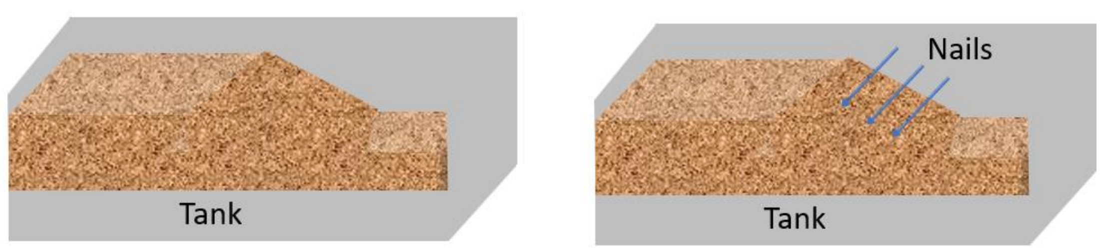


Figure 1.1: Experimental Setup Layout

The study of soil nailing's effect on slope stability is particularly relevant in regions prone to geohazards or where space constraints necessitate the construction of steep embankments. Understanding the interaction between the soil and nails, as well as the factors influencing their performance, is vital for optimizing design parameters and ensuring the long-term safety of slopes.

This project aims to explore the effects of soil nailing on slope stability, examining the influence of factors such as number of nails, nail length and diameter, spacing, and inclination on the structural integrity of slopes. By analyzing both numerical models and, where possible, field data, this study seeks to develop a deeper understanding of how soil nailing contributes to slope stability under various conditions.

The findings will not only contribute to enhancing the efficiency of soil nailing designs but also provide valuable insights into best practices for geotechnical engineers working on slope stabilization projects.

1.2 TYPES OF SLOPES

When analysing slope stability, a number of elements are taken into consideration, including topography, soil characteristics, and geography. One of the most important factors in any information analysis is the type of soil. There are two kinds of slopes: infinite slope and finite slope. Additionally, slopes can be categorised as either natural or man-made, according to Murthy (2003).

1.2.1 Infinite slope

A parallel surface takes into account the original slope's surface in case of an excessively lengthy slope failure. It is possible to do an infinite slope stability analysis based on the balance of forces operating on slices "abcd" in the figure. The FOS equation for an infinite slope surface looks like this:

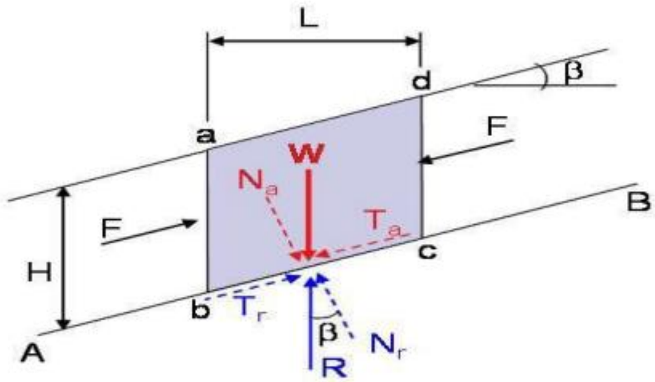


Figure1.2: Analysis of infinite slope Source: Winniyarti, 2010

1.2.2 Finite slope

When the critical height becomes close to the slope height, the slopes are typically regarded as finite. For the analysis of finite slope, the general shape of the surface of probable failure must be taken into account. Slope failures typically take place on the curved failure surface, according to Culmann (1875). The Swedish Geotechnical Commission suggested that the real failure surface might be a cylindrical, circular shape. Following this presumption, slopes are regarded as the arc of a circle in the majority of stability analyses.

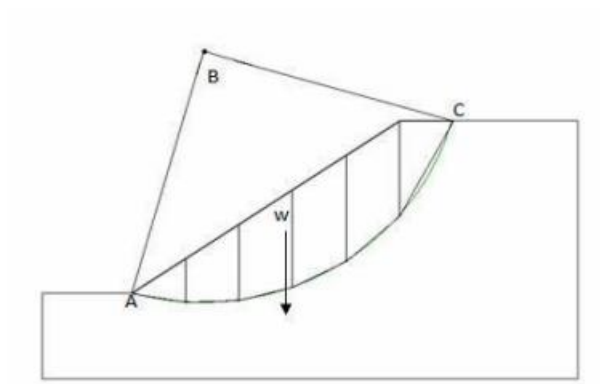


Figure1.3: Circular slip surface Source: Winniyarti, 2010

1.2.3 Natural Slopes

Natural slopes can be found in hilly regions, where formation processes take a long time to complete without disturbance. Slope creation may be influenced by earthquakes and the movement of the earth's core. As long as there are no human activities like mining and logging that compromise the stability of the slope, these kinds of slopes are robust and stable.

1.2.4 Man-made slope

Man-made slopes are those that are created for desired development; man-cut slopes are embankments or slopes that are used to provide ground level to ease construction. To stop landslides, the stability of these slopes is periodically checked. It falls into one of two categories:

- Cut Slopes
- Fill Slopes

Cut Slopes

Cut slope is man-made slope which is generated for the construction of roads and other infrastructures. By altering the slope construction's height and angle, the geometry was altered. Every nation has its own rules for building cut slopes.

Fill slopes

Fill slope is one of the types of artificial slope. Reclamation of land from other locations can produce fill slopes. It is easy to observe this kind of slope in highway construction. Every nation has its own rules for fill slope construction.

1.3 SOIL NAILING TECHNIQUE

Soil nailing is a ground reinforcement method used to stabilize slopes, retaining walls, and excavations. This method involves the insertion of small, elongated steel bars (referred to as "nails") into the soil to improve its strength and stability. These nails are typically installed at an inclination and grouted into pre-drilled holes. Together, the nails and soil form a composite structure that resists shear and tensile forces, enhancing the overall stability of slopes.

1.4 KEY COMPONENTS OF SOIL NAILING:

Nails:

- Typically made of steel, with a corrosion-protection coating if required.
- Installed in drilled or driven holes, then grouted to improve bonding with the surrounding soil.

Grout:

- Used to fill the drilled holes around the nails.
- Provides a strong bond among the nails and the soil and shields the nails from corrosion.

Facing System:

- A surface layer, often consisting of shotcrete, geotextiles, or precast panels.
- Provides additional support and prevents soil erosion.

Drilling and Installation Equipment:

- Tools to create boreholes for the nails and inject grout under pressure.

1.5 DIFFERENT METHODS OF ANALYSIS

Limit Equilibrium Method (LEM)

The limit equilibrium evaluation is one of the typical approaches for determining the level of stability of slopes. According to the concept of equilibrium, a stable slope signifies a state in which all the forces operating on the slope remain in equilibrium. The analysis entails sectioning the slope and evaluating the stability throughout each section separately.

The equilibrium between a stiff body, such a hill, and a slip surface of any shape—straight line, circular arc, logarithmic spiral, etc.—is studied using the limit equilibrium approach. Shear stresses (τ) are computed from this equilibrium and contrasted with the available resistance (τf), which is computed using Mohr-Coulomb's failure criterion. We determine the first measure of stability, the Factor of Safety, from this comparison:

$$F = \frac{\tau_f}{\tau} \tag{1.1}$$

Key Components of LEM are failure surfaces, slices, forces considered, equilibrium condition etc. and some of the common techniques of LEM are Fellenius (Swedish Circle Method), Bishop's Simplified Method, Janbu's Method, Morgenstern-Price Method and Spencer Method.

Morgenstern Price method

The Morgenstern-Price method is a robust and generalized Limit Equilibrium Method (LEM) for determining the Factor of Safety (FOS) for slope stability. It is widely used due to its ability to consider both force and moment equilibrium, making it suitable for complex slope geometries and failure mechanisms.

The method is predicated on the idea that a slope can be separated into multiple slices, each of which has a unique factor of safety over failure. guarantees the soil mass's force and moment equilibrium, yielding more precise findings than more straightforward LEM techniques. It can be applied to a variety of soil types and situations since it takes into account both vertical and horizontal inter-slice stresses and permits both circular and non-circular failure surfaces. By balancing forces and moments across all slices, the approach solves for the FOS using numerical iterations.

Key Features of Morgenstern-Price Method are Force and Moment Equilibrium, Inter-Slice Forces, Failure Surface, Iterative Solution.

Finite Element Method

The Finite Element Method is a numerical approach used to analyze the stability of slopes, embankments, and other geotechnical structures. Unlike traditional Limit Equilibrium Methods (LEM), FEM does not assume a predefined failure surface; instead, it simulates the development of failure naturally based on the material properties and stress-strain relationships.

FEM models the actual stress and strain distribution within the slope, providing a more realistic understanding of soil behavior. The Factor of Safety (FOS) is determined by dropping the soil's shear strength parameters (c and ϕ) until failure occurs. FEM can incorporate complex soil behaviors, such as plasticity, anisotropy, and consolidation and handles external loads, seepage, earthquake effects, and other dynamic factors.

Key Features are Stress-Strain Analysis, No Predefined Failure Surface, Strength Reduction Method (SRM), Material Nonlinearity, Advanced Loading Conditions.

1.6 RESEARCH OBJECTIVE

The objectives of this study involve,

- To evaluate the impact of soil type and properties (e.g., cohesion, angle of internal friction) on the performance of soil nailing in slope stabilization.
- To develop and validate numerical models to simulate the behavior of soil-nailed slopes under various conditions.
- Identify and quantify critical parameters such as nail length, diameter, spacing and inclination angle affecting slope stabilization.
- To perform experimental studies to compare field-scale observations with theoretical and numerical predictions for soil-nailed slopes.

CHAPTER 2

LITERATURE REVIEW

Prashant C Ramteke and Anil Kumar Sahu, (2024), in their study titled "Soil-Slope Stability Investigation Using Different Nail Inclinations: A Comprehensive LSD, FEM, and Experimental Approach," identified a nail inclination of 15° as optimal for maximizing the Factor of Safety and slope stability. This configuration ensured efficient load transfer and distribution, reducing slope failure risks. The findings highlighted soil nailing's adaptability and effectiveness, especially when combined with limit state design approaches.

Prashant C. Ramteke and Anil Kumar Sahu, (2024), in their work "Reliability Assessment of Soil Nailed Slopes under Surcharge Loading: A Numerical and Experimental Investigation with Theoretical Aspects," used 3D-FEM modeling and experimental validation to analyze slope stabilization techniques. The study highlighted grouted soil nails' ability to improve stability under surcharge loads, with optimal performance achieved at a 15° nail inclination.

Divya Jyothi Bathini1 and V Ramya Krishna, (2022), in their paper titled "Performance of Soil Nailing for Slope Stabilization—A Review," highlighted the efficiency of soil nailing as a modern slope stabilization method. The study described how soil nailing reinforces slopes by driving reinforcements into the soil, providing a cost-effective alternative to outdated retaining walls. Case studies demonstrated its success in stabilizing slopes and retaining vertical cuts, although the study noted that soil properties and precise design are critical to its performance.

Tausif E Elahi et al, (2022), in their study titled "Parametric Assessment of Soil Nailing on the Stability of Slopes Using Numerical Approach," found that the slope stability factor of safety declines with steeper slope and backslope angles. Optimal nail inclinations ranged from 0° to 25°, and the factor of safety (FS) increased with nail length, stabilizing when the ratio of nail length to height exceeded 0.9. The study concluded that longer nails reduced lateral movement, and maximum forces occurred in bottom nails, showing FS improvements of 29–75% with optimal parameters.

Mahmoud H. Mohamed et al, (2021), in their study titled "An Experimental Study of a Nailed Soil Slope: Effects of Surcharge Loading and Nails Characteristics," examined the effects of nail length, spacing, and orientation on soil-nailed slope stability. The study concluded that longer nails and steeper inclinations reduced stress and settlement, while tighter spacing minimized stress and enhanced stability.

Panyabot Kaothon et al, (2021), in their study titled "Numerical Evaluation on Steep Soil-Nailed Slopes Using Finite Element Method," evaluated the conventional design parameters for soil-nailed slopes, focusing on nail spacing and inclination across various slope angles using FEM. Results indicate that the standard recommendations (nail spacing: 1–2 m, nail inclination: 10º–20º) are suitable for slopes with angles of 45º and 55º. However, steeper slopes (65º and 75º) require smaller nail spacing (≤1.5 m), reduced inclination (5º–10º), and larger nail heads (minimum size: 400 × 400 × 250 mm) to maintain a factor of safety of at least 1.5.

