Optimizing Soil Nail Configuration for Slope Stability using GeoStudio

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ABSTRACT
Slope stability is a major concern, particularly in regions that are vulnerable to deep excavations, landslides, or infrastructure development on slopes. Because of its cost-effectiveness, adaptability, and capacity to increase slope shear strength without requiring substantial excavation, soil nailing has become one of the most popular stabilizing methods available. In this paper, using various nail inclination angles with horizontal axis, nail length, and nail spacing, an attempt has been made to determine the ideal soil nailing system. To get maximum Factor of Safety (FOS), different nail inclination, length, spacing were applied to a simulated homogenous soil slope (slope angles 30°, 40°, 45°, 50°, 60°, 70°, 75°, 80° and 90°) using SLOPE/W (GeoStudio 2018 R2). The Mohr-Coulomb expression and the limit equilibrium (LE) approach in the Morganstern-Price method were used to calculate the factor of safety (FOS), with pore water pressure functioning as the Ru value. The results show that the slope's stability is significantly impacted by the length, spacing, and inclination of the soil nails. For soil slopes of 30°, 40°, and 45°, the optimum nail inclination angle was found 25°; for soil slopes of 50°, 60°, and 70°, it was 20°; and for soil slopes of 75°, 80°, and 90°, it was 15° with the horizontal axis. The results also show that the FOS increases with the increase in nail length and decreases with the increase in nail spacing.

Keywords
Soil nail, Slope stability, Factor of safety, Landslides, Morganstern-Price method, Limit Equilibrium method.

1. INTRODUCTION
The stability of slopes is a critical concern in geotechnical engineering, as slope failures can cause economic losses, environmental damage, and threats to human safety. Soil nailing is a widely adopted geotechnical engineering technique used to enhance the stability of slopes, retaining walls, and excavations. In this method, slender reinforcing elements, usually steel bars or rods, are driven into a soil mass to make it stronger against tensile and shear forces. Soil nailing is a practical and proven technique used in constructing excavations and stabilizing slopes [1]. Reinforcement forces are mobilized in response to straining in the same way that the soil strength is mobilized as the soil strains [2]. For reinforcement of soil to improve the bearing capacity, geotextiles and jute fibers have a significant effect [3]. Jute fiber mixed randomly with subgrade soil has significant impact on the improvement of subgrade characteristics [4]. It is also evident that the increase in the percentage of geotextile will increase the load bearing capacity of the soil [3]. Another study was conducted with the inclusion of various proportions of ceramic dust with clayey soil and found ceramic dust up to 20% may be used for improving the detrimental properties of clayey soil [5]. A study was also conducted to observe the effect of soda lime glass dust in stabilizing soils and found more percentage of glass dust added to the soil the properties of clayey soil improve more rapidly [6]. To increase the stability of slopes, the reinforcement techniques are also used as effective and dependable stabilization that effectively increases the Factor of Safety (FOS).

Soil nailing has proven to be a flexible and dependable technique because it can be adapted to different soil conditions, is easy to install, and can address specific site challenges. This technology was first reported to be applied for the permanent support of retaining walls in a cut in soft rock in France in 1961. Besides, in North America, soil nails were first introduced for temporary excavation support in Vancouver, in the late 1960's and early 1970's. It continued to grow in the 1970's, in France and Germany [7]. However, the success of soil nailing depends on various parameters, such as nail length, spacing, nail inclination, and the relationship between the nails and the surrounding soil. Also, the stability of a slope is significantly influenced by seismic forces and pore water pressure [8].

Numerous slope failures worldwide cause great financial loss, interruption of transportation, and may lead to loss of human lives in extreme circumstances [9]. To mitigate those losses, several studies were conducted to increase the stability of slopes. For the stabilization of slopes, a study was conducted on the seismic stability reinforced with geosynthetics and found that for large values of the seismic coefficient, the design of reinforced soil structures could prove to be very expensive or even impracticable [10]. Another modelling study was conducted on the hydro-mechanical reinforcements of plants to slope stability and found significant effects of soil stabilization in deeper depths (i.e., 1–2 m), where slip failure is normally of major concern [11]. In reinforcing soil mass, the soil nailing is a proven technique in which the reinforcement is installed horizontally or subhorizontally so that it improves the soil by acting in tension [1]. The soil nail inclination has an influencing performance of soil-nailed slopes [12]. Also, the nails' length has a significant effect on the location of slip surface and factor of safety [12 – 13]. The internal friction angle of soil has the highest impact on FOS for soil-nailed slope followed by the soil cohesion and then the nail's length [14]. In soil nailing, the spacing between nails greatly affects on the FOS. The soil nail spacing should be close to achieve massive soil nails interaction within the soil mass and it is recommended to be 1m to 2.5m in either horizontal or vertical directions [15].

