Optimum to Effective Soil Nail Inclination for Slope Stability using GeoStudio

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ABSTRACT

Soil nailing is a widely adopted and cost-effective technique for enhancing the stability of soil slopes in excavations, landslide-prone areas, and infrastructure projects. In this paper, with optimum soil nail inclination angle, an attempt has been made to find an effective way of nailing the slopes for better stability in terms of Factor of Safety (FOS). Using SLOPE/W (GeoStudio 2018 R2), several nail inclination angles with a horizontal axis were applied to a simulated homogenous soil slope (slope angles 30°, 45°, 60°, 75°, and 90°) to get a higher Factor of Safety. The factor of safety was calculated using the Mohr-Coulomb expression and the limit equilibrium (LE) approach in the Morgenstern-Price method, considering pore water pressure as the Ru value. The results indicate that using the upper nails inclination angle below the optimum angle (25° for 30° and 45°, 20° for 60°, and 15° for 75° and 90° soil slopes) used in the lower nails increases the Factor of Safety for gentle (30°) and medium (45° and 60°) soil slopes. The upper nails inclination angle ranging from 5° to 15° gives a higher value of FOS than with the optimum nail inclination angle for those slopes, but for the steep soil slopes (75° and 90°) the higher FOS value is obtained by nailing the upper and lower nails with the optimum inclination angle. Better stability and a greater Factor of Safety (FOS) result from nailing a soil slope with the optimum nail inclination angle at the lower nails and a lower nail inclination angle at the upper nails (between 5° and 15°) for gentle and medium soil slopes and for steep slopes with optimum nail inclination all over the slope.

Keywords

Slope Failure, GeoStudio, Factor of safety, Inclination, Morgenstern-Price method, Soil nail.

1. INTRODUCTION

Soil nailing has emerged as an efficient and economical technique for stabilizing soil slopes and excavations by installing passive reinforcing elements, typically steel bars grouted into the soil, which mobilize tensile resistance through soil-nail interaction. In soil nailing, the reinforcement is installed horizontally or sub-horizontally so that it improves the shearing resistance of the soil by acting in tension [1]. The grout is applied to protect the steel bars from corrosion and to transfer the load efficiently to the nearest stable ground [2]. Among the key design parameters of soil nailing, the inclination angle of the nails significantly influences the overall stability, pull-out resistance, and deformation behavior of the nailed soil mass. The Factor of Safety (FOS) of slopes 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 [3][4]. At the optimum nail inclination angle, the nails provide a sufficient perpendicular force to resist sliding, maintaining a significant horizontal force for anchorage [4]. Numerous studies have employed the classical limit equilibrium method to analyze the stability of reinforced soil slopes [3][4][5][6][7][11][12]. A study developed an optimal computer-based design method for nailed soil slopes, in which the ideal spacing, orientation, and diameter of the nails are determined to maximize the factor of safety while identifying the critical slip surface [8]. Experimental and numerical analyses have shown that, in addition to slope geometry and soil characteristics, factors such as nail angle, length, spacing, and cable properties significantly influence the stability of nailed soil slopes [9][10]. Very few studies considered the influence of back slope inclination [9][13].

Many studies are conducted worldwide to find the suitable nail inclination, and numerical simulations revealed that horizontal nails are most effective for vertical slopes, while for inclined slopes, optimal nail orientation varies with slope gradient [14]. A case study further revealed that soil nail inclination has only a slight effect on the stability of soil-nailed walls when the inclination angle varies between 5° and 20° from the horizontal [15]. Experimental studies on 60° sand slopes further showed that nails installed at 0° (horizontal) are more efficient in providing stability compared to those at 15° and 30° inclinations [16]. A numerical analysis again indicated that the FOS improved significantly at nail inclination of 40° [17]. These variations observed across previous studies establish a strong foundation for conducting a detailed slope analysis. In this study, an attempt was made to determine the optimal nail inclination angle for different positions on the inclined slope surface using three sets of nails (upper, middle, and lower). Obtaining the optimum nail inclination angles, an attempt was also made to find the effective nailing on the soil slopes.

2. METHODOLOGY [4]

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 were 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 Table 1. The pore water pressure (PWP) condition and seismic coefficients were defined as described in Table 2.

Table 1. The soil properties of slope [4]

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 [4]

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 [4]

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 are described in 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 [6]. 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 angles were used. With a 5° increment in each analysis, the inclinations vary between 5° to 50° with the horizontal axis. For the hypothetical homogeneous soil slopes of gentle and medium gradient (30° to 60°) three sets of nails (upper, middle, and lower) and two sets of nails (upper and lower) for steep slopes (75 ° and 90°) were used in four rows with 1.5m spacing. The soil nail sets are applied to the hypothetical soil slopes at different positions depending on the height along the slope. Figure 1, Figure 2 and Figure 3 show the position of the upper, middle and lower nail sets accordingly. In this study, an optimum inclination angle was determined for each set of nails.