Mohammad Farhad Ayazi et al, (2020), in their paper titled "Soil Nailing—A Review," emphasized the role of soil nailing in stabilizing slopes by enhancing shear strength and reducing deformation. The study pointed out that adherence to FHWA design standards and proper nail inclinations are critical for stability. Compared to traditional methods, soil nailing reduces costs by up to 30%, particularly for repairing old slopes.

A Sharma and R Ramkrishnan, (2020), in their paper titled "Parametric Optimization and Multi-regression Analysis for Soil Nailing Using Numerical Approaches" focuses on optimizing soil nailing by analyzing soil-nail interaction and pull-out strength using PLAXIS 2D and Limit Equilibrium Analysis. Findings show that pull-out strength varies with depth, allowing for optimization of nail length. Seismic stability was assessed with reduced nail lengths, showing slight increases in deformation but remaining within permissible limits. Regression analysis established correlations between geotechnical parameters, nail patterns, and stability conditions, supporting efficient soil nailing designs.

DA Mangnejo et al, (2019) conducted a study titled "Numerical Analysis of Soil Slope Stabilization by Soil Nailing Technique." They determined that the factor of safety of slopes improved meaningly with three rows of 40 mm diameter nails inclined at 40°. The Morgenstern-Price method confirmed the effectiveness of these configurations.

Shanmugapriya Dewedree and Siti Norafida Jusoh, (2019) in their research "Slope Stability Analysis under Different Soil Nailing Parameters Using the SLOPE/W Software," analyzed the effect of nail inclinations on stability using numerical modeling and a case study in Genting Highlands. They found that optimal inclinations varied by slope angle and that small changes in nail inclinations (5°–20°) marginally impacted the Factor of Safety. The study underscored soil nailing's effectiveness as a slope stabilization technique.

Enas B. Altalhe and Hana Abdalftah, (2019), in their paper titled "Study Using Nails in Sand Soil: Stability, Anchored Length," emphasized that optimal nail inclinations, adequate lengths, and tighter spacing improved stability. Finite element analysis demonstrated the effectiveness of longer nails in reducing deformation and preventing slope failure.

Surender Singh and A. K. Shrivastava, (2017), in their paper titled "Effect of Soil Nailing on Stability of Slopes," examined the performance of unreinforced and soil-nailed slopes under static loads. The study found that nails with a 0° inclination provided the best stability, while a staggered pattern was the most effective arrangement compared to square and diamond patterns. Stress and strain variations were measured based on nail position and inclination, revealing that soil-nailed slopes exhibited superior load-settlement behavior, emphasizing the importance of optimal design in soil nailing systems.

Shamsan Alsubal et al, (2017) in their paper "A Typical Design of Soil Nailing System for Stabilizing a Soil Slope: Case Study," identified optimal nail inclinations based on slope steepness. For instance, 50° nails were optimal for 30° slopes, 40° for 45°, 20° for 60°, 15° for 70°, and 10° nails suited 90° slopes. Stability decreases with increasing nail spacing, and longer nails are crucial for deep-seated slip surfaces. Validation on a real-case study slope confirmed the effectiveness of the optimal design parameters.

S. Rawat and A.K. Gupta, (2016), in their paper titled "An Experimental and Analytical Study of Slope Stability by Soil Nailing," examined unreinforced and soil-nailed slopes under cumulative surcharge loads. Using experimental testing and finite element modeling (PLAXIS 3D), the study analyzed sand slopes at 45° and 60° angles with nails inclined at 0°, 15°, and 30°. The 45° slope with 0° nail inclination demonstrated the highest load-bearing capacity, underscoring the efficiency of soil nailing in improving slope stability.

Ramin Ebrahimi and Adel Asakereh, (2016), in their paper titled "Parametric Evaluation of Soil Nailing Method in Slopes Stabilization," examined the effectiveness of soil nailing for slope stabilization. For a 10m slope at a 60° angle, the study found that nails inclined at 30° provided the highest stability. It emphasized optimal nail lengths (0.5–1 time the slope height) and discouraged spacing greater than 2m for technical and economic reasons.

Md. Akhtar Hossain and Ashraful Islam, (2016), in their paper titled "Numerical Analysis of the Effects of Soil Nail on Slope Stability," studied the influence of nail inclination on the factor of safety (FOS) for dry slopes using SLOPE/W and LE Method. The study observed an increase in FOS up to an optimal nail inclination of 30°, after which it decreased with further inclination, emphasizing the need for optimization.

Midhula Jayanandan and S. Chandrakaran, (2015), in their paper titled "Numerical Simulation of Soil Nailed Structures," analyzed soil-nailed slopes using PLAXIS 2D. The study focused on a 10m vertical cut of lateritic soil, finding that horizontal nails significantly improved stability by reducing lateral deformation by 41% and increasing the FoS by 1.2 times compared to unreinforced slopes.

Ali Fawaz et al, (2014), in their paper titled "Slope Stability Analysis Using Numerical Modeling," used PLAXIS software to analyze slope stability with soil parameters resulting from laboratory and in-situ tests. The research identifies the failure surface and evaluates the FOS, considering factors contributing to slope instability. Various reinforcement methods are assessed for their effectiveness in strengthening the slope and enhancing stability.

CHAPTER 3

MATERIAL AND METHODOLOGY

3.1 METHODOLOGY

The proposed methodology for this research are as follows:

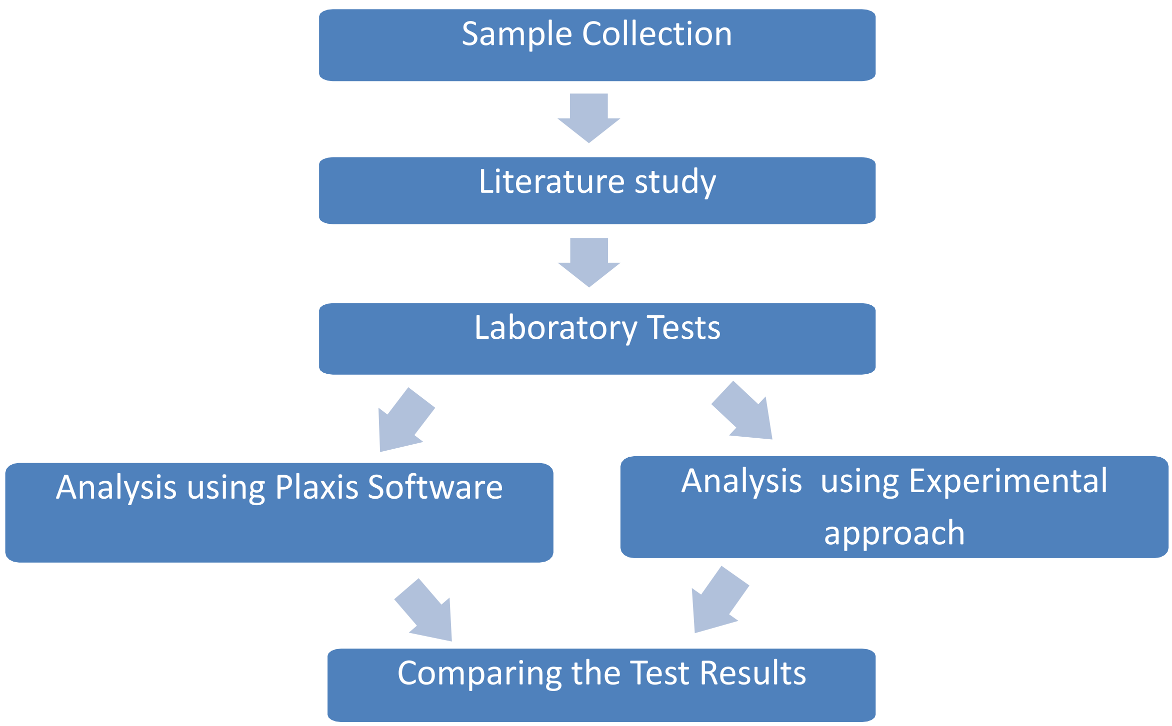


Figure 3.1: Proposed methodology for slope stability using soil nailing

3.2 MATERIAL USED

The materials which have been used in this experiment for backfill are collected from DTU and aluminium nails as soil nails. The following is a list of tests that were performed on certain materials in order to determine their engineering and index properties.

3.2.1 Tank

A tank of dimension 0.40m x 0.15m x 0.20m made of steel is used in experimental analysis.

Figure 3.2: Experimental Tank

3.2.2 Nails Used

Nails are used to stabilize the soil, Solid aluminium tubes are used as a strengthening material as they can produce strain and stabilize the soils. Dimensions of nails are finalized by doing software analysis at different length and different diameter and is of 6mm of diameter and of 80mm of length.

Figure 3.3: Nail used

3.2.3 Magnetic Dial Gauge

It is used to record the deformation produced after applying load statically.

3.3.3 Backfill Material

The materials which have been used in this experiment for backfill are collected from DTU ground. The following is a list of tests that were performed on certain materials in order to determine their engineering and index properties.

3.3 PROPERTIES OF SOIL

To assess the soil properties for ensuring the stability, safety and durability of the soil slopes. These tests help to determine the soil's load-bearing capacity and shear strength to guide the slope stability analysis.

The Sample used in this experiment was collected from DTU.

Some of the tests conducted are as follows:

- Classification Tests
    - Grain Size Analysis
    - Atterberg Limits: Liquid limit and plastic limit
- Physical properties
    - Moisture Content Test
    - Specific Gravity Test
- Compaction Test
    - Standard Proctor Test
- Shear Strength Tests
    - Direct Shear Test

Figure 3.4: Soil sample

3.3.1 Grain Size Analysis:

Grain size analysis is a method used to determine the size distribution of particles in soil, sediments, or aggregates. It helps in understanding the textural class of the material, which can influence properties like permeability, strength, and stability.

Main purpose of Grain size analysis is to identify whether soil is sand, silt, clay, or gravel. It helps in interpreting depositional environments, determines permeability and drainage properties and assesses suitability for foundations and other structures.

Sieve Analysis is done for the distribution of particles. Sieve Analysis involves passing soil through a stack of sieves with progressively smaller mesh sizes after that retained material is weighed to determine the percentage of each size fraction.

Figure 3.5: Sieve analysis arrangement

Figure 3.6: Particle Size

Parameters calculated are as:

- D_{10} (Effective size): Particle size at 10% finer, indicates drainage capacity.
- D_{30}: Particle size at 30% finer.
- D_{60}: Particle size at 60% finer, used to calculate uniformity coefficient (Cu) and gradation coefficient (Cc).

Table 3.1: Sieve analysis of soil

Seive size(mm)	Weight Retained (g)	Percentage % Weight Retained	Cumulative % Weight Retained	Passing percentage %
4.75	100.00	33.33	33.33	66.67
2.36	30.00	10.00	43.33	56.67
1.18	48.00	16.00	59.33	40.67
0.6	30.00	10.00	69.33	30.67
0.3	24.00	8.00	77.33	22.67
0.15	24.00	8.00	85.33	14.67
0.075	34.00	11.33	96.66	3.34
PAN	10.00	3.33	99.99	0.01

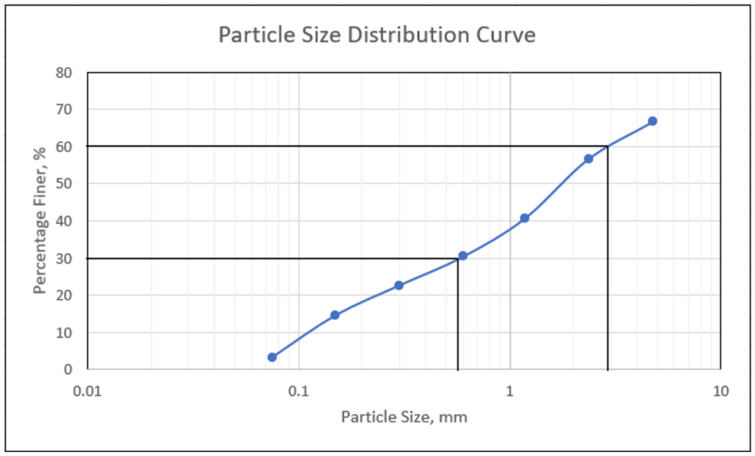


Figure 3.7: Particle Size Distribution of soil

From graph, we found,

D_{60} = 3.16mm, D_{30} = 0.6mm, D_{10} = 0.6mm

- Uniformity coefficient Cu = 26.33
- Coefficient of curvature Cc = 0.95

Cu > 6 and Cc does not lie between 1 and 3, so this sand is poorly graded.