The study of slope stability began in the early 1900s, with the Swedish Circle Method arising in the 1910s as an innovative technique that assumed circular failure surfaces to evaluate slope stability. This was succeeded by notable progress in the

1950s with the Bishop method, which improved the analysis by including interslice forces in a simplified way, thereby increasing accuracy for circular failures. The 1960s saw a significant advancement with the launch of the Morgenstern-Price and Spencer approaches, which ensured complete force and moment equilibrium, addressing complex slope geometries and heterogeneous soil conditions. In GeoStudio 2018 R2 software, the Morgenstern-Price method is prominently utilized for its thorough equilibrium analysis, suitable for both general slope stability and complex scenarios in SLOPE/W. The Spencer method provides detailed equilibrium solutions for varied soil profiles. The Bishop and Janbu methods are ideal for vertical slices and simplified conditions. For certain engineering assignments and complicated geology, the Corps of Engineers #1 and #2, Lowe-Karafath methods are used. Dynamic analyses like QUAKE/W (Newmark Deformation) and SIGMA/W (Stress) are also used to evaluate the seismic and pseudo-static stability. This makes a solid foundation for a full slope analysis. In this study, an attempt was made to find the optimum nail inclination angle, ideal nail length and nail spacing, varying the nail inclination angle with horizontal axis, nail length with optimum nail inclination and nail spacing with optimum nail inclination angle and ideal nail length.

2. METHODOLOGY

In this study, numerical simulation was carried out using GeoStudio SLOPE/W software. The analysis aimed to evaluate the factor of safety (FOS) under different design conditions using the limit equilibrium method. Hypothetical slope models were created in SLOPE/W to simulate the behavior of reinforced soil slopes. The Morgenstern-Price method was selected as the analysis type. The slip surface was defined using the "Half-Sine" function for both the entry and exit sides. The Entry and Exit slip surface search method was applied with movement from left to right, storing one critical slip surface without optimization, and no tension crack was included. Geometry was defined with a minimum slip surface depth of 0.1 m, divided into 30 slices. Factor of safety (FOS) convergence was achieved using the Root Finder search method, allowing up to 100 iterations with a tolerable FOS difference of 0.001. The analysis used effective stress strength parameters to represent the behavior of the homogeneous soil slope with and without nailing. Pore water pressure conditions defined by the Ru method, with Effective Stress Strengths considered for staged pseudo-static analysis and a unit water weight of 9.807 kN/m³. The physical properties of soil were considered as described in the Table 1. The pore water pressure (PWP) condition and seismic coefficients were defined as described in the Table 2.

Table 1. The soil properties of slope

Parameter	**Unit Weight, g (KN/m^3)**	**Cohesion, c (KN/m^2)**	**Angle of Internal Friction, Φ (°)**
Value	18	05	33

Table 2: Pore water pressure and Seismic coefficient

Parameter	**value**
Horizontal seismic coefficient (k_h)	0.15
Vertical Seismic coefficient (k_v)	0.10
PWP as R_u coefficient	0.25

Table 3. The soil nail properties

Parameter	**Value**
Tensile Capacity	300 KN
Pullout Resistance	100 kPa
Bond Diameter	0.318 m
Resistance Reduction Factor	1.5
Tensile Capacity Reduction Factor	1.5
Shear Reduction Factor	1.0
Apply Shear	Parallel to slip

The soil nail's properties used in this study as described in the Table 3. The designated bar capacity used 300 KN with a safety factor of 1.5 and a spacing of 1.5m. Consequently, the maximum load that can be applied 133.333 KN (300/1.5/1.5). The defined bond skin friction used 100 kPa with a safety factor of 1.5. Thus, the bond resistance that can be applied 44.444 KN/m (100/1.5/1.5). In this situation, the necessary bond length for the bar to utilize its allowable load of 133.333 KN is 3m (133.333/44.444). Therefore, the bond length available behind the slip surface must be sufficient to permit the nail to employ its maximum load [12]. So, the available bond length behind the slip surface should be long enough to allow the nail to use its maximum load.

2.1 Model parameters used in the stability analysis of slopes

For the purpose of the study, a variety of nail inclination, length, and spacing criteria were used. With a 5° increment in each analysis, the inclinations vary between 5° to 85° with the horizontal axis. For the hypothetical homogeneous soil slopes of 30° and 40° inclination with specific height of 14m, 45°, 50° and 60° with 12m and 70°, 75°, 80° and 90° with 10m were considered for the analysis. Also, for the analysis of inclinations, soil nails of length 16m for soil slopes 30° and 40° and 14m for soil slopes 45°, 50°, 60°, 70°, 75°, 80° and 90° were used in four rows with 1.5m spacing.

For the analysis of the effect of soil nail lengths, nails of 8m,

10m, 12m and 14m lengths were used with optimum nail inclination angle in the 40°, 60° and 80° soil slopes, which were modeled for the analysis of nail inclination angle.

Nail spacing of 1m, 1.5m, 2m and 2.5m were used with optimum nail inclination angle for the analysis of the effect of soil nail spacing in 30° soil slope that was modeled for the analysis of nail inclination angle. The model parameters used in the analyses as described in Table 4.

