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THE EFFECT OF SOIL NAILING INCLINATION FOR IMPROVEMENT OF GYPSUM SAND SOIL IN DIFFERENT SLOPES

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Research Paper

Abstract: *This study investigates the effect of nailing inclination angles on the stability of gypsum sand soil slopes, using 2D-Slope/W software within Geostudio 2018. The analysis focuses on gypsum sand soil with a 29% gypsum content, employing nine nailing inclination angles (5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°) across four levels of nailing. The nails are installed with a horizontal spacing of 2 m. Five slope angles (β) of 45°, 55°, 65°, 75°, and 85° were examined to evaluate their improvement under various nailing configurations. The study also analyses the effect of nailing length, applying the Mohr–Coulomb failure criterion to assess slope stability. The findings indicate that the factor of safety (FS) consistently increases with larger nailing inclination angles, particularly as the angle rises from 5° to 40°. Similarly, an increase in nailing length enhances the FS across all inclination angles and slope geometries. Based on these results, nine design tables were developed, providing empirical equations to determine*

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optimal nailing lengths, inclination angles, and slope conditions for effective stabilisation. These findings offer valuable insights for improving slope stability in gypsum sand soils and contribute to the optimisation of soil nailing techniques in geotechnical engineering.

Keywords: *Factor of Safety, Geostudio 20182d, Gypsum Sand Soil, Nailing Inclination Angle, Nailing Length, Side Slopes.*

1. Introduction

Soil stability is a critical consideration in geotechnical engineering, particularly when working with problematic soils like gypsum sand (Srivastava et al., 2025). This type of soil is characterised by its high gypsum content, collapsibility, and sensitivity to moisture, which present significant challenges for construction and infrastructure development (Al Watar & Al-Kifae, 2024). Stabilising slopes in such soils is essential to mitigate risks of failure, protect infrastructure, and ensure the safety and longevity of projects. Over the years, soil nailing has gained widespread recognition as an effective method for enhancing slope stability. By inserting steel nails into the soil, this technique increases shear strength and prevents slope failure (Omoregie et al., 2025). Originally developed in the 1970s in Germany and the USA, soil nailing has since been applied globally in diverse geotechnical scenarios, including retaining walls, excavation support, and tunnel construction (Bruce D, 1986). Its adaptability to varying soil conditions and terrains has made it a preferred choice for projects where traditional methods may not be feasible.

The technique of soil nailing is, therefore, underlined as a versatile technique that finds applications in slope stabilisation, excavation support, and retaining wall construction, with immense benefits in geotechnical engineering (Cassani et al., 2022). Among various concerns in geotechnical engineering, soil stability is one major consideration, which has been recognized to be affected in regions vulnerable to slope failure because of weakness or collapsible soils (Mittal & Samanta, 2025). Such is the challenge with gypsum sand soil, given its high content and sensitivity to water-induced collapsibility. The inherent mechanical properties demand novel approaches towards its stabilization as steep slopes, for example, and heavy loads in structures tend to be unsuitable for most gypsum sand applications (Abdolvand & Sadeghiamirshahidi, 2024). Among all types of soil reinforcement, soil nailing has emerged as a versatile and effective means to enhance slope stability (Singh et al., 2024). However, when applied in gypsum-rich soils, soil nailing needs to be further studied so that its applicability can be felt under various site conditions.

Soil nailing is a technique whereby tension-resisting elements like steel bars are introduced into the soil to enhance shear strength and stability (Cheriet et al., 2024). Several design parameters determine the effectiveness of the technique, which includes length, spacing, and angle of inclination of the nails as well as geometry and material properties of the slope. While previous studies Zhi et al. (2022) and Sahoo et al. (2021), have extensively evaluated the performance of soil nailing in general soil types, very few studies have considered soils with a high gypsum content. Thus, the interplay between nailing configurations and properties of gypsum-rich soils is a critical gap that is yet to be addressed by existing literature, which this study will address. Despite its advantages, the effectiveness of soil nailing largely depends on factors such as nail inclination, length, and slope geometry (Bathini & Krishna, 2022). While previous research has explored these parameters in general soil types, there is a noticeable gap in understanding their impact on gypsum sand soils, which have unique geotechnical properties. Addressing this gap is essential for advancing the application of soil nailing in regions where gypsum-rich soils are prevalent.

This study aims to evaluate the effect of nailing inclination angles and nail lengths on the stability of gypsum sand soil slopes with varying geometries. Using Geostudio 2018 (SLOPE/W) software and the Mohr–Coulomb failure model, the research conducts a parametric analysis to identify optimal configurations for slope stabilisation. The findings contribute to existing knowledge by offering empirical equations and design guidelines that practitioners can use to enhance stability in challenging soil conditions. By focusing on gypsum sand soils, this research provides practical insights and theoretical advancements that will help engineers design safer and more efficient soil nailing systems. These findings have the potential to improve infrastructure resilience in regions with similar soil.

2. Literature Survey

Soil nailing has emerged as an important technique for slope stabilization since it can improve soil shear strength and provide additional resistance to failure. Differences in nail length, angle, and material properties have a strong impact on the performance of nailing systems. Earlier studies reported that gypsum-rich soils are problematic due to their moisture sensitivity and collapsibility (Herrero & Zartman, 2021; Pu et al., 2021). Numerical modelling Mohammed et al. (2022) and experimental research have shown that optimized nailing configurations can overcome these issues, thus improving the factor of safety for the critical slopes. Advanced simulation tools have been implemented to accurately simulate soil-nail interaction under varied conditions. Sharma and Shrivastava (2025) demonstrated the evaluation of using construction and demolition wastes as fill materials in highway embankments with recycled concrete aggregates (RCA) and recycled brick aggregates (RBA) used. It assesses the stability of slopes by conducting a simulation of 12 models by using GeoStudio software with LS, RCA, RBA, and their blends. The test embankments mimic a six-lane road with a changing height of the slope: 3 m, 6 m, and 9 m; and different slope ratios horizontally-to-vertically (H:V) - 2:1, 1:1, 1:2, and 1:3. Applying the Morgenstern-Price approach, it reveals that including either RCA or RBA considerably increases FOS for all embankments, more than for angles >45°. FOS varied from 1.38 to 5.91, that showed stable slopes are appropriate for highway construction. Based on the present studies, stability will be enhanced while replacing LS by RCA or RBA, not only that the embankment construction will increase in environmental sustainability and economic efficiency; however, the outcomes are specifically true for the type of waste like C&D having similar characteristics .In addition to this, Ranjan et al. (2025) addresses the influence of design parameters on the behaviour of a hybrid wall consisting of an MSE wall overlaying a soil nail (SN) wall. The analysis produced two primary patterns of failure, one initiated from the base of the hybrid wall and propagated up through the SN wall, and another developed behind the MSE wall. A tension crack zone was also observed near the end of the soil nail reinforcement, extending upward into the MSE wall. Stability is highly dependent on factors such as wall height, reinforcement length, and soil friction angles.