3.3.2 Atterberg Limits

Liquid Limit (W_L)

The liquid limit is a fundamental property of fine-grained soils, representing the moisture content at which a soil changes from a plastic state to a liquid state. It represents the boundary where soil can flow under its own weight.

Main purpose is to determine the consistency and behavior of clayey soils and helps to predict soil strength, compressibility, and settlement.
Casagrande apparatus is used for finding out the liquid limit.

Figure 3.8: Liquid Limit

Table 3.2: Liquid limit of soil

Observation and Calculation				
Container Number	1	2	3	4
Weight of Container W_1, in g	20.42	24.28	21.37	20.18
Weight of Container and wet soil W_2, in g	39.58	40.14	36.1	38.24
Weight of Container and dry soil W_3, in g	35.32	36.43	32.46	33.52
Weight of water $(W_2 - W_3)$, in g	4.26	3.71	3.64	4.72
Weight of dry soil $(W_3 - W_1)$ in g	14.9	12.15	11.09	13.34
Moisture content (%) = $\frac{(W2 - W3)}{(W3 - W1)}$ x 100%	28.59	30.52	32.82	35.38
No. of blows	34	27	23	17

By Interpolation,

For 25 number of blows,

Water content = 31.69%

:. Liquid Limit = 31.69%

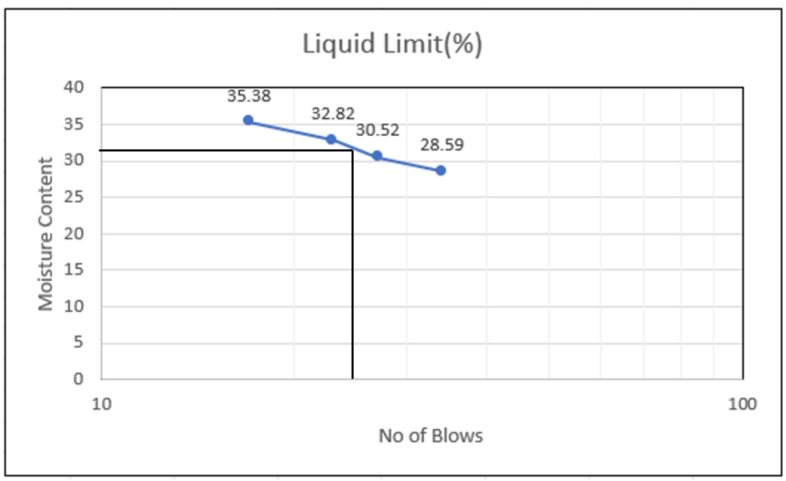


Figure 3.9: Variation of moisture content with no. of blows

With the help of graph, the Liquid Limit value is **31.69%**

Plastic limit (W_P)

The water content at which a soil transitions from a plastic to a semisolid form is known as the plastic limit.

It is the property of the soil which is defined as the minimum water content at which a soil will just begin to crumble when it is rolled into a thread of approximately to 3mm diameter.

Figure 3.10: Plastic Limit

Observation and calculation

Table 3.3: Plastic Limit

Sample No.	1	2
Weight of Container W_1, in g	23.10	21.86
Weight of Container and wet soil W_2, in g	32.29	34.74
Weight of Container and dry soil W_3, in g	31.20	32.51
Weight of water (W_2 –W_3), in g	1.09	2.23
Weight of dry soil (W_3 –W_1) in g	5.10	10.65
Moisture content (%) = $\frac{(W_2 - W_3)}{(W_3 - W_1)}$ x 100%	21.37	20.94

After calculating it the average plastic limit will be = $\frac{(21.37+20.94)}{2}$ **= 21.16%**

Plasticity Index (I_p):

The plasticity index (PI) is the range of water content over which a soil exhibits plastically. It is calculated as:

$$PI = LL - PL$$

$$I_p = W_l - W_p$$

$$= (31.69-21.16)\ \%$$

$$\therefore\ \mathbf{I_p = 10.53\%}$$

Through the A line and Plasticity index we find that the soil has Low plasticity.

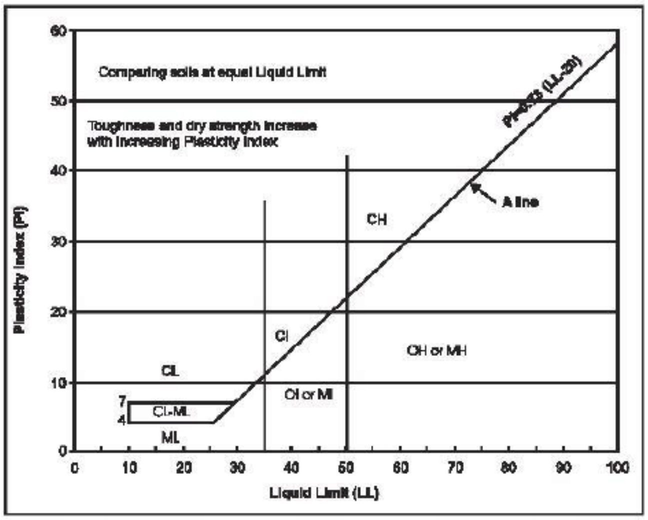


Figure 3.11: Plasticity Chart

3.3.3 Moisture Content Test

Moisture content is the amount of water present in a soil or material, expressed as a percentage of the dry weight. It is a critical property in soil mechanics, agriculture, and material science, as it affects the strength, compaction, and behavior of soil.

Many methods of determining moisture content are oven dry method (105°C – 110°C), calcium carbide method, Torsion balance and electronic moisture meters.

Moisture Content of this soil from moisture meter is found to be **8.97%**

3.3.4 Specific Gravity Test

Specific gravity is used for soil classification, to calculate various soil properties like void ratio and porosity., It is the ratio of the weight of soil solids to the weight of an equal volume of water. It is beneficial in computing the unit weight of the soil under different conditions and also in the determination of particle size by wet analysis.

Pycnometer is used to determine specific gravity of soil sample.

(a) (b) (c) (d)

Figure 3.12: Specific Gravity

Calculations

The specific gravity (G) is calculated using the formula:

$$\text{Specific gravity of soil } (\mathbf{G}) = \frac{(W_2 - W_1)}{(W_4 - W_1) - (W_3 - W_2)}$$

Where:

W_1 = Weight of empty pycnometer.

W_2= Weight of pycnometer with soil

W_3 = Weight of pycnometer with soil and water

W_4 = Weight of pycnometer with water only

Table 3.4: Specific Gravity

Weight (g)	Sample 1	Sample 2	Sample 3
W_1	688	688	688
W_2	886	886	888
W_3	1676	1672	1670
W_4	1556	1556	1556
G	2.538	2.415	2.325

Sample calculation

For sample 1: $G = \frac{(886-688)}{(1556-688)-(1676-886)} = 2.538$

Average value of specific gravity is **2.43** at room temperature.

3.3.5 Standard Proctor Test

Compaction is the process of mechanically rearranging and packing soil particles into a closer state of contact in order to reduce the soil's porosity (or voids ratio) and, as a result, increase the dry density of the soil mass by rapidly and dynamically expelling the air that is present in the voids. The density of the compacted soil mainly depends upon its water content, compactive effort, type of soil and admixtures.

The primary objective of a laboratory compaction test is to find the ideal water content-also known as the maximum dry density (MDD) and optimal moisture content (OMC)-at which the weight of the soil grains in a unit volume of the compacted material is at its highest.

Observations

- Diameter of mould = 10.2 cm
- Height of mould = 11.8 cm
- Volume of mould = 964.21 cm^3
- Empty weight of mould (W_1) = 4184 g
- Weight of rammer = 2.6 kg

Calculations

- Bulk Density, $\gamma_b = \frac{(W_2 - W_1)}{\text{Volume}}$ g/cc
- Dry Density, $\gamma_d = \frac{\gamma_b}{(1+W)}$ g/cc

Where,

W_1 = Weight of mould

W_2 = Weight of compacted soil + mould

W = Moisture content

Table 3.5: Standard Proctor Test

S.No.	Weight of mould (Kg), W_1	Weight of compacted soil + mould (Kg), W_2	Volume of mould (cm^3)	Water added (%), W	Bulk density (g/cc), γ_b	Moisture content (%)	Dry density (g/cc), γ_d
1	4.184	5.880	964.21	0	1.759	8.97	1.614
2	4.184	6.110	964.21	4	1.997	10.12	1.813
3	4.184	6.120	964.21	8	2.008	13.12	1.775
4	4.184	6.042	964.21	12	1.930	16.45	1.657
5	4.184	6.220	964.21	16	1.875	19.12	1.574

So, from the above table we obtain,

Max. dry density = 18.13 KN/m^3

Optimum moisture content = 10.12 %

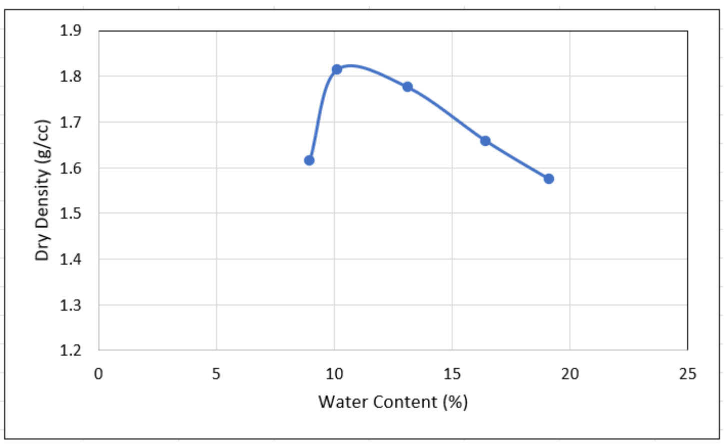
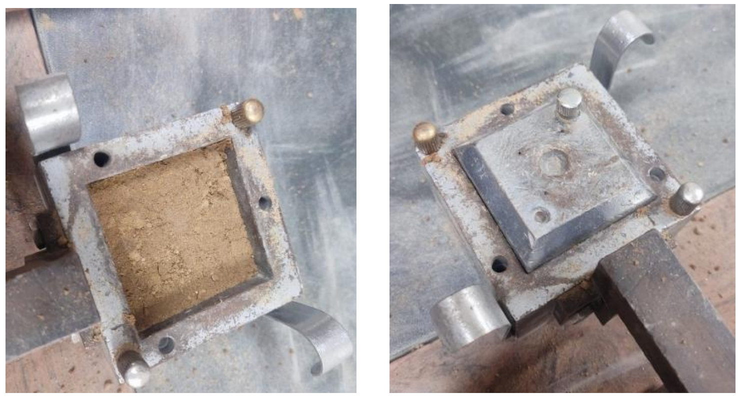


Figure 3.13: Variation of Dry Density with Water Content

3.3.6 Direct Shear Test

Direct shear test is widely used in geotechnical engineering to evaluate the stability of slopes, retaining walls, and foundations. It helps in determining the soil's resistance to shearing forces, assesses the likelihood of slope failure, ensures adequate shear strength for bearing capacity and evaluates lateral earth pressure.

Direct Shear Test is a laboratory process used to determine the shear strength parameters of soil, as well as the **cohesion (c)** and **angle of internal friction (ϕ)**.