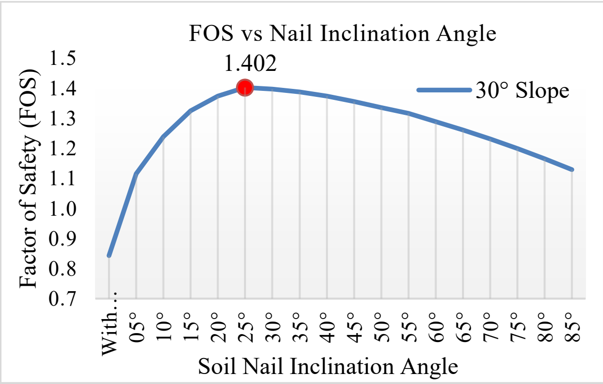
Table 4. Model parameters used in analysis

Soil Slope	30°	40°	45°	50°	60°	70°	75°	80°	90°
Slope Height	14m		12m			10m			
Nail Length	16m		14m						

3. RESULT AND DISCUSSION

3.1 Effect of soil nail inclinations on the stability of slopes

This study was conducted to determine the highest Factor of Safety (FOS) in order to evaluate the optimum soil nail inclination angle for different soil slopes. The FOS initially increases with an increase in nail inclination angle, but after attaining its maximum at the optimum angle, it starts decreasing. For 30°, 40° and 45° soil slopes the maximum FOS obtained was 1.402, 1.255 and 1.391 respectively for the optimum soil nail inclination of 25° with the horizontal axis. Also, for 50°, 60° and 70° soil slopes it was 1.335, 1.302 and 1.596 respectively for the optimum soil nail inclination of 20° with the horizontal, whereas it was 1.571, 1.584 and 1.574 for soil slopes of 75°, 80° and 90° respectively for optimum inclination angle of 15°. This result clearly shows that the ideal soil nail inclination is 15° for soil slopes 75° to 90°, 20° for soil slopes 50° to 70° and 25° for soil slopes 30° to 45°. Figure 1 shows the influence of soil nail inclinations on the Factor of Safety of slopes.



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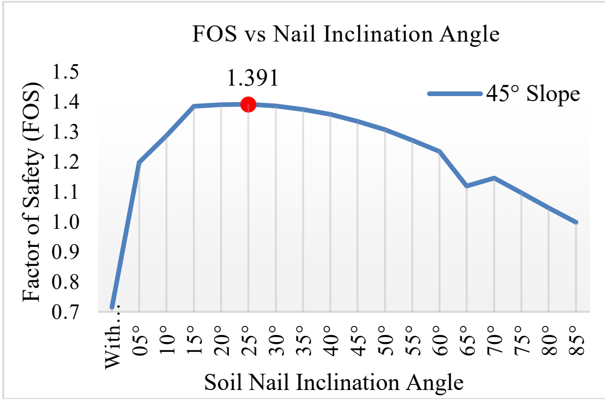

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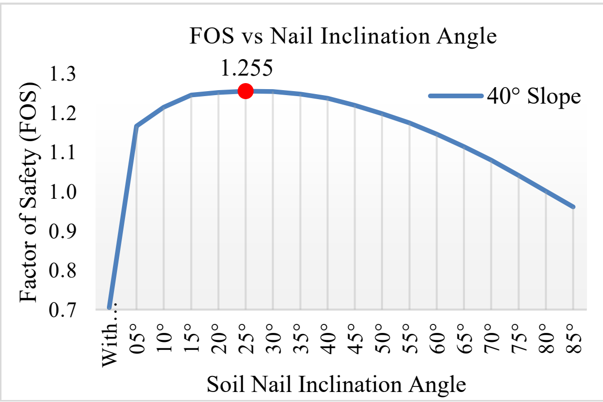

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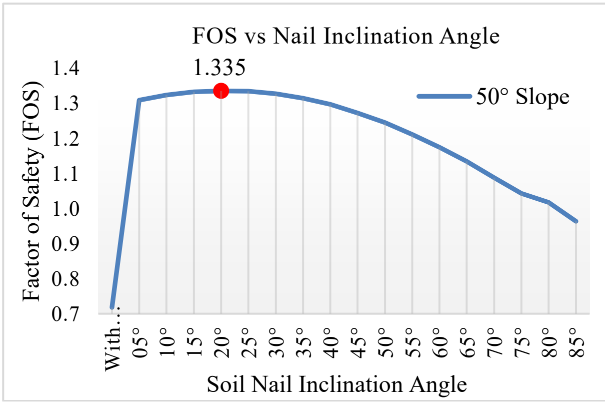

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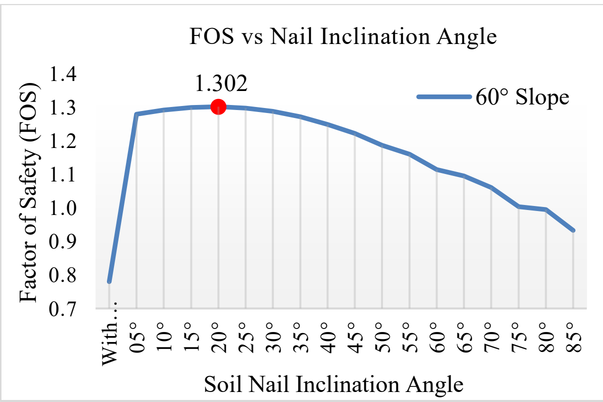