The soil nailing technique is widely accepted for the stabilization of both natural and man-made slopes as well as retaining and offshore structures. Ramteke and Sahu (2024), explores the effect of uniformly distributed vertical and horizontal loading on soil slopes and studies how soil nailing can be advantageous to stabilize them. The research used a new numerical approach to assess the maximum factor of safety (FOS) at different nail inclinations (0°, 5°, 10°, 15°, 20°, and 25°) in relation to the horizontal plane. To evaluate the effectiveness of the soil nailing system, the study applied the limit state design (LSD) method and conducted numerical simulations to analyse slope displacement, nail movement, and laboratory experiments. The results demonstrated that soil nailing would be an effective solution in the stabilization of slopes. Therefore, the most effective application in terms of stability as well as FOS occurred at 15° inclination of the nails. This angle in particular optimizes load distribution, reduces slope failure likelihood, and significantly enhances slope stability.

Soil nailing is the process of stabilizing steep slopes by embedding steel bars, or "nails," to stabilize the ground during construction. This technique is especially useful for creating stable cuttings and working with retaining systems. The study by Alali (2024), highlights that the optimal nail angle for soil nailing lies between 10° and 25° below the horizontal, significantly improving slope stability. Moreover, Cheriet et al. (2024) proposes an investigation into the stability of an unstable soil and fractured rock slope of 35 meters high located on the railway line that connects Boughezoul to Djelfa cities in Algeria. A parametric study is conducted to study the effects of groundwater levels and the nail's length, using 25 mm diameter with 15° angle, yielded from 500 MPa, steel nails for reinforcement and shotcrete. The test is simulated by PLAXIS 2D. A minimum reference value of 1.38 was achieved with a safety factor of 1.63, confirming slope stability. The results are fruitful in showing the effects of groundwater levels on railway projects in geotechnical engineering.

Slope stability is a crucial aspect in geotechnical engineering, and its potential treatment with effective reinforcement methods is almost a necessity to prevent slope failures. Pathak (2023), examines the application of soil nails and cable anchors for soil stabilization, including their advantages and disadvantages and general applicability. Numerical simulations were carried out using the Rocscience Slide2 program. The slopes were varied from 10 m to 60 m in height, slope angles between 35° and 90°, and friction angles from 27° to 36°. The results indicate that the maximum economic length of soil nails decreases with an increase in the depth of the slip surface, slope height, and slope angle. Another fact of the soils in this project was that friction angles had minor contributions toward the nails' maximum economical lengths. Arvin et al. (2022), examines the optimal design of soil nail walls by using a method from the FHWA manual in combination with nonlinear programming. The best nail inclination angle (η) that maximizes safety against failure is focused upon. The study considers various factors, including nail diameter, length, soil friction, slope angle, back slope angle, and nail layout. From the investigation, increased nail diameter leads to increased values of FS and η opt. Long nail length up to 1.875H is the best slope stability with higher values in FS, and higher soil friction gives increased FS but increases η opt slightly.

Jaiswal et al. (2022) explores how different soil nailing parameters, such as the length and inclination of the nails, affect the stability of a steep soil slope (with an angle of 40°). Using the Optum G2 finite element software and the shear strength reduction method, the research analysed a 6-meter-high slope with nail inclinations ranging from 0° to 50°. The findings highlight that both nail length and inclination are crucial for slope stability. The study also suggests optimal nail lengths and orientations and discusses how the slope's failure modes change with and without reinforcement. Furthermore, Elahi et al. (2022), examines the stability of slopes that are reinforced by soil nails and evaluates the effect of slope geometry and nail parameters using PLAXIS 2D. The results show that the factor of safety decreases as the slope and backslope angles increase. It was observed that nail inclination has a significant effect with FS peaking at an optimal angle between 0–25° before it decreases. The benefits of increasing nail length were FS improvement and a reduction in lateral slope movement. However, these benefits plateaued when the L/H ratio exceeded 0.9. Soil nailing with optimal parameters can increase FS by 29–75%, making it an effective tool for slope stabilisation.

3. Materials and Methods

This work incorporating the finite element method by Geo Slope/W 2D 2018, the relationship among three variables: nine inclination angles of nailing, five nailing lengths, and the slope of construction; will be considered. Inclination angle takes the form of the angle at which the soil nails are installed, with reference to the horizontal plane. In this study, nine inclination angles take value at 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40° and 45°. By varying the inclination angle, an inquiry can be made into how the orientation of the soil nails influences their efficacy in stabilizing the slope. The nailing length represents the depth at which the soil nails are driven into the slope. Five nailing lengths at 8m, 10m, 12m, 14m, and 16m were considered. The variation in nailing length is related to the study of how soil nail depth influences the capacity of slope stability.

Presumably, this is with regard to the original angle of inclination of the site of construction development that gives a benchmark in assessing the efficiency that soil nails will offer in holding the slope in position. These may differ widely depending upon the features of a building site and the particular level of stability that a project is designed to attain. Assessment of these interactions between angles and lengths, through the finite element method, may provide information on how various combinations of angles and nailing lengths achieve stability along with reinforcement effects on the slope. Such information is very useful in ensuring that the design and application of soil nailing systems in similar developments are optimally performed with due regard to the material conditions, geometrical conditions, and objectives of the work.

The model two-dimensional had a height of 20 m, a top width of 35 m, and five angles of slope excavation dimension angles of 45°, 55°, 65°, 75°, and 85° β. To give a vivid representation of the system, the structure's sizes and dimensions are focused on the most. The schematic shape of the model used is shown in Figure 1. It is based on the Mohr–Coulomb model, which has found extensive application in slope stability, especially in trench excavation, analysis of soil and rock mechanics, and subterranean excavation stability analysis (Goel & Chatterjee, 2025; Peng et al., 2025). A finer mesh, which was 0.25 m, was used for the Finite Element analysis to build up accuracy. The soil properties for this model is from Al-Najaf City in Iraq as illustrated in Table 1.

Table 1: The Soil Properties of the Used Soil.