(a) (b)

Figure 3.14: Direct Shear Test

Calculations

The shear strength (τ) of soil is calculated using **Mohr- Coulomb's Law**:

$$\tau = c + \sigma \tan\phi$$

Where,

τ = Shear strength

c = Cohesion (intercept on the y-axis)

σ = Normal stress

ϕ = Angle of internal friction (slope of the line)

Table 3.6: Direct Shear Test

S.No.	Normal Stress (KN/m^2)	Max. Shear Stress (KN/m^2)
1	0.5	2.948
2	1	3.698
3	1.5	3.715

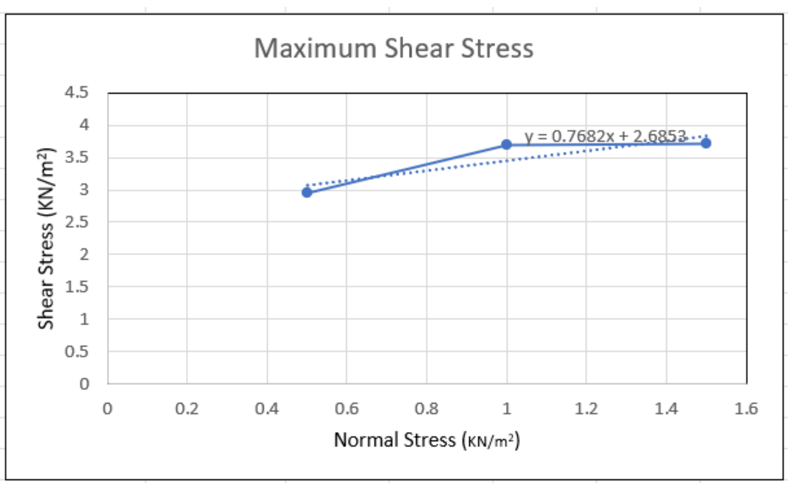


Figure 3.15: Variation of Shear Stress with Normal Stress

From the above graph,

cohesion (c) = 2.685 KN/m^2

Angle of internal friction (φ) = 37.59°

3.4 RESULT

The below table shows the properties of soil obtained from lab test.

Table 3.7: Properties of Soil

Properties		Test Result
Grain Size Analysis	Uniformity coefficient, Cu	26.33
	Coefficient of curvature, Cc	0.95
Atterberg Limits	Liquid Limit, LL	31.69%
	Plastic Limit, PL	21.16%
	Plasticity Index, PI	10.53%
Moisture Content		8.97%
Specific Gravity		2.43
Standard Proctor Test	Max. dry density	18.13 KN/m^3
	Optimum moisture content	10.12 %
Direct Shear Test	Cohesion, c (kPa)	2.685 KN/m^2
	Angle of internal friction, (φ)	37.59°
Type of soil	Poorly Graded Sand with Low Plasticity SP-ML	

CHAPTER 4

ANALYTICAL STUDY TO FIND FACTOR OF SAFETY USING PLAXIS SOFTWARE

4.1 GENERAL

Plaxis is a powerful software widely used for geotechnical engineering analysis. One of its key modules is designed for slope stability analysis, enabling engineers to determine the Factor of Safety (FOS) for various slope configurations.

In this study, a 2D geometry model was settled with a total height of 20 meters and a width of 40 meters. The slope itself has a height of 12 meters. The length of the slope crest varies depending on the slope angle: for a 30° slope, the crest length is 8 meters; for a 45° slope, it is 12 meters; and for a 60° slope, the crest length increases to 18 meters.The slope models were examined using the Mohr-Coulomb failure criterion, incorporating soil parameters such as cohesion and the angle of internal friction, which were determined from preliminary soil tests.

Three different slope angles—30°, 45°, and 60°—were inspected to find the suitable slope angle. For that angle, nail inclinations of 0°, 10°, 20°, and 30° with respect to the horizontal were evaluated, along with varying nail lengths of 6 m, 8 m, 10 m, and 12 m. Both unreinforced and reinforced slope conditions were assessed and identify the most effective slope and nail configuration.

4.2 NUMERICAL MODELLING

4.2.1 Geometry of the model:

The geometry of the slope model was carefully defined to simulate realistic site conditions for slope stability analysis. The overall dimensions of the model were set to 40 meters in width and 20 meters in height. Within this model, the slope itself was designed with a height of 12 meters. The crest length of the slope at 45° slope produced of 12m. The geometry was developed in 2D using Plaxis software, ensuring accuracy and compatibility with the chosen analysis methods. Figure below illustrates the typical cross-section of the slope model used in the analysis.

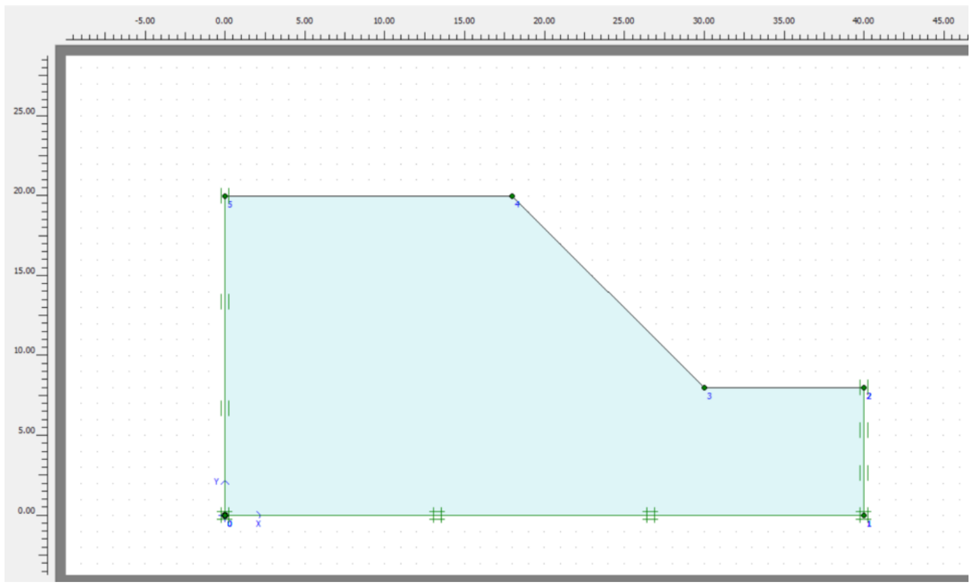


Figure 4.1: Geometry of the model

4.2.2 Parameters Input:

The analysis used the Mohr-Coulomb soil model with key input parameters including unit weight, cohesion, angle of internal friction, and Poisson's ratio. Soil properties were derived from laboratory tests. Appropriate boundary conditions and mesh refinement were applied to ensure accurate simulation results.

Nail used as an elastoplastic material of length 6 m, 8 m, 10 m, and 12 m at an inclination angles of 0°, 10°, 20°, 30° with horizontal, and diameter 6 mm were defined.

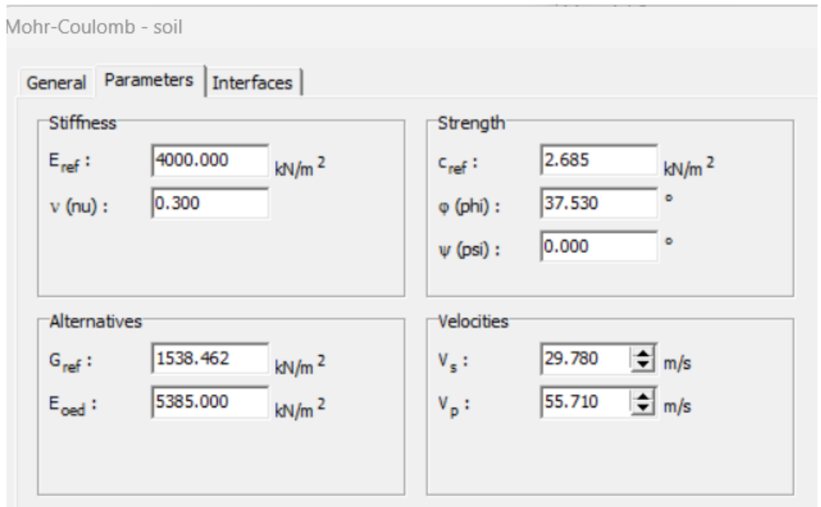


Figure 4.2: Parameters Input

4.2.3 Mesh Generated

A finite element mesh was generated in Plaxis to discretize the model domain for analysis. The mesh consisted of triangular elements, with finer refinement applied around the slope face and reinforcement zones to capture stress concentration and deformation behavior accurately. Global coarseness was set to medium, ensuring a balance between computational efficiency and result accuracy. Mesh quality was checked to avoid distorted elements that could affect the reliability of the simulation.

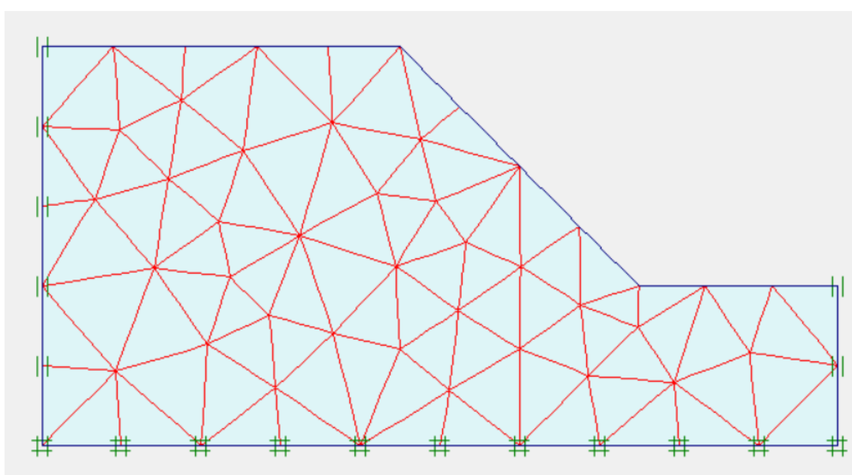
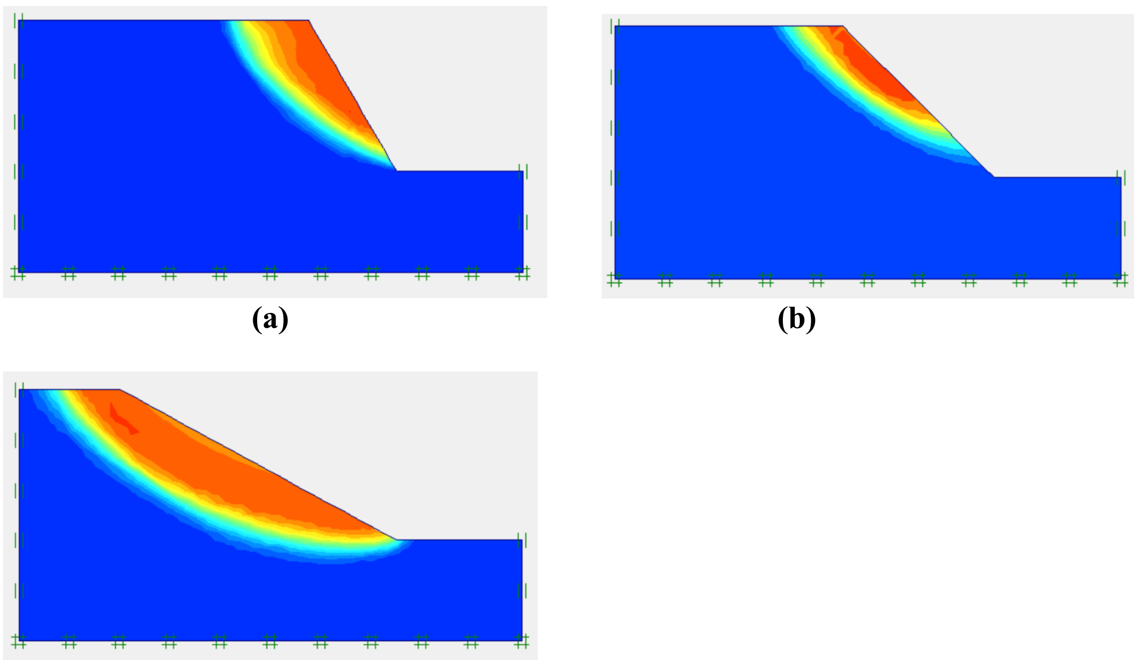


Figure 4.3: Model with mesh

4.3 RESULTS FROM SOFTWARE ANALYSIS

The models were initially analyzed to determine the optimum slope angle. Slope angles of 30°, 45°, and 60° were modeled, and the corresponding Factors of Safety (FOS) were calculated to assess their stability.



(a) **(b)**

(c)

Figure 4.4: Numerical model slope inclinations: (a) 30°, (b) 45°, and (c) 60°

Table 4.1: Fos estimated for different angles of slope

Slope Angle (°)	Factor of Safety
30	1.605
45	1.276
60	0.991

It was observed that the Factor of Safety (FOS) decreases with an increase in slope angle. Although a slope angle of 30° yielded an FOS greater than 1.5, indicating stability, further experimental analysis was conducted on the 45° slope to improve its stability. Based on the results, a slope angle of 45° was found to be optimal for reinforced conditions.