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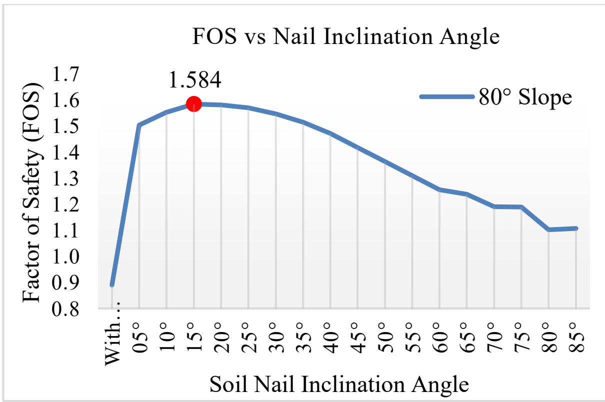

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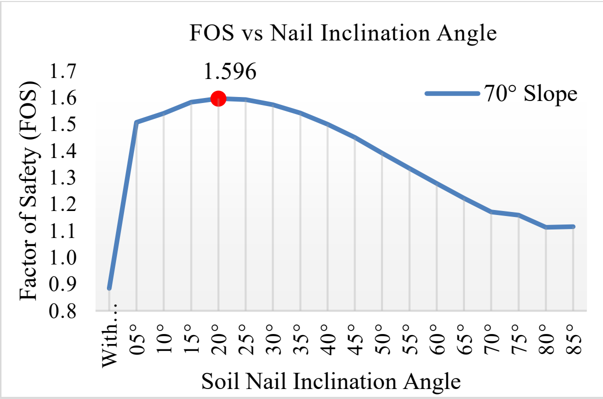

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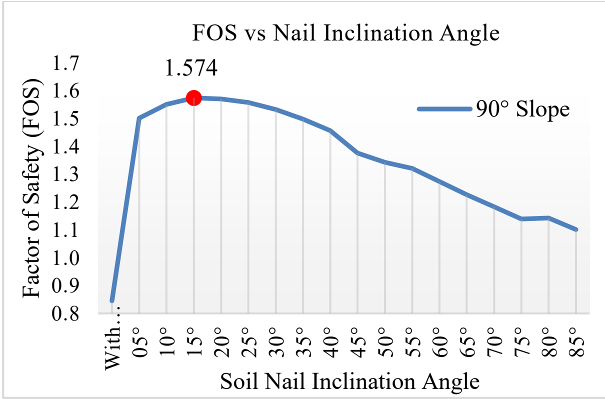
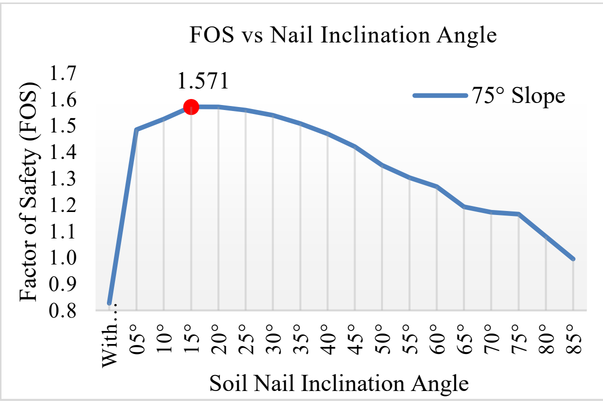


(i)



(g)

Fig 1: Shows the variations of FOS with respect to nail inclination angles on soil slopes of (a) 30°, (b) 40°, (c) 45°, (d) 50°, (e) 60°, (f) 70°, (g) 75°, (h) 80°, (i) 90°

The values of Factor of Safety (FOS) obtained from the analysis for different soil nail inclination angles on various soil slopes are also shown in Table 5. From the data in the table and Figure 1, it is clearly seen that the use of soil nails in soil slopes effectively increases the Factor of Safety. It also seen that initially the Factor of Safety (FOS) increases with an increase in the nail inclination angle with the horizontal axis and at an optimum angle of nail inclination it obtains the highest value then starts decreasing with further increase in the nail inclination angle. At the optimum nail inclination angle the nails provide a sufficient perpendicular force to resist sliding, maintaining a significant horizontal force for anchorage.

Thus, it is clearly evident that the soil nail inclination angle plays a crucial role in the stabilization of slope failures, as it directly influences the distribution of resisting forces within the soil mass. While improper angles may result in decreased effectiveness and early failure mechanisms, an ideal inclination increases the nail's ability to intercept possible slip surfaces, improve load transfer, and raise the overall factor of safety.