S. No	Test Type	Values
1	In-Place Density (Sand Cone Test)	1.829 gr/cm^3
2	Max. Dry Density (Proctor Test)	1.825 gr/cm^3
3	Specific Gravity (Gs)	2.38
4	Void Ratio of 90% of Max. Dry Density	0.45
5	Gypsum Content	29 %
6	Optimum Moisture Content (Proctor Test)	15 %
7	Inclination Angle ($Ø^b$)	14^o
8	The Angle of Internal Friction (Ø)	32^o
9	Porosity, n	0.31
10	Soil Type According to USCS	SW
11	Cohesion (C)	20 kPa

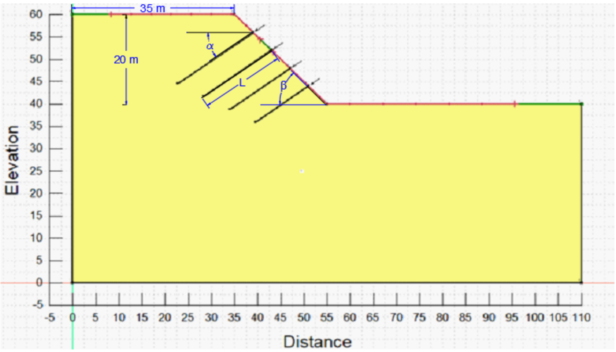


Figure 1: The Schematic Shape of the Used Model.

In this paper, entry and exit method are used to calculate the critical slip surface. As in the analysed model, the search zone can be observed before solving the exploration, and the entry-exit approach is the most natural way to find the critical slip surface in SLOPE/W. Additionally, combining the entry-exit method with radius tangent lines can further limit the search zone. The nailing properties are shown in Table 2.

Table 2: Nailing Properties of the Used Model.

Define Reinforcement Load (Nailing System)	Details
F of S Dependent	No
Force Distribution	Distributed
Face Anchorage	Yes
Pull-out Resistance (PR = F/Area)	200 kPa
Resistance Reduction Factor (RRF)	1.5
Bond Diameter (D)	0.3183
Nail Spacing	2 m
Tensile Capacity	1500 kN
Reduction Factor	1.5
Shear Force	0 kN
Shear Reduction Factor	1
Factored Pull-out Resistance (FPR)	66.67 kN/m
Maximum Pull-out Resistance (PR)	0-500 kN

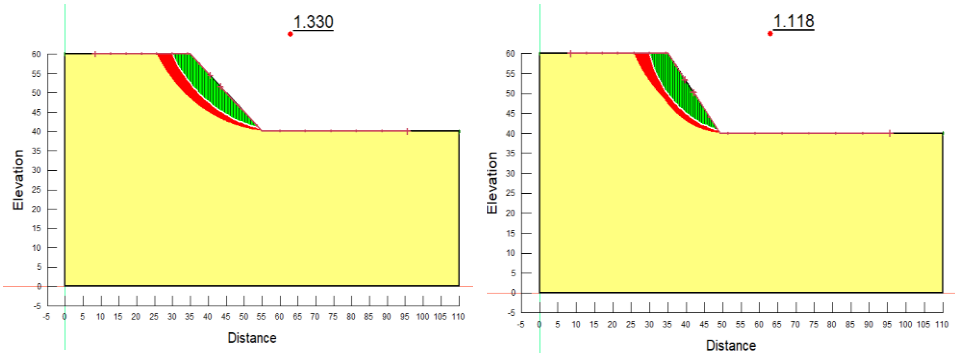
The Resistance Factor (RF) reduces resistance and adjusts for scale effects on stress reduction. Bond Diameter (D) affects the bond strength between reinforcement and soil. Spacing (S) ensures uniform reinforcement for stability. Tensile Capacity (TC) defines the reinforcement's maximum strength under tension. The Reduction Factor accounts for decreased tensile capacity due to factors like damage and durability. Shear Force, ranging from 0 to 1, controls the orientation of stress in the reinforcement. The Shear Reduction Factor adjusts shear force based on soil and reinforcement properties. Pull-Out Resistance measures the reinforcement's ability to resist being pulled from the soil. These factors are essential for designing soil nail systems, ensuring safety and durability in slope stabilization and retaining walls.

4. Results and Interpretative Discussion

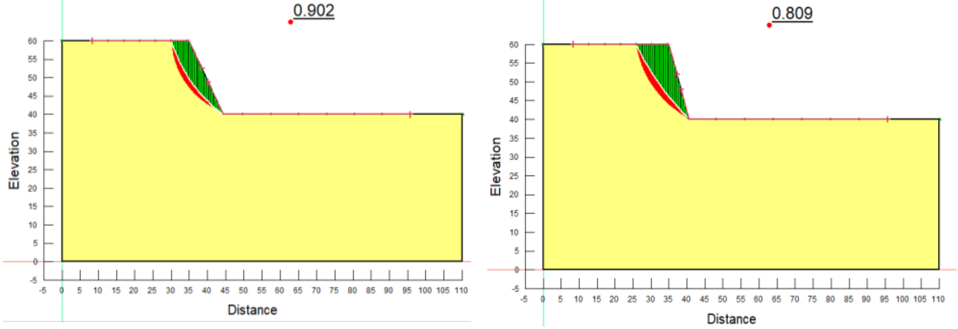
4.1 Unreinforced Soil Slope

Among other things, the type of soil and the slope's geometry affect how the slope fails. The five types of soil slopes (45o, 55o, 65o, 75o, and 85o) that are considered have different forms of slope failure depending on the nailing slopes and lengths. All the previously reinforced soil slopes with four layers of nails were compared with unreinforced cases. Figure 2 shows the results of the Factor of Safety of the unreinforced soil slopes. The Factor of Safety decreased as the slope angle increased because its magnitude is calculated using Equation (1), as follows:

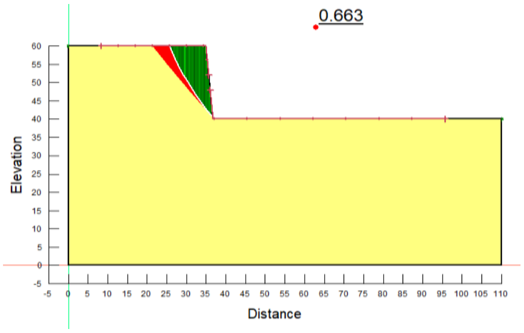
$$SF = \frac{\text{summation of moments of maximum resisting forces}}{\text{summation of moments of moving forces}} \quad (1$$



a: $\beta = 45^o$ b: $\beta = 55^o$



c: $\beta = 65^o$ d: $\beta = 75^o$



e: β = 85o

Figure 2: The Results of the Factor of Safety of the Unreinforced Soil Slopes (β).