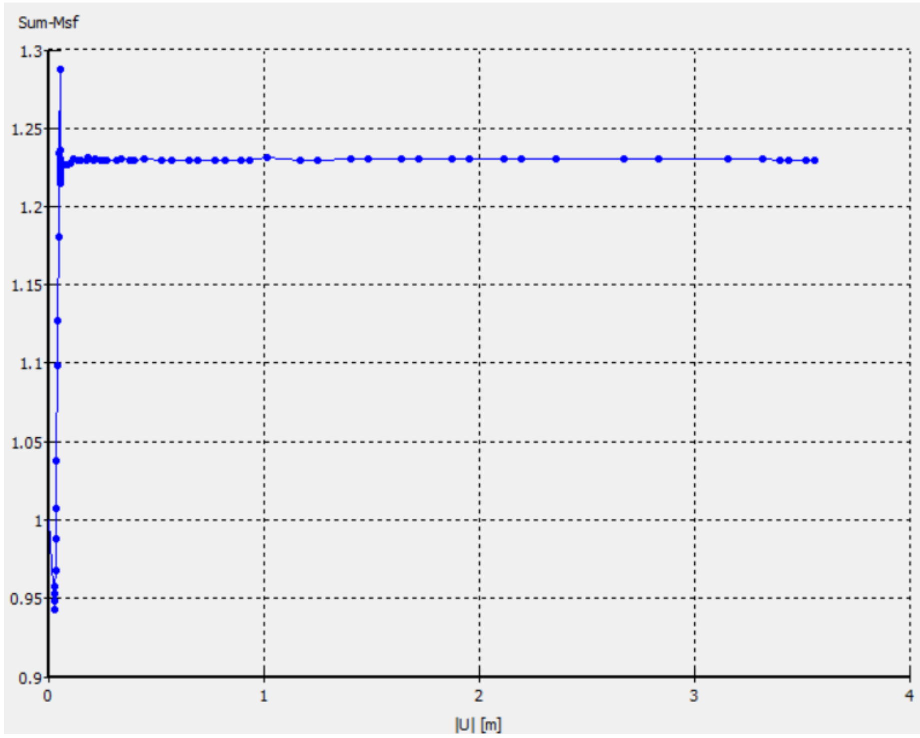


Figure 4.5: FOS Graph of soil slope at 45°

The graph represents the stability of the soils. X-axis denotes the deformationand Y-axis represents the sum of modified forces. As the displacement increases, the sum-Msf values stabilize at 1.23 and remain mostly constant indicating that it reaches maximum FOS.

4.4 REINFORCED GEOMETRY RESULTS

The reinforcement was modeled using soil nails of varying geometries to evaluate their effect on slope stability. Nail lengths of 6 m, 8 m, 10 m, and 12 m were used, with inclinations of 0°, 10°, 20°, and 30° from the horizontal. All nails had a uniform diameter of 6 mm. These configurations were tested to identify the most effective combination for maximizing the Factor of Safety. The best performance was achieved with a nail length of 8 m and an inclination angle of 10°, which provided the highest slope stability. The below table represents the FOS calculated at different nail inclination using various nail length.

Table 4.2: Factor of safety estimated for different angles of slope

Nail Length	**Nail Inclination**			
	0°	**10°**	**20°**	**30°**
6m	1.239	1.347	1.268	1.273
8m	1.254	1.539	1.327	1.224
10m	1.236	1.345	1.316	1.356
12m	1.237	1.295	1.217	1.219

The results indicate that both nail length and inclination significantly influence slope stability. The highest FOS of 1.539 was achieved with a nail length of 8 m and an inclination of 10°, identifying this as the most effective configuration for slope reinforcement.

4.4.1 Test Results for Varoius nail length at different nail inclination:

The Factor of Safety (FOS) was evaluated for various combinations of nail lengths and inclinations. The results are summarized in the table below:

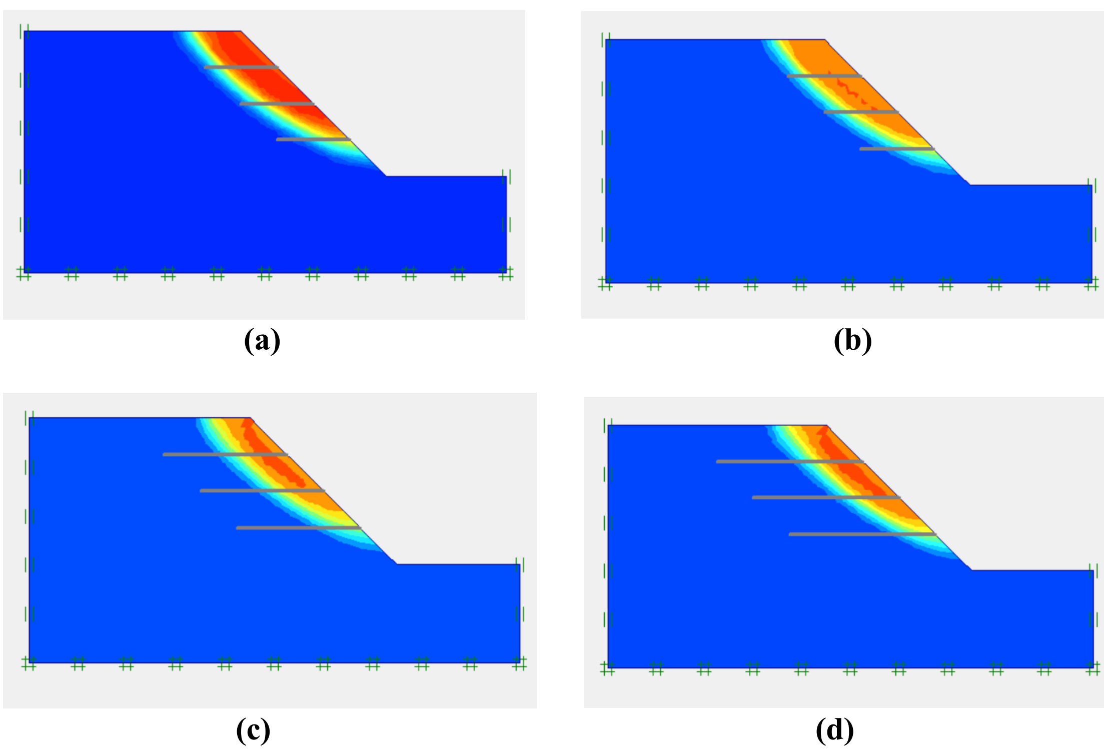
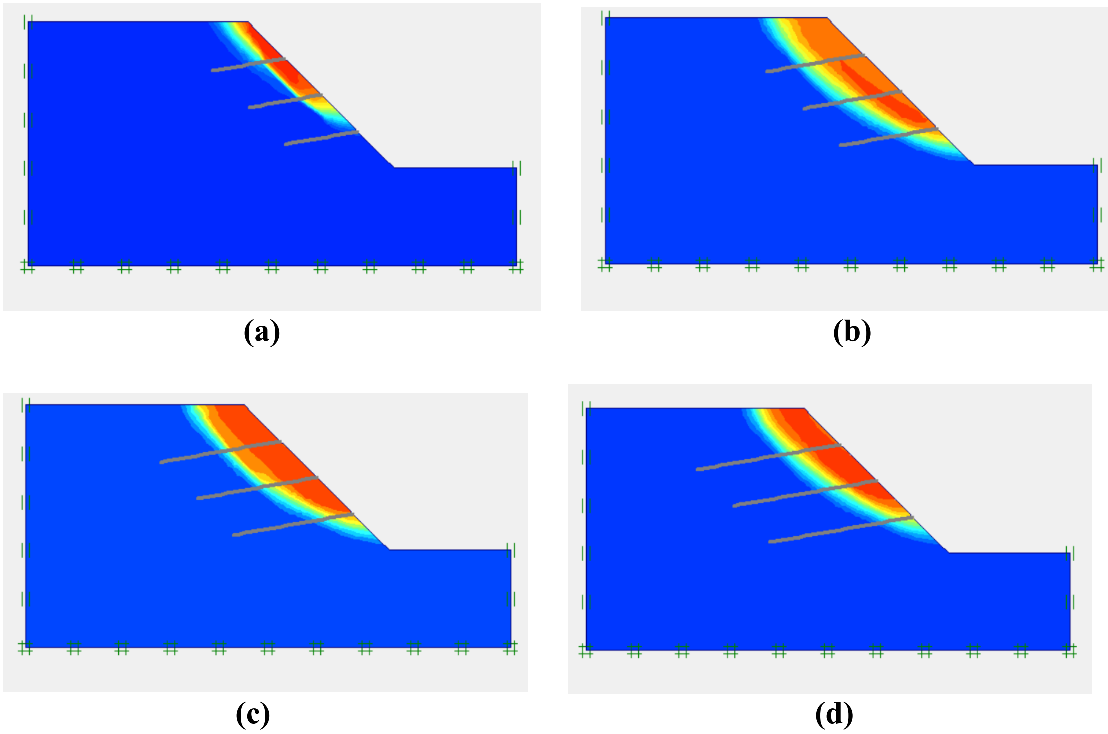


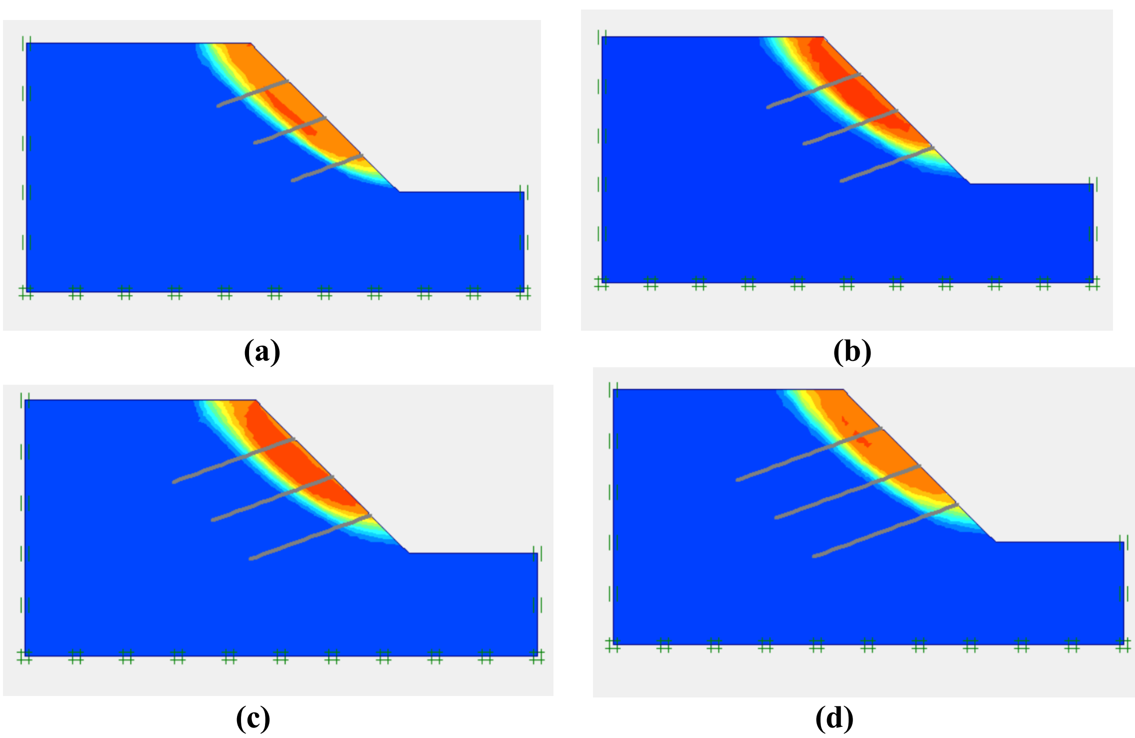
Figure 4.6: Nail inclination: 0° with horizontal, with varying nail length: (a) 6m, (b) 8m, (c) 10m and (d) 12m.



(a) (b)

(c) (d)

Figure 4.7: Nail inclination: 10° with horizontal, with varying nail length: (a) 6m, (b) 8m, (c) 10m and (d) 12m.