Table 5. Variations of FOS with respect to nail inclination angles on slopes

Nail Length	**16m**		**14m**						
Slope Height	**14m**		**12m**			**10m**			
Nail Inclination	**Factor of Safety (FOS) for Soil Slope**								
	30°	**40°**	**45°**	**50°**	**60°**	**70°**	**75°**	**80°**	**90°**
Without Nail	0.843	0.705	0.715	0.718	0.780	0.884	0.827	0.890	0.845
05°	1.115	1.166	1.197	1.309	1.280	1.507	1.484	1.503	1.501
10°	1.238	1.214	1.286	1.323	1.292	1.540	1.525	1.552	1.550
15°	1.325	1.245	1.384	1.332	1.300	1.582	1.571	1.584	1.574
20°	1.373	1.252	1.390	1.335	1.302	1.596	1.570	1.581	1.570
25°	1.402	1.255	1.391	1.334	1.298	1.592	1.559	1.570	1.557
30°	1.397	1.254	1.385	1.327	1.288	1.573	1.539	1.547	1.532
35°	1.387	1.248	1.374	1.314	1.272	1.542	1.508	1.514	1.498
40°	1.373	1.237	1.358	1.297	1.249	1.500	1.469	1.472	1.456
45°	1.355	1.219	1.334	1.272	1.222	1.450	1.420	1.418	1.376
50°	1.335	1.198	1.306	1.245	1.187	1.392	1.350	1.363	1.342

55°	1.316	1.174	1.271	1.211	1.160	1.334	1.303	1.310	1.321
60°	1.288	1.146	1.234	1.174	1.114	1.277	1.269	1.256	1.274
65°	1.261	1.114	1.119	1.134	1.095	1.222	1.192	1.238	1.227
70°	1.231	1.080	1.145	1.088	1.061	1.170	1.172	1.191	1.183
75°	1.199	1.041	1.096	1.043	1.004	1.159	1.165	1.189	1.139
80°	1.165	1.001	1.046	1.017	0.995	1.113	1.080	1.102	1.142
85°	1.129	0.961	0.998	0.963	0.933	1.115	0.995	1.107	1.101

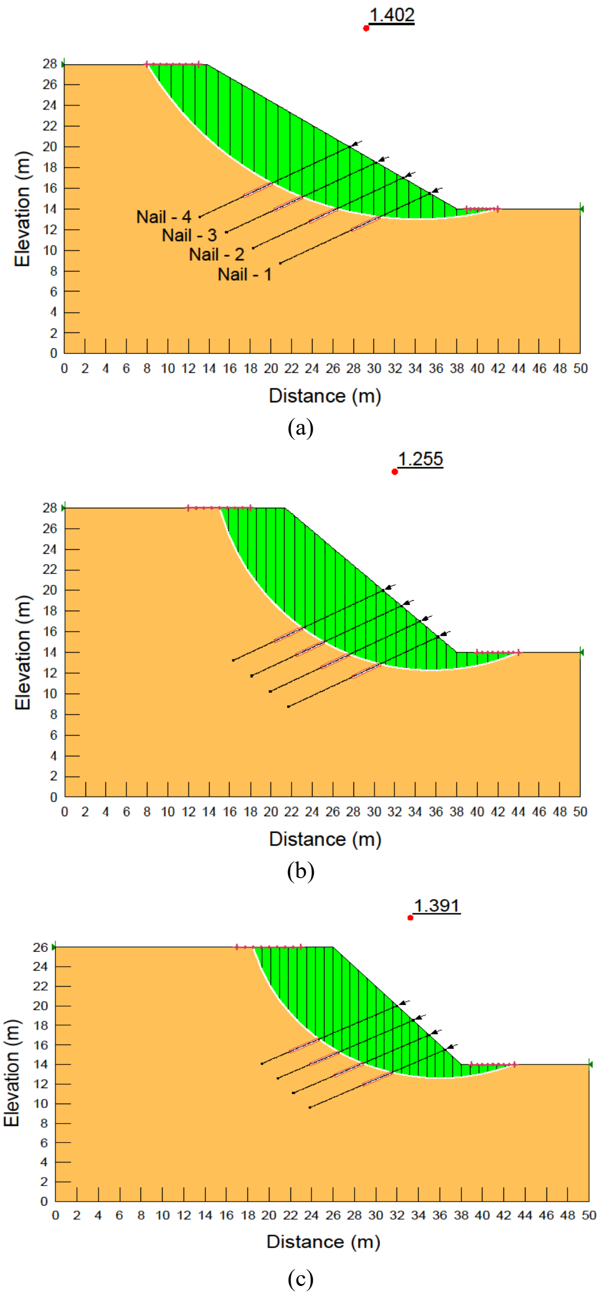


Fig 2: Shows FOS with optimum nail inclination angle 25° in modeled soil slopes of (a) 30°, (b) 40°, (c) 45°