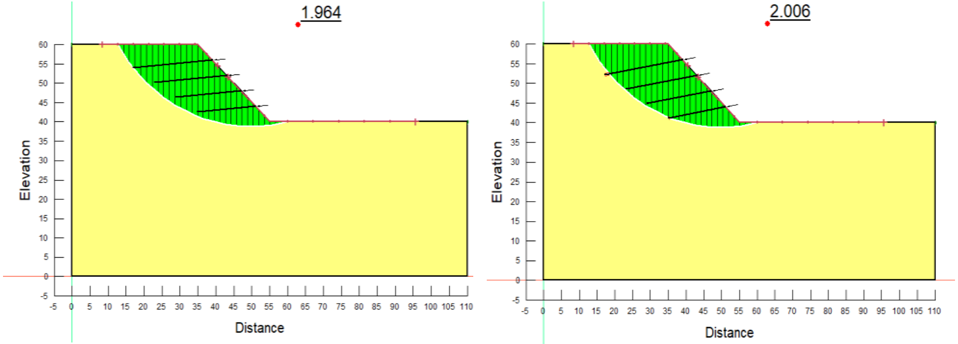
In the first two cases (a and b), the maximum shear resistance due to the vertical soil weight is larger than the soil weight causing the sliding. In other cases (c, e, and d), the force component that causes vertical resistance is smaller than the horizontal sliding force component.

4.2 The Effect of Soil Inclination (β)

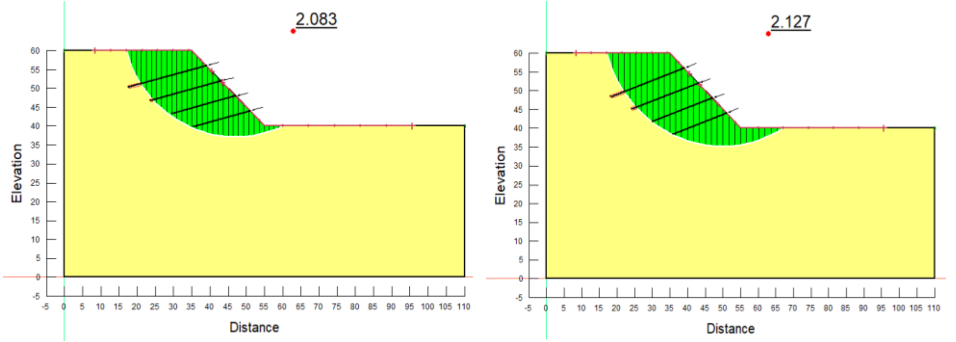
As mentioned earlier, there are 4 levels of soil nails with a horizontal nail spacing of 2 m with 5 groups: Group 8, Group 10, Group 12, Group 14, and Group 16, as illustrated in Table 3. The difference in length between the nail rows was 2 m. As an example, in Group 8, the length of the first (lower) nails row was 8 m, the length of the second nails row was 10 m, the length of the third nails row was 12 m, and the length of the fourth (upper) nails row was 14 m. Figure 3 shows the finite element analysis for the case of β = 45o and α = 5o, 10o, 15o, 20o, 25o, 30o, 35o, 40o, and 45o, for Group 16.

Table 3: The Group Nailing Details.

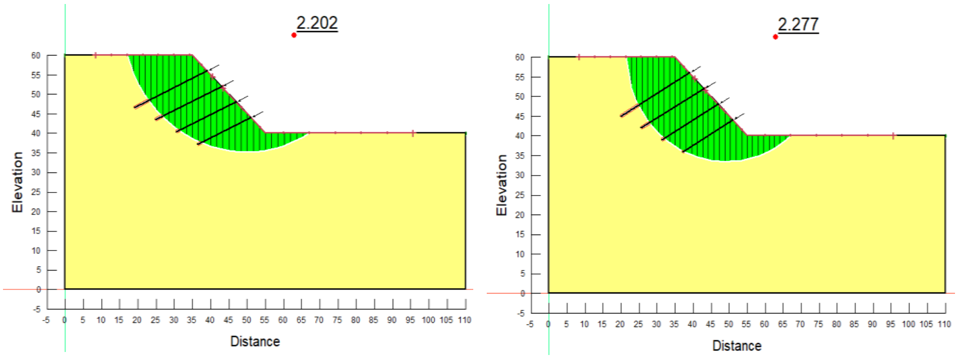
Group No.	Row No.	Nailing Length, m
Group 8	1	8
	2	10
	3	12
	4	14
Group 10	1	10
	2	12
	3	14
	4	16
Group 12	1	12
	2	14
	3	16
	4	18
Group 14	1	14
	2	16
	3	18
	4	20
Group 16	1	16
	2	18
	3	20
	4	22