(a) (b)

(c) (d)

Figure 4.8: Nail inclination: 20° with horizontal, with varying nail length: (a) 6m, (b) 8m, (c) 10m and (d) 12m.

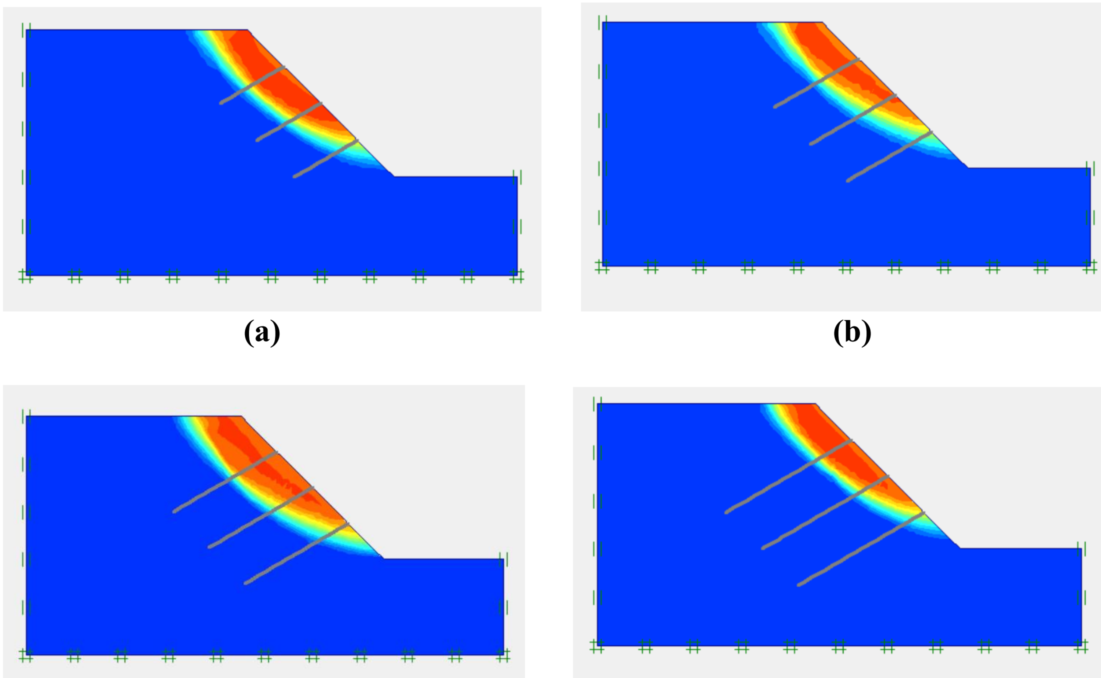


Figure 4.9: Nail inclination: 30° with horizontal, with varying nail length: (a) 6m, (b) 8m, (c) 10m and (d) 12m.

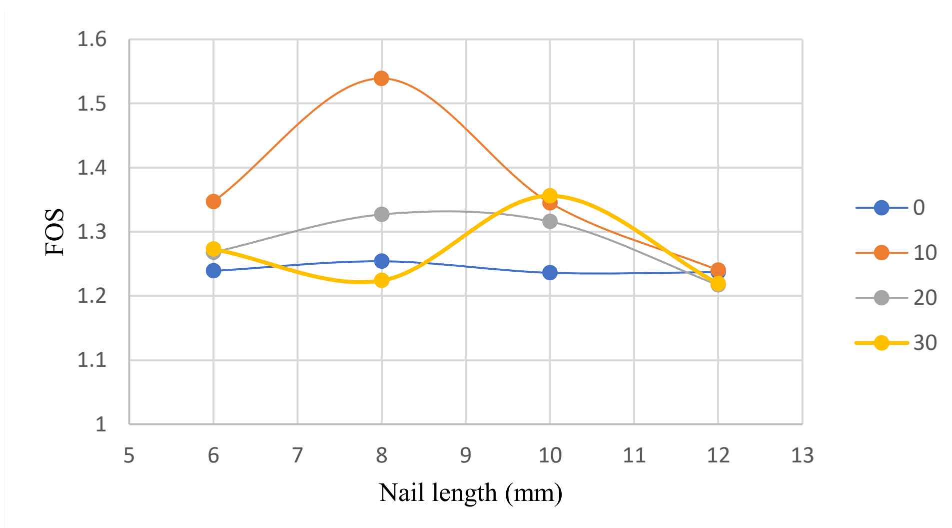


Figure 4.10: Variation of FOS with different nail length

4.4.2 Analysis at optimum nail parameters

The reinforcement was modeled using soil nails based on the optimum parameters identified through numerical analysis. A nail length of 8 m and an inclination angle of 10° with respect to the horizontal were found to be the most effective configuration. All nails used in the analysis had a uniform diameter of 6 mm. The figures below illustrate the reinforced slope geometry, the generated finite element mesh, test results, and the graphical representation of the Factor of Safety (FOS) for the reinforced model. These visuals collectively demonstrate the enhanced stability achieved through optimal soil nailing design.

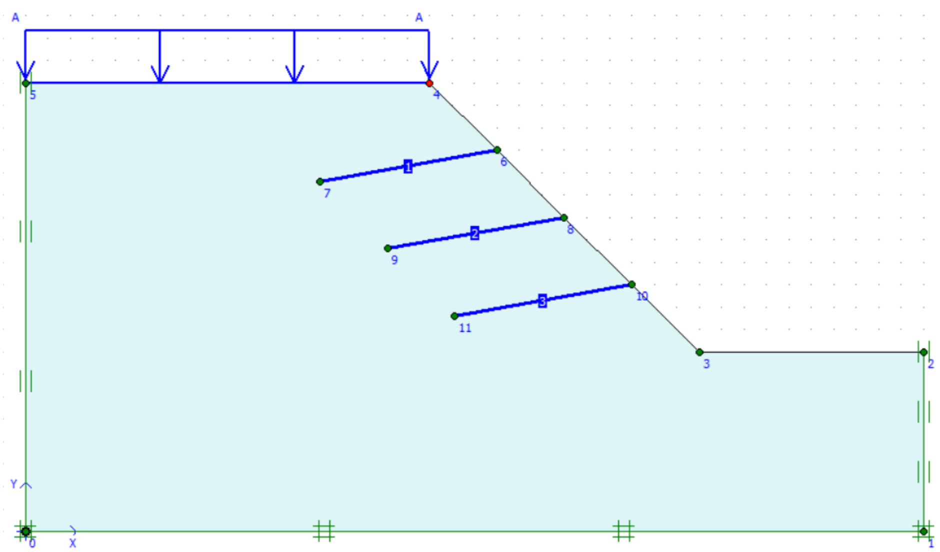


Figure 4.11: Geometry of the reinforced model

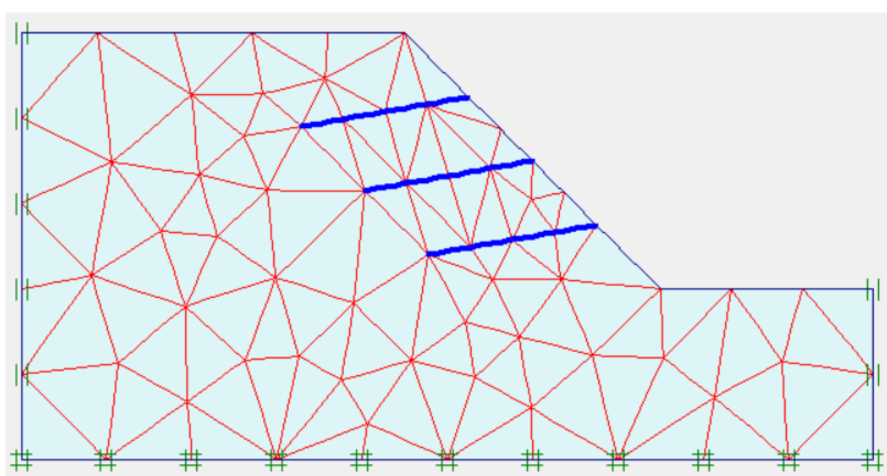


Figure 4.12: Reinforced Model with mesh

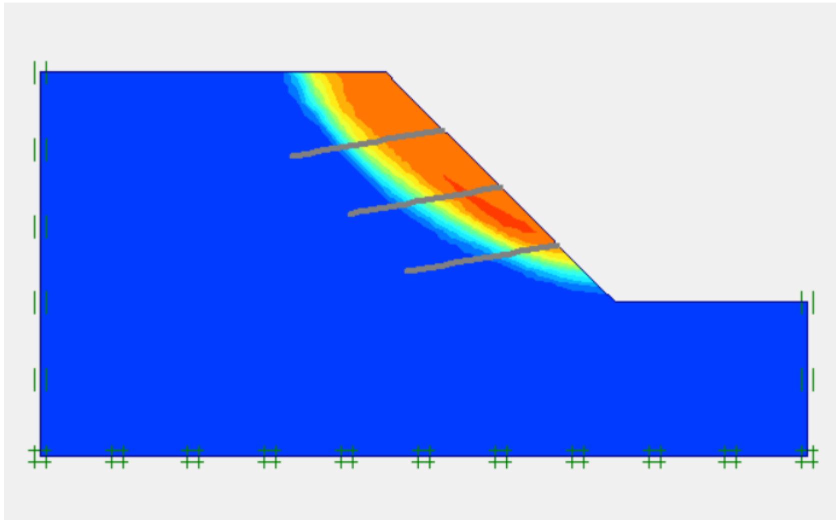


Figure 4.13: Test Result of Reinforced model

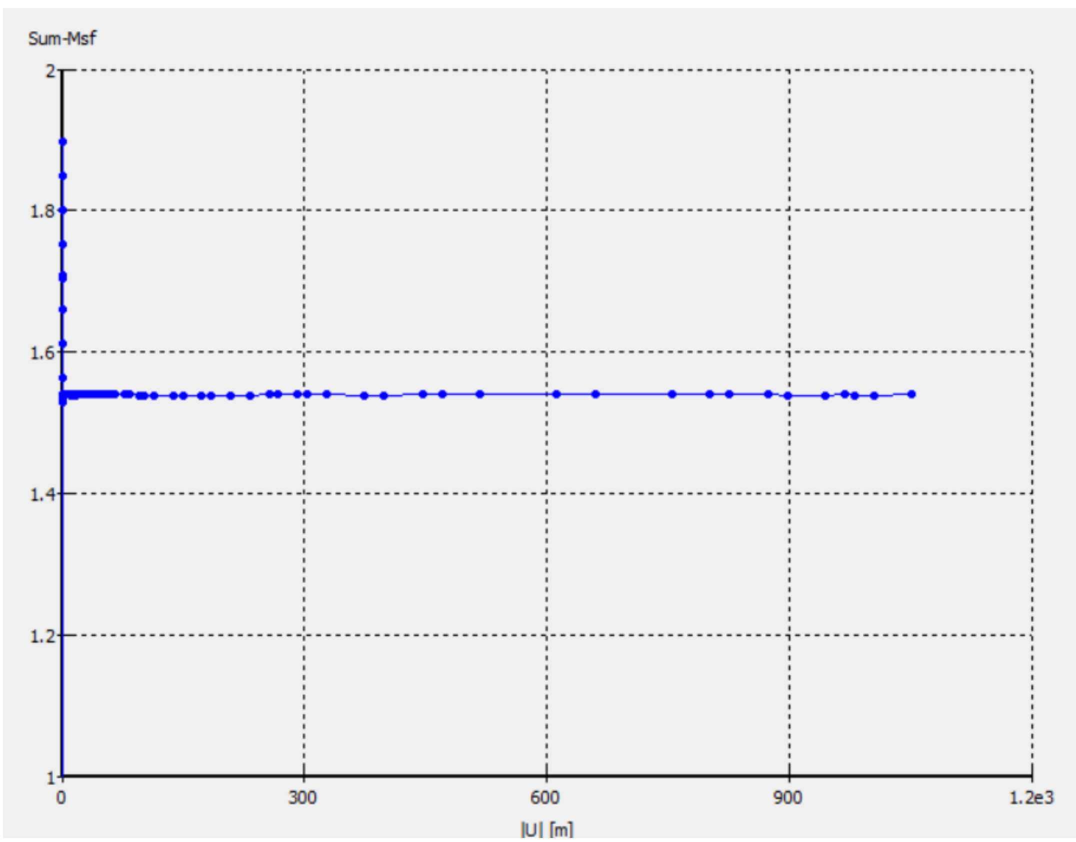


Figure 4.14: FOS Graph with nail parameters

CHAPTER 5

EXPERIMENTAL ANALYSIS FOR VALIDATION

5.1 MODEL PREPARATION

A soil sample collected from the DTU ground at Optimum Moisture Content was used to construct a physical slope model with the optimum slope angle of 45°, as determined from the PLAXIS software analysis. The test tank dimensions were 0.40 m (length) × 0.15 m (width) × 0.20 m (height). The slope height was 0.12 m, measured from the base to the crest. The horizontal distance at the crest was approximately 0.18 m, while the distance from the toe to the base of the slope was about 0.10 m.