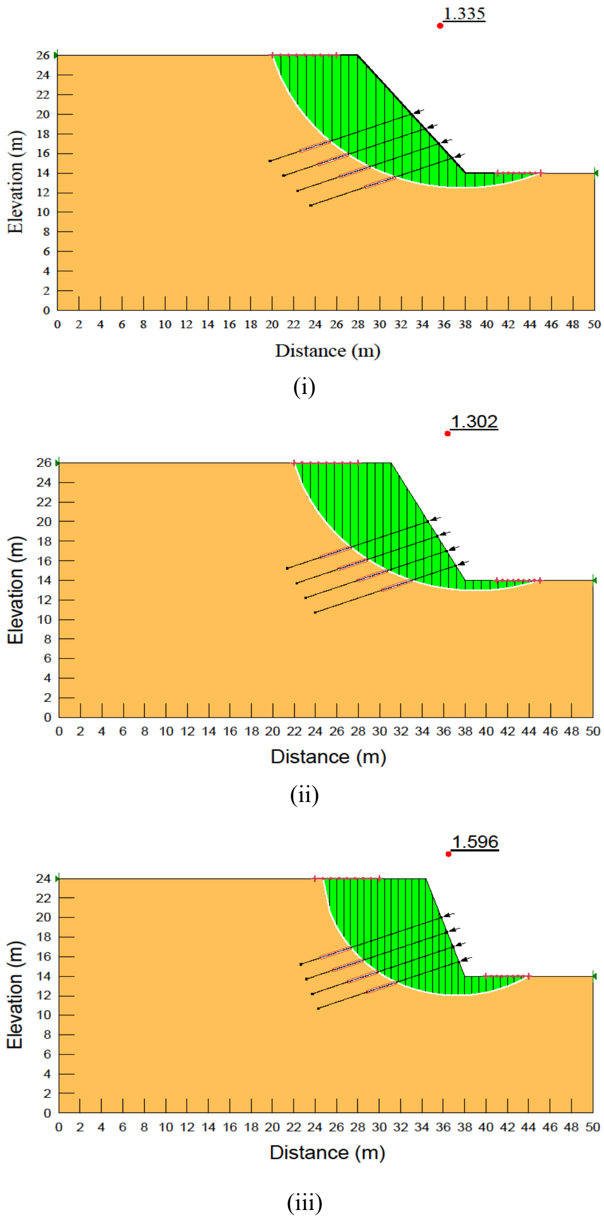
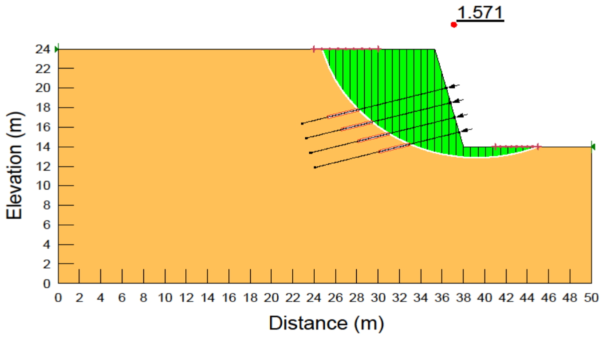


Fig 3: Shows FOS with optimum nail inclination angle 20° in modeled soil slopes of (i) 50°, (ii) 60°, (iii) 70°



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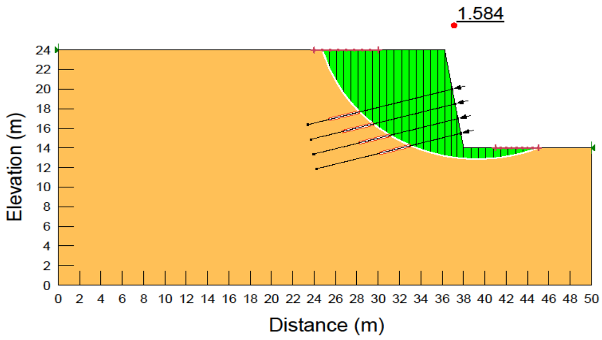

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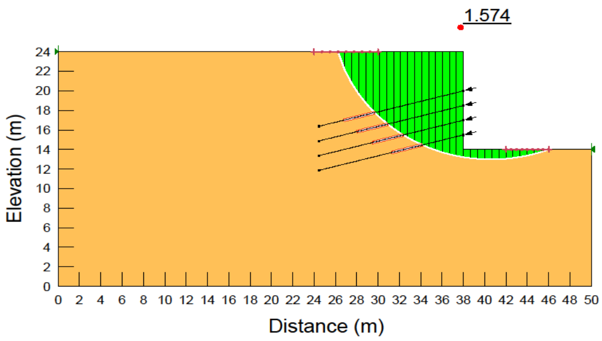

(3)

Fig 4: Shows FOS with optimum nail inclination angle 15° in modeled soil slopes of (1) 75°, (2) 80°, (3) 90°

For this analysis, in all the cases the available bond length was greater than 3m. The available bond length for one of the analyses of 60° soil slope is shown in Figure 5. This evidence shows that for optimum nail inclination is not dependent on the available bond length of soil nail behind the slip surface.