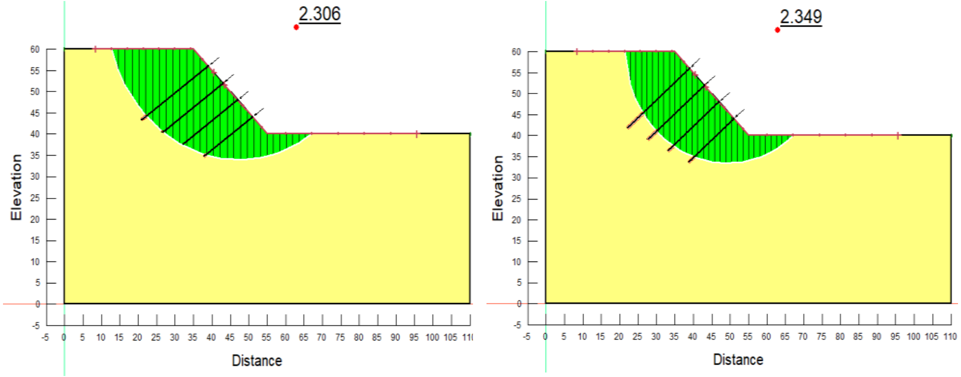
a: α = 5°
b: α = 10°



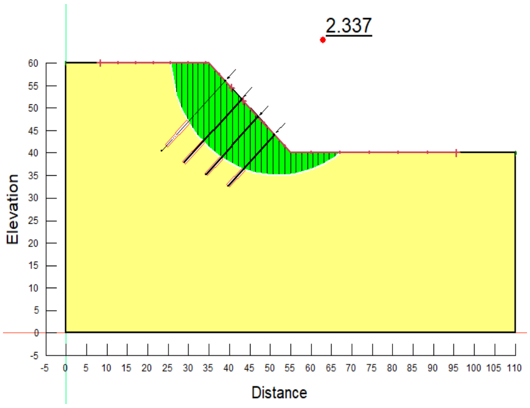
c: α = 15°
d: α =20°



e: α = 25°
f: α =30°



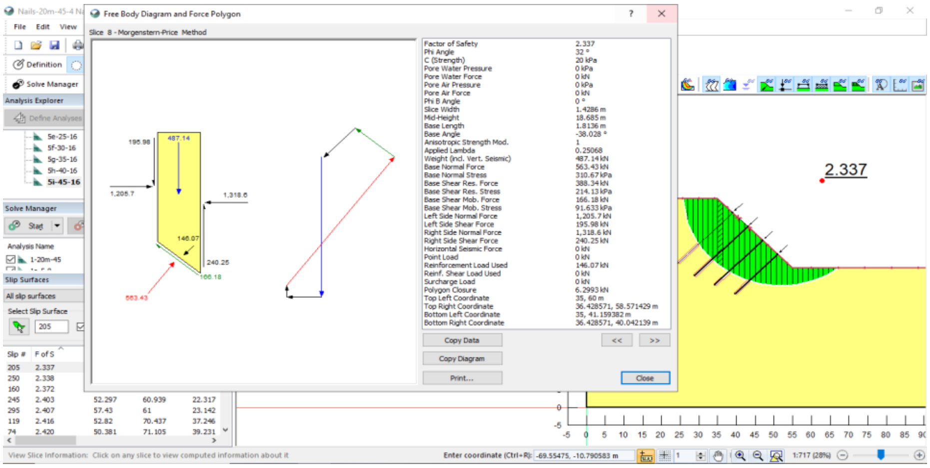
g: α = 35°
h: α =40°



i: α =45º

Figure 3: The Finite Element Analysis for β = 45o and Different α.

The results show that the safety factor is maximized when the nailing system is aligned perpendicular to the soil inclination angle, given that the critical slip surface intersects all the nails in the system (Pinuji et al., 2024). Figure 4 illustrates the free body diagram of the critical slice of the case of Fig. 3-i. From Figure 5 it can be noticed that how the safety factor is affected due to side slope angle, β. This factor is correlated to nailing angle, α; the length of nails under equivalent conditions varies from one case to another. When side slope angle β increases, this tends to result in a low safety factor value because gravitational forces and shear stress are more powerful. The nailing angle (α) is crucial to the stability. The steeper slopes need nearly horizontal or slightly downhill angles (for example, 5°–15°) to get an anchor into stable subsurface layers without significantly disturbing the slope surface (Azim & Sengupta, 2024).

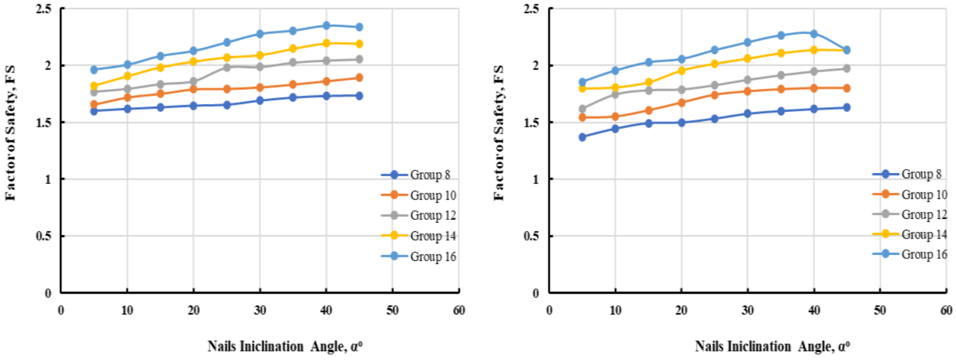


Slip #	F of S			
205	2.337			
250	2.338			
160	2.372			
245	2.403	52.297	60.939	22.317
295	2.407	57.43	61	23.142
119	2.416	52.82	70.437	37.246
74	2.420	50.381	71.105	39.231

Factor of Safety	2.337
Phi Angle	32 °
C (Strength)	20 kPa
Pore Water Pressure	0 kPa
Pore Water Force	0 kN
Pore Air Pressure	0 kPa
Pore Air Force	0 kN
Phi B Angle	0 °
Slice Width	1.4286 m
Mid-Height	18.685 m
Base Length	1.8136 m
Base Angle	-38.028 °
Anisotropic Strength Mod.	1
Applied Lambda	0.25068
Weight (incl. Vert. Seismic)	487.14 kN
Base Normal Force	563.43 kN
Base Normal Stress	310.67 kPa
Base Shear Res. Force	388.34 kN
Base Shear Res. Stress	214.13 kPa
Base Shear Mob. Force	166.18 kN
Base Shear Mob. Stress	91.633 kPa
Left Side Normal Force	1,205.7 kN
Left Side Shear Force	195.98 kN
Right Side Normal Force	1,318.6 kN
Right Side Shear Force	240.25 kN
Horizontal Seismic Force	0 kN
Point Load	0 kN
Reinforcement Load Used	146.07 kN
Reinf. Shear Load Used	0 kN
Surcharge Load	0 kN
Polygon Closure	6.2993 kN
Top Left Coordinate	35, 60 m
Top Right Coordinate	36.428571, 58.571429 m
Bottom Left Coordinate	35, 41.159382 m
Bottom Right Coordinate	36.428571, 40.042139 m

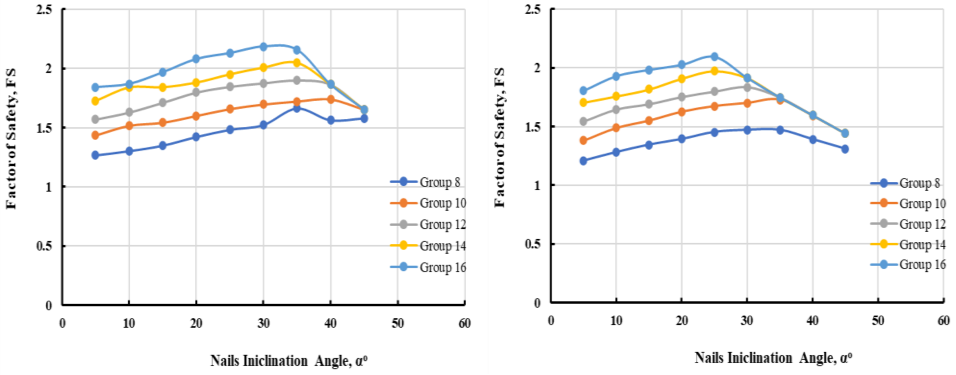
Figure 4: The Free Body Diagram of the Critical Slice of the Case of Fig. 3-i.

For gentler slopes, larger angles, for example, 15°–30°, are better for force distribution and increased stability. Furthermore, the length of the nails is a critical factor; longer nails normally improve the safety factor by going further into deeper stable soil or rock strata and thus transferring loads better (Zhang et al., 2022). Shorter nails are less expensive but may not offer adequate stabilization, particularly for steeper slopes. From Figure 5, it can be observed that for a given set of values for β and α, longer nails are more proficient in preventing slope instability than shorter nails. Based on that, optimizing nail lengths and angles of inclination considering the slope gradient and relevant geotechnical conditions is essential for developing an equilibrated design that better meets safety with cost-effectiveness (Benayoun et al., 2021). This analysis underscores the importance of tailoring stabilization strategies to specific slope geometries to realize robust and reliable outcomes.