The soil was placed in the tank in layers, compacted to ensure uniform density, and filled up to the required height. The sloped surface was then formed by carefully trimming the compacted soil to match the desired slope angle. This physical model was used to observe and assess slope failure mechanisms under controlled conditions.

(a) **(b)**

Figure 5.1: Unreinforced Experimental setup

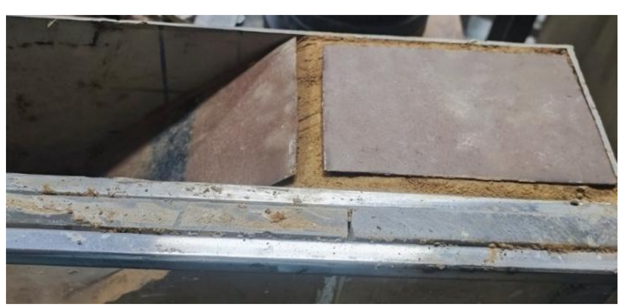


Figure 5.2: Model with Bearing plate

After the slope was prepared, bearing plates were placed on the crest and along the length of the slope to simulate loading conditions. Digital magnetic dial gauges were positioned on the crest and near the sloped surface of a small-scale soil model inside a rectangular tank to measure the deformation of the slope in response to loading. Two digital dial gauges are in contact with the soil surface, used to record vertical settlement and horizontal displacement during loading. Static loads were applied incrementally, and the resulting deformations were carefully recorded using the dial gauges. This setup allowed for a detailed observation of slope behavior and failure mechanisms under load.

Figure 5.3: Deformation measuring

5.2 NAIL INSTALLATION

For the reinforced slope, nails were inserted at a spacing of 0.035 m along the width and 0.045 m along the length of the slope. The nails were arranged in both rectangular and staggered patterns to evaluate the effectiveness of different reinforcement layouts.

Figure 5.4: Aluminium solid tubes of 0.08m inserted at 10° to horizontal plane

5.3 RESULTS AND OBSERVATIONS

To evaluate the effectiveness of soil nailing in enhancing slope stability, a series of controlled laboratory tests were conducted on a 45° slope model under both unreinforced and reinforced conditions. Incremental static loads were applied at the crest of the slope, and corresponding horizontal and vertical deformations were recorded using digital dial gauges. The observed changes in slope angle (Δθ) were calculated from the displacement measurements to better understand the deformation behavior of the slope under loading.

The following table presents the recorded values of load, horizontal and vertical settlements, and the computed change in slope angle (Δθ) for both unreinforced and reinforced conditions.

Table 5.1: Observation table for load and settlement for with and without reinforcement

Load (N)	Settlement without reinforcement		Change in angle	Settlement with reinforcement		Change in angle
	Horizontal (mm)	Vertical (mm)	Δθ (deg)	Horizontal (mm)	Vertical (mm)	Δθ (deg)
16.63	0	0				
38.83	0.07	0.07	45			
66.58	0.58	0.34	30.37	0.04	0.05	51.34
101.70	1.82	1.76	44.73	0.18	0.16	41.89
171.15	2.24	2.16	43.66	0.82	0.81	44.77
240.60	2.80	2.51	41.25	1.19	1.11	43.05
309.97	3.12	3.15	45.29	1.73	1.75	45.39
351.47	3.57	3.38	43.37	2.09	2.02	43.45
393.00	4.24	4.41	46.75	2.46	2.16	41.09
434.66				2.79	2.76	44.77
476.28				3.12	3.07	44.60
504.02						

The table presented is for slope without reinforcement and for slope with reinforcement for staggered pattern. From the table below we can clearly see that The failure load for unreinforced slope is 434.66N and for reinforced slope is 504.02N. The change is angle is also found out by measuring both horizontal and vertical deformation.

Change in Length

Slope length L=180 mm

Formula:

$$\Delta\theta = \tan^{-1}(\frac{\Delta y}{\Delta x}) \text{ (in radians)} \tag{4.1}$$

$$\Delta\theta^{\circ} = \Delta\theta \times \frac{180}{\pi} \ (180\pi)$$

Where,

Δy = Vertical Displacement

Δx = Horizontal Displacement

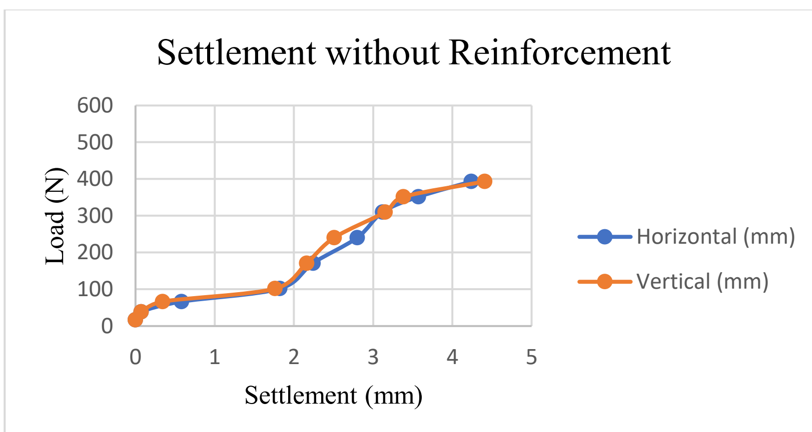


Figure 5.5: Load vs settlement curve for without reinforcement slope

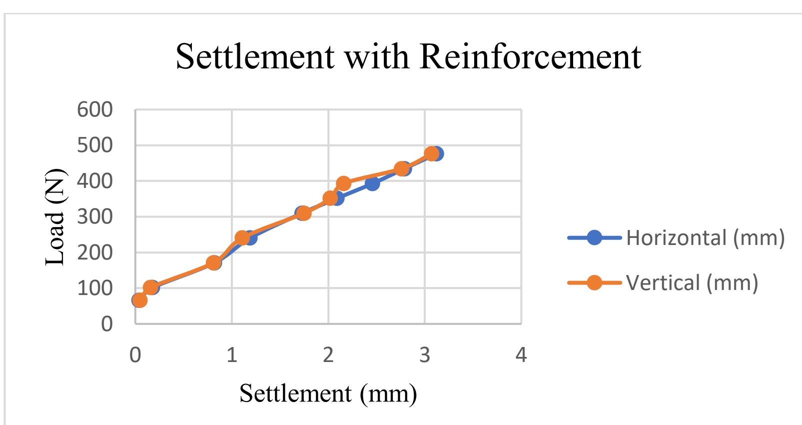


Figure 5.6: Load vs settlement curve for with reinforcement slope

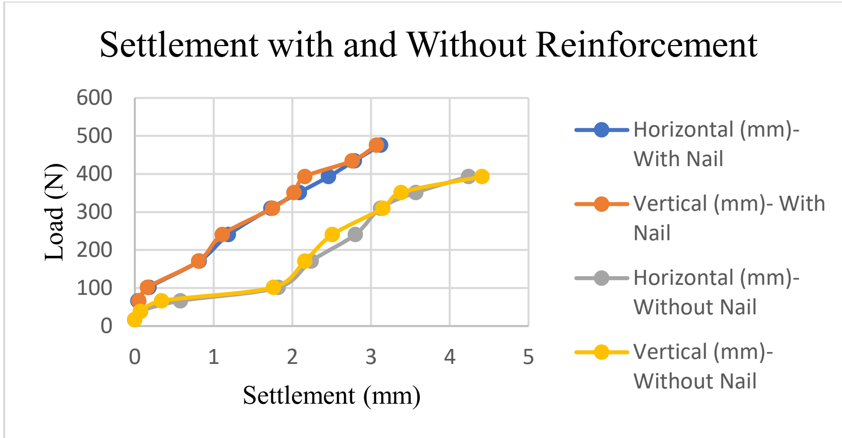


Figure 5.7: Combined Load vs settlement curve

From the above graph it is clear that soil slope in which nails are installed are more stable and can sustained the maximum load before failure.

5.4 COMPARISON OF NAIL ARRANGEMENT PATTERNS

The two different soil nail arrangement patterns used in the experimental shows the rectangular nail pattern, where nails are placed in a grid layout with uniform spacing in both vertical and horizontal directions. In contrast staggered (triangular) nail pattern, where nails are alternated in adjacent rows to form a triangular arrangement. This configuration is intended to provide better coverage and improved resistance to shear deformation by distributing the reinforcing effect more effectively throughout the slope mass. These patterns were evaluated to compare their impact on slope deformation and stability under applied loads.

Figure 5.8: Rectangular Nail Pattern

Figure 5.9: Staggered (Triangular) Nail Pattern

Table 5.2: For both nail pattern (horizontal deformation)

Load (N)	Triangular pattern (mm)	Rectangular pattern (mm)
16.63	0.00	0.00
38.83	0.00	0.01
66.58	0.04	0.79
101.70	0.18	1.02
171.15	0.82	1.14
240.60	1.19	1.78
309.97	1.73	2.19
351.47	2.09	2.24
393.00	2.46	2.80
434.66	2.79	3.16
476.28	3.12	3.46
504.02		

To assess the influence of nail arrangement on slope deformation, horizontal displacement was recorded for both rectangular and staggered (triangular) nail patterns under incrementally static applied loads. The results clearly show that the triangular pattern consistently exhibits lower horizontal deformation than the rectangular pattern, indicating improved slope stability.

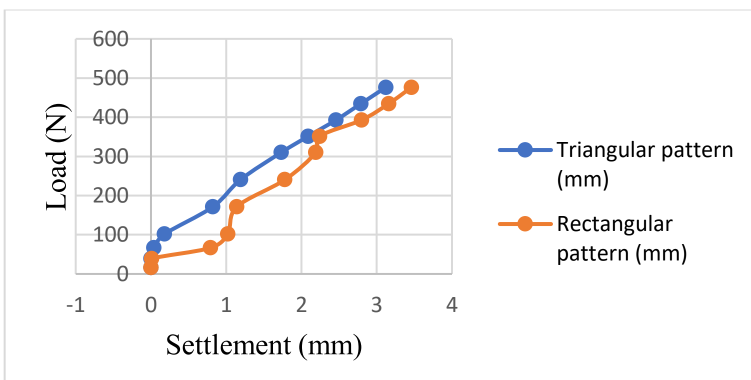


Figure 5.10: Load vs settlement curve for both nail pattern

From the above graph it is clear that soil slope in which nails are installed with triangular pattern are more stable.

5.5 CALCULATION OF FACTOR OF SAFETY

5.5.1 For Unreinforced slope

Culmann's approach is used to compute the factor of safety for an unreinforced slope. A planar failure surface that passes through the slope's toe was examined by Culmann (1866) as a failure mechanism for a slope of uniform soil.