The nail's bearing capacity specially the tensile force of the nail is divided into parts that are parallel and perpendicular to the slip surface (factored tensile capacity = 133.333 kN). The perpendicular component resists sliding, while the parallel component anchors the nail in the stable soil. In a slope stability analysis using soil nails, the FOS is obtained by how well the nails mobilize their tensile capacity and pullout resistance against the driving forces. At optimum nail inclination angle a sufficient balanced slide resistance force and anchorage force are developed that maximize the FOS as well as the stability of the slopes. But, at nail inclinations lower than the optimum, the perpendicular component of the nail force to the potential failure plane is reduced, leading to lower shear resistance and a reduced Factor of Safety (FOS). On the other hand, at inclinations higher than the optimum, the effective axial resistance is reduced, which also lowers the FOS. The optimum inclination is achieved when the balance between perpendicular shear resistance and axial anchorage is maximized, resulting in a higher FOS and improved slope stability.

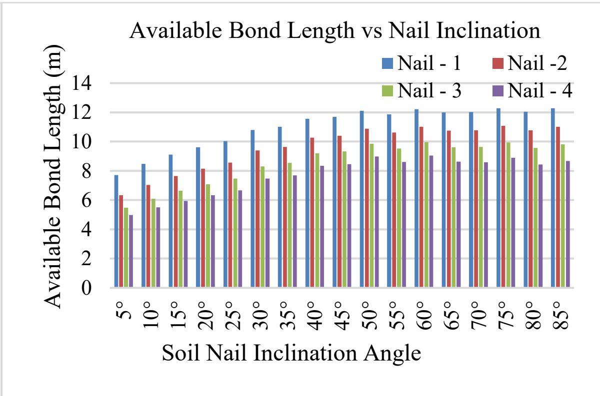

Fig 5: Shows available bond length with various nail inclination angles on soil slope of 60°

3.2 Effect of soil nail length on the stability of slopes

The nail length has a significant effect on the stability of slopes. With optimum nail inclination angle, for 2m increase in nail length the rate of increase in FOS was found 5%, 6.05% and 11.35% for the increase in nail length from 8m to 10m, it was 6.6%, 6.55% and 11.65% for 10m to 12m and 4.5%, 0% and 1.55% for 12m to 14m for soil slopes of 40°, 60° and 80° respectively. The result clearly shows that the FOS increases with the increase in nail length as the bond length increases behind the slip surface. As the nail length increases, deeper reinforcement of the slope is achieved, which enhances the stability of the slope. Figure 6 shows the influence of soil nail length on the Factor of Safety of slopes.

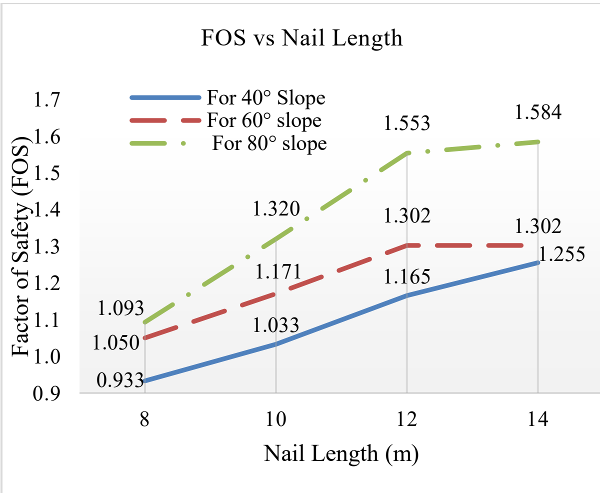

Fig 6: Variations of FOS with respect to nail length on 40°, 60° and 80° soil slopes with optimum nail inclination

Figure 7 shows the available bond length behind the slip surface. To utilize the nails allowable capacity the available bond length behind the slip surface should be enough for the nailing criteria (for this analysis, it should be at least 3m). As the length of nail increases, the allowable bond length of nail also increases allowing the best utilization of the allowable capacity of the bar. So, the bond length is the governing component. The factor of safety (FOS) increases with the increase in nail length resulting the higher stability of the slopes.

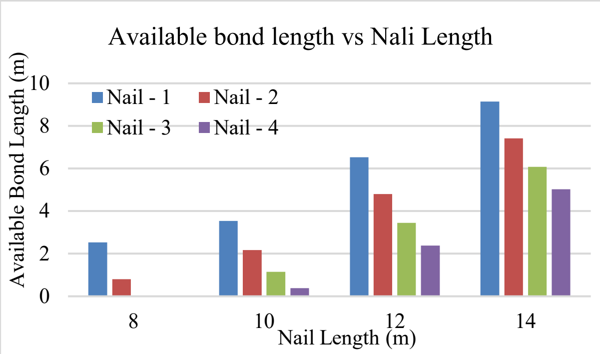

Fig 7: Shows available bond length with various nail lengths on soil slope of 80°

From the obtained data, it was found that for the range of nail length from 10m to 12m the rate of increase in FOS is higher than others. For smaller nails, some upper nails remain within the active failure zone that makes them inactive for providing resistance. On the other hand, longer nail can't provide more resistance than capacity, this makes the deeper part of nail useless to prevent failure. So, the ideal nail length for gentle slope of 30° to 40° should be 75% to 85%, for medium slope of 45° to 60° should be 85% to 100% and for steep slope of 70° to 90° should be 100% to 120% of the height of the soil slopes.