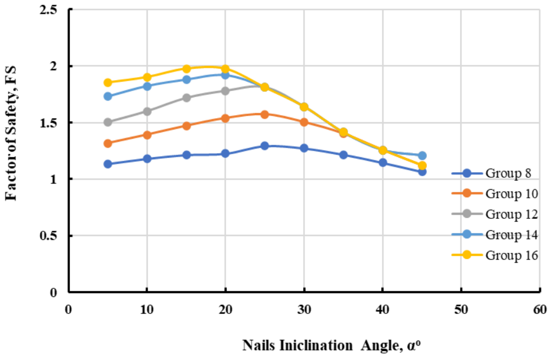
a: β = 45°

b: β = 55°



c: β = 65°

d: β = 75°

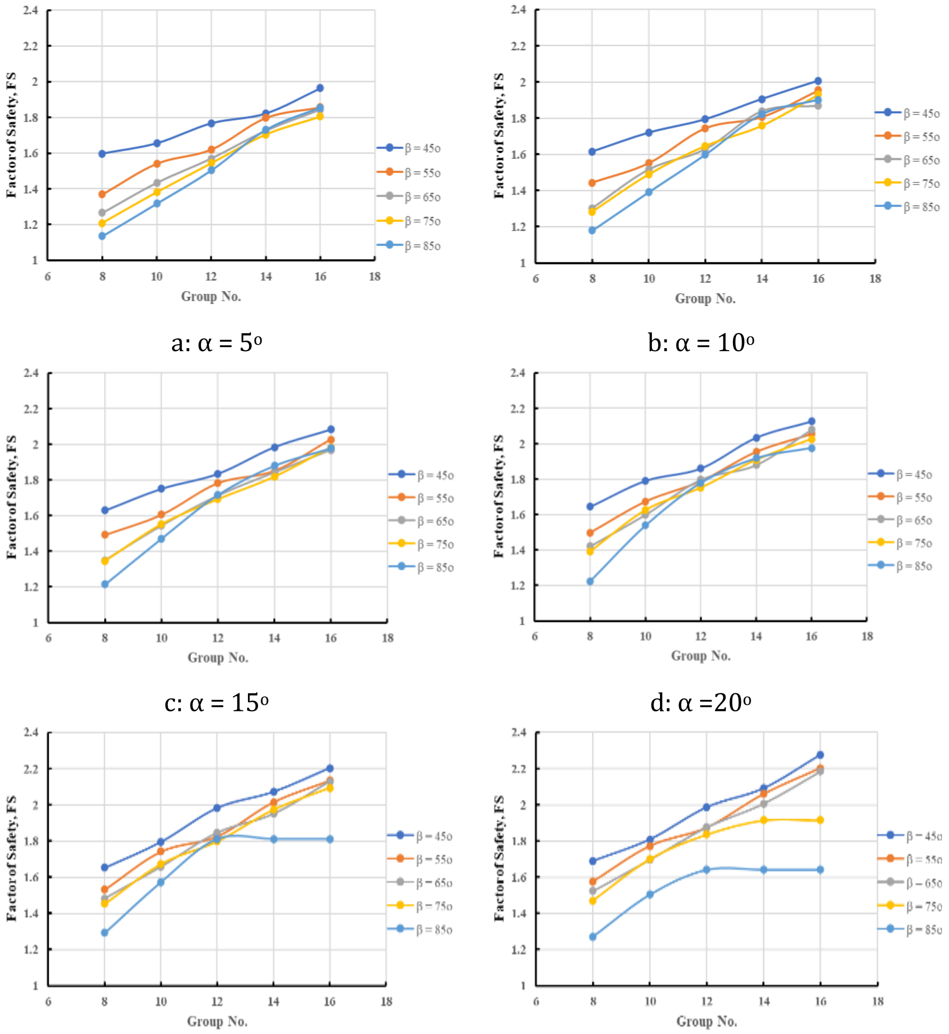


e: β = 85°

Figure 5: The Factor of Safety Results in Different Soil Inclination Angles (β).

4.3 The Effect of Nailing Inclination (α)

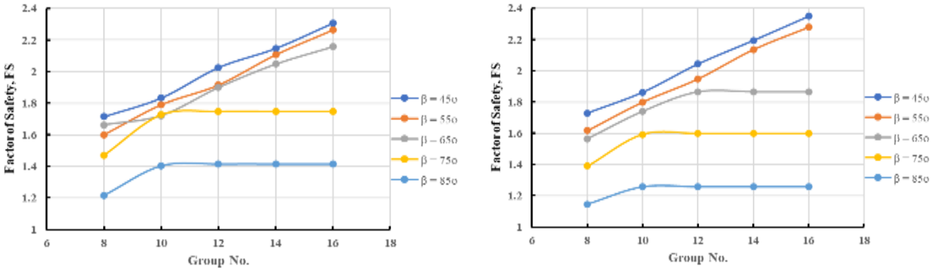
According to Fig. 6, it can be inferred that the safety factor increases with the increase in the inclination angle of the nailing system for all cases, as shown in Figs. 6-a to 6-d. But in cases of α = 25o, the factor of Safety (FS = 1.8) has not changed in Group 12, Group 14, and Group 16 (Fig. 6-e). When α was increased to 30o, the FS did not change in Group 14 and Group 16 with β = 75o; also, in β = 85o, the FS had the same value as in Group 12, Group 14, and Group 16. There were three variables in this study: the soil slope (β), nail inclination (α), and nail lengths (L). The obtained results of the study summarize findings indicating a decreasing safety factor as the angle β was increased from 45° to 85° and α and Group No. kept constant. As indicated in Fig. 5, the same behaviour is observed at all nail lengths in Groups 8, 10, 12, 14, and 16. Equations for trendlines of Group 16 are shown in Table 4.



a: α = 5^{o} b: α = 10^{o}

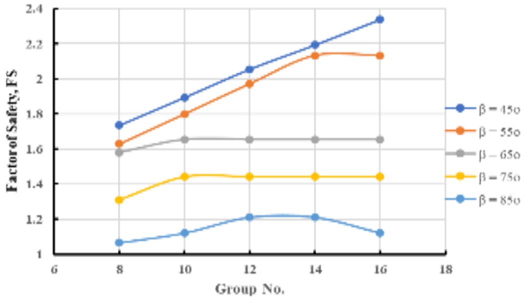
c: α = 15^{o} d: α =20^{o}

e: α = 25^{o} f: α =30^{o}



g: α = 35°

h: α = 40°



i: α = 45°

Figure 6: The Factor of Safety Results in Different Soil Inclination Angles (β).

Table 4: The Equations of the Trendline of Group 16.