Calculated Data:

- Cohesion, c = 2.685 kPa
- Friction angle, $\phi = 37.53°$
- Slope angle, $\beta = 45°$
- Tank dimensions:
  - Length = 40 cm = 0.40 m
  - Height = 20 cm = 0.20 m
  - Width = 15 cm = 0.15 m
- Soil unit weight, $\gamma = 18\ kN/m^3 = 18000\ N/m^3$
- Applied Load: W = 44.308 kg

$$= 44.308 \times 9.81$$

$$= 434.66\ N = 0.4347\ kN$$

We Know,

$$FoS = \frac{R}{T}$$

Where:

- R: Resisting force (shear strength along failure surface)
- T: Driving force (weight and surcharge components driving failure)

Determining the Critical Failure Plane

Culmann's method assumes the most likely failure surface occurs at:

$$\theta = 45° + \frac{\phi}{2}$$

$$= 45° + \frac{37.53°}{2}$$

$$= 63.765°$$

The difference between the failure plane and slope face:

$$\theta - \beta = 63.765° - 45°$$
$$= 18.765°$$

Calculating the Wedge Area and Self-Weight

$$\cot(18.765°) = \frac{1}{\tan(18.765°)} \approx 2.958$$

$$\text{Area of wedge} = \frac{1}{2} \times (0.2)^2 \times 2.958$$
$$= 0.05916 \text{ m}^2$$

Self-weight of slope wedge = 0.05916 ×18

=1.065 kN

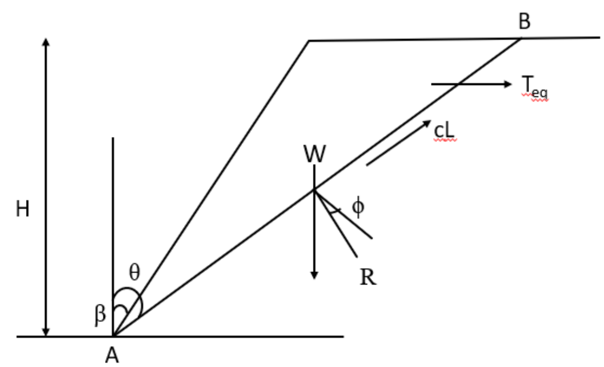


Figure 5.11: Unreinforced soil slope

Total weight

$$W_{total} = 1.065 + 0.4347$$
$$= 1.4997 \text{ kN}$$

Driving Force Along the Failure Plane

Driving force:

$$T = W \cdot \sin(\theta)$$

$\theta = 63.765°$

$\sin(63.765°) \approx 0.8957$

$$T = W \cdot \sin(63.765°)$$
$$= 1.4997 \text{ x } 0.8957$$
$$= 1.3433 \text{ KN}$$

Resisting Force Along the Failure Plane

Resisting force:

$$R = c \cdot L + W \cdot \cos(\theta) \cdot \tan(\phi)$$

C = 2.685 kPa

Length of failure surface, L:

$\sin(18.765°) \approx 0.322$

$$L = \frac{0.2}{\sin(18.765°)} = 0.6217 \text{ m}$$

cos(63.765°) ≈ 0.444

tan(37.53°) ≈ 0.768

W = 1.4997 kN

Total resisting force R = (2.685 × 0.6217) + (1.4997 × 0.444 × 0.768)

= 1.669 + 0.511

= 2.18 kN

Factor of Safety

$$\text{FoS} = \frac{R}{T}$$

$$= \frac{2.18}{1.3433}$$

= 1.622

Therefore, Calculated Factor of Safety for unreinforced slope is **1.62**

5.5.2 For reinforced slope

For the reinforced slope where nails are positioned at a 10° angle to the horizontal plane, the factor of safety is computed.

Calculated Data:

- Cohesion, c = 2.685 kPa
- Friction angle, ϕ = 37.53°
- Slope angle, β = 45°
- Tank dimensions:
  - Length = 40 cm = 0.40 m
  - Height = 20 cm = 0.20 m
  - Width = 15 cm = 0.15 m
- Soil unit weight, γ = 18 kN/m^3 =18000 N/m^3
- Applied Load: W = 51.378 kg

  = 51.378 × 9.81

  = 504.01 N = 0.5040 kN
- Number of nails = 6
- Diameter of nail, d = 6mm = 0.006m
- Length of nail, l = 0.08m

- Horizontal spacing of nails, S_h = 0.045m
- Overburden pressure at nail depth, $\sigma_v = \gamma$ x Height

$$= 18 \times 0.2$$

$$= 3.6 \text{ kPa}$$

Determining the Critical Failure Plane

Culmann's method assumes the most likely failure surface occurs at:

$$\theta = 45° + \frac{\phi}{2}$$

$$= 45° + \frac{37.53°}{2}$$

$$= 63.765°$$

The difference between the failure plane and slope face:

$$\theta - \beta = 63.765° - 45°$$

$$= 18.765°$$

Calculating the Wedge Area and Self-Weight

$$\cot(18.765°) \approx 2.958$$

$$\text{Area of wedge} = \frac{1}{2} \times (0.2)^2 \times 2.958$$

$$= 0.05916 \text{ m}^2$$

Self-weight of slope wedge = 0.05916 ×18

$$= 1.065 \text{ kN}$$

Total weight

$$W_{total} = 1.065 + 0.5040$$

$$= 1.569 \text{ kN}$$

Driving Force Along the Failure Plane

Driving force:

$$T = W \cdot \sin(\theta)$$

$$\theta = 63.765°$$

$$\sin(63.765°) \approx 0.8957$$

$$T = W \cdot \sin(63.765°)$$

$$= 1.569 \times 0.8957$$

$$= 1.4046 \text{ KN}$$

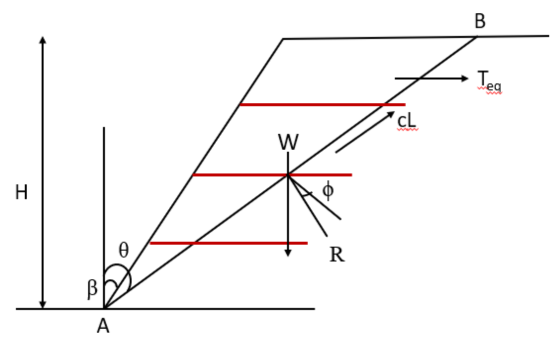


Figure 5.12: Reinforced soil slope

Equivalent Nail Tensile Force

$$T_j = \frac{(c + \sigma_v \tan\delta)\pi dl}{S_h}$$

tan(18.765°) ≈ 0.3339

$$T_j = \frac{(2.685 + 3.6 \text{ x } 0.334)\ \pi \text{ x } 0.006 \text{ x } 0.08}{0.045}$$

= 0.1303

Total equivalent tensile force, Teq = 6 × T_j

= 6 x 0.1303

= 0.7818

Resisting Force Along the Failure Plane

Resisting force:

R = c·L + W·cos(θ)·tan(ϕ) + Teq. cos(θ)

Length of failure surface, L:

$$L = \frac{0.2}{\sin(18.765°)} = 0.6217 \text{ m}$$

cos(63.765°) ≈ 0.444

tan(37.53°) ≈ 0.768

W = 1.569 kN

Total resisting force R = (2.685 × 0.6217) + (1.569 × 0.444 × 0.768) + (0.7818 x 0.444)

= 1.669 + 0.535 + 0.3471

= 2. 5511 kN

Factor of Safety

$$FoS = \frac{R}{T}$$

$$= \frac{2.5511}{1.4046}$$

= 1.816

Therefore, Calculated Factor of Safety for reinforced slope is **1.82**

5.6 ALLOWABLE LOAD FOR SOIL SLOPE

The minimum factor of safety suggested by FWHA manual (2003) is 1.35 for soil nailed structure. Factor of safety calculated for different failure plane are greater than the minimum suggested value. Hence assuming the factor of safety to be 1.82 from the above calculations, we can calculate the allowable load that can be sustained by the unreinforced and soil nailed slope.

Table 5.3: Allowable load calculation

Slope	Failure Load (N)	Factor of Safety	Allowable load(N)
Unreinforced	434.66	1.622	266.66
Reinforced	504.02	1.816	321.03

$$\text{Allowable Load} = \frac{\text{Failure load}}{\text{Factor of safety}}$$

The above table represents the maximum failure load at which the slope becomes unstable, while the allowable load is calculated by dividing the failure load by the FOS, ensuring a safe design margin.

For the unreinforced slope, the failure load was recorded as 434.66 N, with a calculated FOS of 1.622, resulting in an allowable load of 266.66 N. In contrast, the reinforced slope exhibited a higher failure load of 504.02 N. Although the FOS was slightly lower at 1.816, due to the increased applied load, the allowable load increased significantly to 321.03 N. The increase in allowable load from unreinforced to reinforced condition validates the effectiveness of the reinforcement system used in the study.

5.7 COMPARISON WITH NUMERICAL ANALYSIS

The experimental results were compared with the outcomes from the numerical simulations performed using PLAXIS 2D to validate the effectiveness of soil nailing in enhancing slope stability. Factor of safety decreases from unreinforced to reinforced as the failure load increases for reinforced slopes. As adding more load increases the driving force, which tries to destabilize the slope decreasing the factor of safety.

Table 5.4: Factor of safety comparison

Factor of Safety	Analytical	Experimental
Unreinforced	1.229	1.622
Reinforced	1.539	1.816

The table compares for both the unreinforced and reinforced slope, the analytical simulation for unreinforced slope predicted a FOS of 1.229, whereas the experimental analysis yielded a higher FOS of 1.63. Similarly, the analytical simulation for unreinforced slope predicted a FOS of 1.539, whereas the experimental analysis yielded a higher FOS of 1.816 indicating a strong correlation between two approaches. This variation can be attributed to the conservative assumptions made in software modeling and the scale effects present in laboratory testing.

The results demonstrate that while there may be slight deviations between numerical and experimental outcomes. The close agreement, particularly in the reinforced case, validates the reliability of the PLAXIS software model and confirms the practical effectiveness of the reinforcement configuration used.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 CONCLUSION

The conclusions of the work covering all the research objectives are summarized below ;

The experimental investigations confirmed that the soil sample collected from the DTU ground is poorly graded with low plasticity, as indicated by grain size analysis and Atterberg limits. The Direct Shear Test further provided essential strength parameters: cohesion (2.685 kPa) and angle of internal friction (37.53°). These parameters are critical for assessing the shear strength and slope stability potential of the soil and were subsequently used in the numerical modeling process.

This research examined the effectiveness of soil nailing for slope stabilization through both analytical modeling using PLAXIS software and experimental validation. The study demonstrated that introducing soil nails significantly improves the Factor of Safety, confirming soil nailing as a reliable method for enhancing slope stability.

The numerical analysis explored the impact of various design parameters, including nail length, inclination, spacing, and material properties, on slope stability. Slope angles of 30°, 45°, and 60° were evaluated. While the 30° slope showed a higher unreinforced FOS, the 45° slope was selected for physical modeling due to its practicality and effective reinforcement response, making it suitable for real-world application. Among the different nail configurations tested, the most effective was identified as a nail length of 8 m, 10° inclination, and 6 mm diameter. This configuration achieved the highest FOS of 1.539, confirming its superior performance in resisting potential slope failure. The results highlight the importance of optimizing nail geometry, as improper combinations led to reduced safety margins.

Laboratory model tests further validated the numerical results. Soil was compacted in layers inside a steel tank, and a 45° slope was formed. Under incremental static loading, deformations were measured using magnetic dial gauges. The reinforced slope showed significantly reduced vertical and horizontal deformations compared to the unreinforced model, confirming the efficacy of soil nails in limiting soil displacement and improving slope performance. Two nail arrangement patterns rectangular and staggered were evaluated. The staggered pattern exhibited better deformation resistance, especially under higher loading, due to better stress distribution.

To validate the results analytically, Culmann's method was applied. The analysis showed a decrease in FOS from 1.622 (unreinforced) to 1.816 (reinforced) as the failure load increased. This reduction is due to the higher driving force associated with increased loading in reinforced slopes. Despite the decrease, the reinforced slope supports a significantly higher load, proving the success of the reinforcement system.

The study emphasizes the importance of selecting the appropriate nail length, inclination, and arrangement to maximize performance. These findings support the integration of design optimization and field validation as essential steps in the development of safe and economical geotechnical slope stabilization strategies.

6.2 FUTURE WORK

Future experimental analysis will be essential in further validating the numerical findings obtained from PLAXIS simulations. These tests will offer deeper insights into the complex interactions between soil properties and reinforcement mechanisms, which are often simplified in numerical models. Upcoming experiments will focus on identifying the critical failure loads under various slope configurations, helping to understand stress distribution and failure behavior in both reinforced and unreinforced slopes.

Further studies will investigate the influence of key soil nail parameters including length, diameter, inclination, and spacing on overall slope performance. This will aid in determining the most effective reinforcement strategies and contribute to the refinement of design parameters used in slope stabilization projects.

The outcomes of these extended analyses will support the development of more accurate and reliable design guidelines for geotechnical engineers, allowing for optimized soil nailing solutions tailored to different soil conditions and site requirements. All procedures, observations, and results will be comprehensively documented to serve as a valuable reference for future research and real-world geotechnical applications.

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