3.3 Effect of soil nails spacing on the stability of slopes

The nail spacing also has a significant effect on the stability of slopes. With optimum nail inclination angle of 25° in soil slope of 30°, the FOS was found to be 1.587, 1.402, 1.226 and 1.133 for nail spacing of 1m, 1.5m, 2m and 2.5m respectively. The result clearly shows that the FOS decreases with the increase in nail spacing as the bar's capacity is divided by bar spacing. However, installing too many nails too closely may adversely affect slope stability, as it can reduce the effective area of each nail. Figure 8 shows the influence of soil nail spacing on the Factor of Safety of slope.

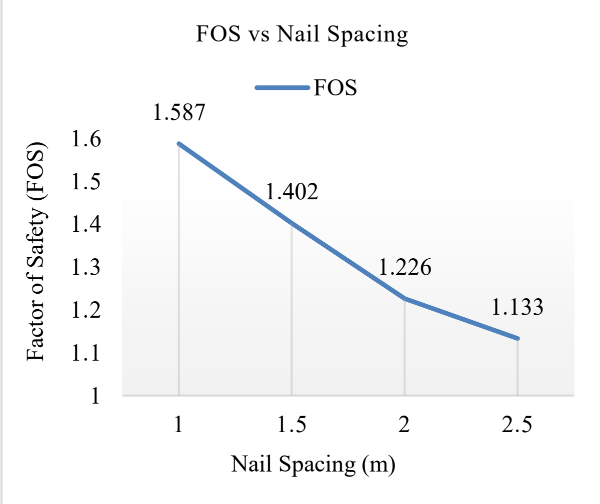

Fig 8: Variations of FOS with respect to nail spacing on 30° soil slope with optimum nail inclination of 25°

As the allowable capacity of nails is divided over the nail spacing, the capacity decreases with the increase in nail spacing. Also, the FOS increases with the increase in the allowable capacity of nails. As a result of this, the stability of the slope increases resulting higher Factor of Safety. Figure 9 shows the decrease in allowable load capacity and the bond resistance for nail spacing from 1m to 2.5m. As the nail spacing increases the effective mass of soil supported by a nail is also increased this decreases the resisting capacity of the nail. With the same strength a nail can't effectively support the larger soil mass this reduces the overall stability of the slope as well as factor of safety (FOS). For this the nail spacing should be in the range that provides better stability with optimum cost.

From the obtained data it was found that for the increase in nail spacing from 1m to 1.5m, 1.5m to 2m and 2m to 2.5m the rate of decrease in FOS was 37%, 35.2% and 18.6% respectively. For better stability with cost effectiveness the nail spacing should be within the range of 1m to 2m in both horizontally and vertically.

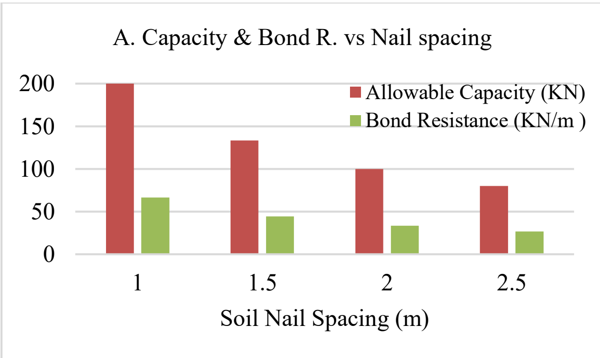

Fig 8: Shows the allowable load capacity and bond resistance with various nail spacing

4. CONCLUSION

The analyses were carried out to determine the best way to use soil nailing to reinforce soil slopes. Using nails has a significant effect on enhancing the stability of the slope. Based on the above investigation and Discussion, the main conclusions can be summarized as follows:

- To obtain greater FOS as well as greater stability of slopes by nailing the angle of installation of nails should be set at its optimum value. The optimum values are 25° for soil slopes of 30°, 40° and 45°; 20° for soil slopes of 50°, 60° and 70°; 15° for soil slopes of 75°, 80° and 90°.
- At the optimum angle of inclination of soil nail the tensile force of nails is effectively divided into balanced parts that resist sliding and develop efficient anchorage
- As steeper slopes are more vulnerable than gentle slopes, the ideal nail length should be about 75% to 85% of the slope height for gentle slopes (30° to 40°), 85% to 100% for medium slopes (45° to 60°) and 100% to 120% for steep slopes (70° to 90°).
- The FOS decreases with the increase in nail spacing as the allowable capacity of nails is divided over the spacing resulting in a decrease in the stability of slopes. For the increase in nail spacing from 1m to 1.5m, 1.5m to 2m and 2m to 2.5m the rate of decrease in FOS was 37%, 35.2% and 18.6% respectively. For better stability with cost effectiveness the nail spacing should be within the range of 1m to 2m in both horizontally and vertically.

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