No.	β	Equation
1	45°	$FS = -0.0001\alpha^2 + 0.0171\alpha + 1.862$
2	55°	$FS = -0.0004\alpha^2 + 0.0265\alpha + 1.7154$
3	65°	$FS = -0.001\alpha^2 + 0.0511\alpha + 1.518$
4	75°	$FS = -0.001\alpha^2 + 0.0399\alpha + 1.632$
5	85°	$FS = -0.0008\alpha^2 + 0.0209\alpha + 1.8036$

When α was increased from 5° to 45°, the safety factor also increased, with the best results observed when the nailing system was oriented perpendicular to the soil slope, i.e., when β = 45° and α = 45°, as shown in Fig. 6. Furthermore, increasing the length of the nailing system led to an increase in the safety factor in all cases, as shown in Fig. 5. Tables 5 to 13 contain the trends for all values of the angle of inclination in nailing system relative to that in soil (β) and to length in m for nailing system (L). For illustration purposes, whenever L is given as 9.5m it implies grouping for lengths equal to 9.5m, 11.5m, 13.5m, 15.5m and finally 17.5m. The minimum group magnitude should be in the range 8 to 16. Based on these results, nine tables have been derived that provide equations for predicting the right nailing length, nailing inclination angle, and side slope for stabilization purposes.

Table 5: The Equations of the Trendline of α = 5o.

No.	β	Equation
1	45°	$FS = 0.0019L^2 - 0.0018L + 1.4871$
2	55°	$FS = -0.0023L^2 + 0.1166L + 0.5877$
3	65°	$FS = -0.0015L^2 + 0.1071L + 0.5047$
4	75°	$FS = -0.0026L^2 + 0.1387L + 0.263$
5	85°	$FS = -0.0013L^2 + 0.1242L + 0.2179$

Table 6 deals with relatively shallow nailing angles. The equations indicate that for lower slope angles, FS generally increases with higher nailing lengths. For the higher slope angles, for example, β = 85°, FS improvements are much smaller, suggesting that the benefits saturate at steep slopes. Thus, relatively shallow nailing angles are appropriate for moderate slopes, β ≤ 55°.

Table 6: The Equations of the Trendline of α = 10o.

No.	β	Equation
1	45^{o}	$FS = 0.0006L^{2} + 0.0347L + 1.3045$
2	55^{o}	$FS = -0.0009L^{2} + 0.0863L + 0.8059$
3	65^{o}	$FS = -0.0048L^{2} + 0.1884L + 0.1033$
4	75^{o}	$FS = -0.0021L^{2} + 0.1275L + 0.4027$
5	85^{o}	$FS = -0.0044L^{2} + 0.2L - 0.1477$

Whereas, Table 7 indicates that at an angle of 15°, the curves are quite parabolic for all slope angles except the largest ones, indicating that FS increases with nail length at first but then levels off. For slopes between 45° and 65°, this nailing angle provides a significant increase in stability. However, for steeper slopes (β = 85°), the advantage of this angle is less, and the nails need to be longer to provide the same FS values.

Table 7: The Equations of the Trendline of α = 15o.

No.	β	Equation
1	45^{o}	$FS = 0.0003L2 + 0.0489L + 1.2179$
2	55^{o}	$FS = 0.5975L0.4356$
3	65^{o}	$FS = 0.8899\ln(L) - 0.5032$
4	75^{o}	$FS = -0.0017L2 + 0.1174L + 0.5239$
5	85^{o}	$FS = -0.0071L2 + 0.2681L - 0.4804$

As shown in Table 8, at α = 20°, the equations indicate a sharp increase of FS with length of nail, especially for middle slopes (β = 45° and 55°). This angle forms a good trade-off between the nail length and the angle of slope inclination and therefore might be used for a relatively wide range of slope conditions. At steeper slopes of β = 75° and β = 85°, the increase of FS seems to be slower. This implies that the angle may not be optimal for very steep slopes.

Table 8: The Equations of the Trendline of α = 20o.

No.	β	Equation
1	45^{o}	$FS = 1.2808e^{0.0321L}$
2	55^{o}	$FS = -0.0018L^{2} + 0.1123L + 0.7158$
3	65^{o}	$FS = 1.0017e^{0.046L}$
4	75^{o}	$FS = -0.0036L^{2} + 0.1636L + 0.3237$
5	85^{o}	$FS = -0.0109L^{2} + 0.3568L - 0.9299$

Moreover, Table 9 indicates a clear quadratic relationship between FS and nailing length for all slope angles. The equations indicate that at this angle, FS significantly improves for moderate to steep slopes (β = 55°–75°), which makes it very useful for challenging terrain. For extremely steep slopes (β = 85°), longer nailing lengths are required to achieve stability.

Table 9: The Equations of the Trendline of α = 25o.

No.	β	Equation
1	45^{o}	$FS = -0.0022L^{2} + 0.1211L + 0.8185$
2	55^{o}	$FS = -0.0014L^{2} + 0.1069L + 0.7766$
3	65^{o}	$FS = -0.0014L^{2} + 0.1118L + 0.6782$
4	75^{o}	$FS = -0.0026L^{2} + 0.1425L + 0.4896$
5	85^{o}	$FS = -0.0143L^{2} + 0.4067L - 1.0489$

In addition to this, the results in Table 10 show that a 30° angle gives significant improvements in stability for a wide range of slopes. The quadratic equations indicate that FS increases uniformly with longer nails, especially for the slopes up to β = 75°. For β = 85°, FS continues to improve, but the increase is less pronounced and calls for supplementary reinforcement measures for very steep slopes.

Table 10: The Equations of the Trendline of α = 30o.

No.	β	Equation
1	45^{o}	$FS = 0.0011L^2 + 0.0468L + 1.2429$
2	55^{o}	$FS = -0.0004L^2 + 0.0865L + 0.9184$
3	65^{o}	$FS = -0.0007L^2 + 0.0988L + 0.7801$
4	75^{o}	$FS = -0.0092L^2 + 0.2761L - 0.1461$
5	85^{o}	$FS = -0.0107L^2 + 0.3013L - 0.4448$

According to data shown in Table 11, at α = 35°, the equations show that FS increases smoothly with all angles of slope, and moderate slopes (β = 55° and 65°) benefit the most. For gentler slopes (β = 45°), this angle may be only slightly better than smaller angles such as 20° or 25°.

Table 11: The Equations of the Trendline of α = 35o.

No.	β	Equation
1	45^{o}	$FS = 0.0002L^2 + 0.0699L + 1.1367$
2	55^{o}	$FS = 2E\text{-}05L^2 + 0.0818L + 0.9506$
3	65^{o}	$FS = 0.0013L^2 + 0.0349L + 1.2835$
4	75^{o}	$FS = -0.0095L^2 + 0.2576L + 0.0473$
5	85^{o}	$FS = -0.0068L^2 + 0.1834L + 0.2045$

The data indicate that this angle is particularly effective for intermediate terrain. Whereas, Table 12 presents a near-linear relation between FS and nail length for moderate slopes, β = 45°–65°. For steeper slopes, β = 75° and 85°, the equations give diminishing gains which may not be enough to stabilize extreme slopes alone. The α = 40° is effective to stabilize moderately steep terrain.

Table 12: The Equations of the Trendline of α = 40o.

No.	β	Equation
1	45^{o}	$FS = 0.0002L^2 + 0.0729L + 1.1262$
2	55^{o}	$FS = -0.0007L^2 + 0.1004L + 0.8618$
3	65^{o}	$FS = -0.0085L^2 + 0.2408L + 0.1852$
4	75^{o}	$FS = -0.0073L^2 + 0.1953L + 0.3162$
5	85^{o}	$FS = -0.004L^2 + 0.1072L + 0.5562$

From the equations of Table 13, it can be concluded that maximum FS values occur when nails are placed perpendicular to the slope surface (i.e., β = 45° and α = 45°). In this way, the force is transferred in an efficient manner from the nail to the soil. For the steep slopes (β = 75° and 85°), FS is still improved, but longer nails have to be used to get a similar level of stability. From the above discussion, we suggest that:

Shallow Inclinations (α ≤ 20°): These angles are suitable for gentle to moderate slopes, providing stability enhancements with moderate nail lengths.

Intermediate Inclinations (α = 25°–35°): These are a balance between nail length and slope stabilisation, hence suitable for most conditions.

Steeper Inclinations (α ≥ 40°): These are best suited to steeper terrain with maximum FS realized at perpendicular configurations (α = β = 45°). Nevertheless, in extreme slopes (β ≥ 75°), their efficiency is diminished, and longer nails or support is needed.

Such valuable tools for optimization of nailing systems under the given slope conditions are the equations in each table. Precise calculations of length and inclination will be made during nailing that would save expenses and ensure that slope stabilization has been efficiently implemented

Table 13: The Equations of the Trendline of α = 45o.

No.	β	Equation
1	45°	$FS = -0.0009L^2 + 0.0971L + 1.0151$
2	55°	$FS = -0.0063L^2 + 0.2183L + 0.2715$
3	65°	$FS = -0.0026L^2 + 0.0708L + 1.191$
4	75°	$FS = -0.0047L^2 + 0.1263L + 0.6161$
5	85°	$FS = -0.0068L^2 + 0.1725L + 0.1044$

5. Conclusion

This paper investigated the effect of the nailing angle on smooth and graben side slopes in gypsum sand soil. Using Geostudio 20182d - Slope/W software, the research calculated the safety factor and stability improvement due to soil nailing. Results indicated that the safety factor increased with an increase in the nailing angle from 5° to 40°. In addition, increase in nailing length enhanced the safety factor for any angle of incline and side slope. Results indicate that by optimizing nailing parameters, the stability of gypsum sand soil in vertical cuts can be enhanced. From the above results, nine design tables were generated, specifying nailing length, angle, and side slope for definite conditions. Thus, these tables could guide engineers and practitioners working on ground stabilization projects involving gypsum sand soil. The work contributes to a better understanding of gypsum sand soil behaviour, providing valuable ideas for improvement in soil nailing techniques for reinforcement. The findings also suggest that further research into the long-term performance and durability of soil nailing in gypsum sand soil is necessary. Field studies and experiments can be conducted to validate and refine these guidelines for real-world applications.

6. Study Limitations

The study primarily focuses on the effect of soil nailing inclination and length in gypsum sand soil with limited experimental setups narrowed down to specific slope angles and nailing parameters. It is a laboratory-scale finite element simulation by means of SLOPE/W software, which cannot closely mimic field conditions. Soil properties, including gypsum content and moisture content, were measured for a particular geographic region, namely Iraq, and therefore findings are not generalizable to other soil types or regions. Moreover, long-term durability and environmental factors, including weathering or groundwater dynamics, were not evaluated, which could influence the soil-nail interaction. Variability in soil compaction and heterogeneity were not considered, which could influence the stability outcomes. In conclusion, the findings lacked real-time validation through full-scale field testing. The spaced uniformity in spacing of nails as well as using a fixed model soil may fail to represent varied real field practices. Only a limited number of five slope angles along with specific configurations were tested thereby weakening the strengths of the resulting conclusions. Key geotechnical activities like seismic shocks have not been taken into account. Lastly, the use of 2D analysis may not capture three-dimensional stress distribution, hence not being as effective for large projects.

7. Future Research Directions

Future studies should also examine the long-term stability and durability of soil nailing systems in various climatic and geological conditions with real world field trials and three-dimensional modelling. Research on the effect of dynamic loads, for example, earthquakes, on the stability of nailed slopes is important. The impact of variability in gypsum content and other soil properties such as compaction and water retention in nailed soil masses is also necessary to be known. Further extension includes the consideration of non-uniform nail spacing or novel materials, such as fibre-reinforced composites; and integration with groundwater flow and hydro-mechanical coupling simulating soil and nail interaction are two other critical research areas. Such investigations could advance into the issue of environmental sustainability for soil-nailing techniques where carbon footprint would be considered along with resource utilization issues. Adaptive nailing might also be more advanced in those highly heterogeneous soils in the long term. Further validation through full-scale field tests across different terrains is required to generalize the results.

8. Implications

The study offers optimized nailing inclination and length parameters for the stabilization of slopes in gypsum sand soil to engineers and geotechnical practitioners. The results are crucial in designing economical and stable soil nailing systems, thus minimizing the risk of structural failures in infrastructure projects. The design tables given here are quick references for field applications, thereby enhancing efficiency in slope reinforcement. The research contributes to the geotechnical engineering literature by extending the understanding of the interaction between nailing parameters and slope stability in gypsum-rich soils. It provides empirical equations to predict safety factors for different configurations, thereby providing a theoretical basis for further studies. The results point out the importance of nailing angle in the effective slope reinforcement process, which conflicts with conventional practice. This research also opens doors for the mechanical behaviour of gypsum soils under different techniques of nailing, thereby enriching geomechanically modelling theories.

9. Practical Applications

The research offers practical design guidelines for soil nailing systems in gypsum-rich soils, and engineers can effectively stabilize slopes using the guidelines. The empirical tables can be directly applied to find the optimal nailing configurations to reduce the risk of failure in infrastructure projects. These insights are particularly useful in arid regions where gypsum soils are prevalent. In addition, the findings can guide cost-effective slope stabilisation strategies, minimizing construction delays and resource wastage. Engineers can utilize these parameters in order to strengthen the safety and durability of retaining walls and excavation supports, particularly in road construction, tunnelling, and foundation works.

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