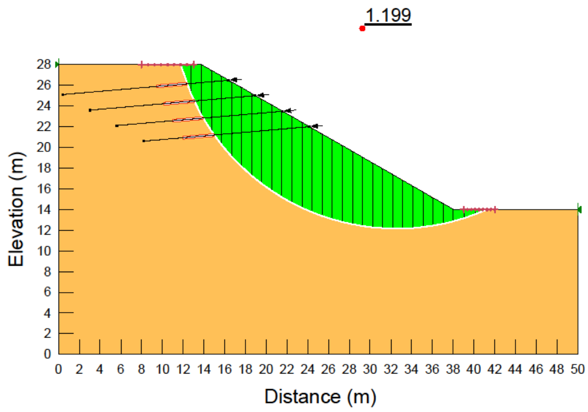

Fig 1: Shows FOS with upper nail set inclination angle 5° in modeled soil slopes of 30°

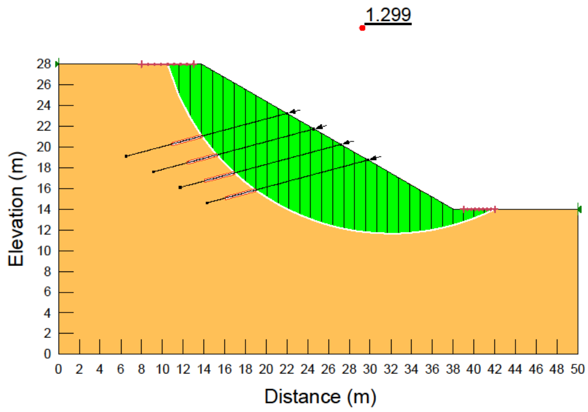

Fig 2: Shows FOS with middle nail set inclination angle 15° in modeled soil slopes of 30°

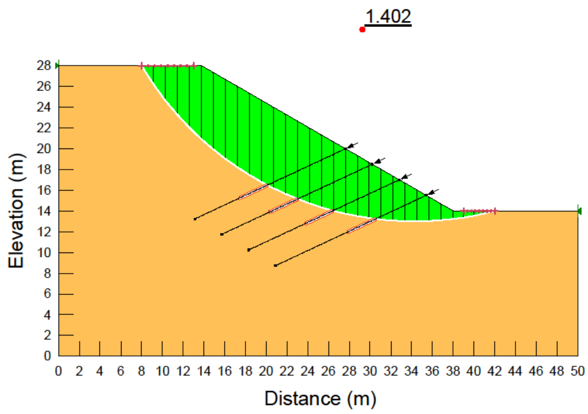

Fig 3: Shows FOS with lower nail set inclination angle 25° in modeled soil slopes of 30°

The model parameters used in the analyses are described in Table 4.

Table 4. Model parameters used in analysis

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

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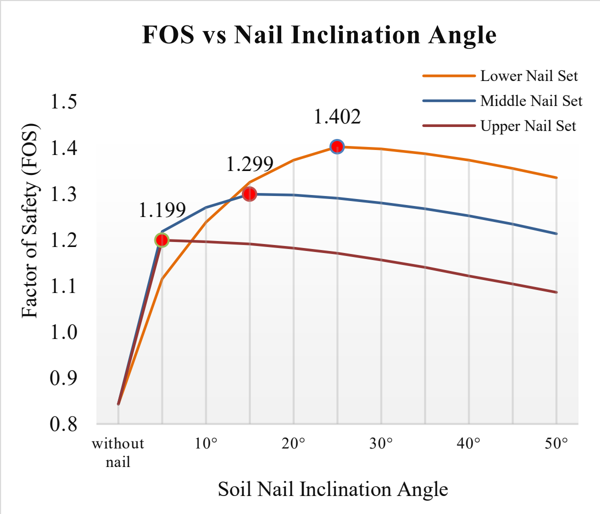
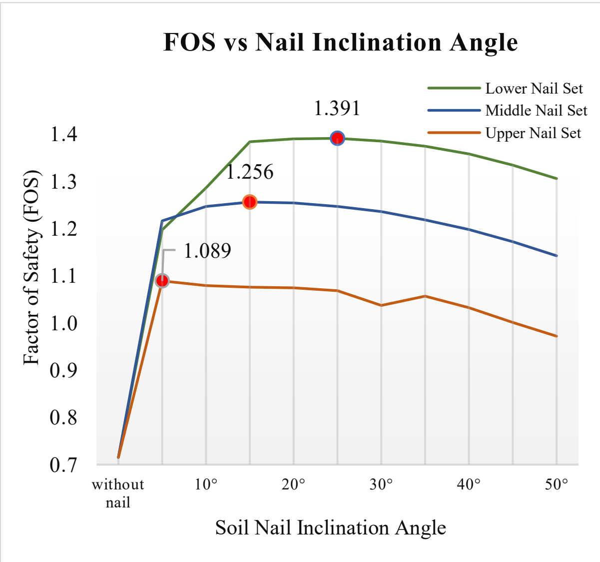
3. RESULT AND DISCUSSION

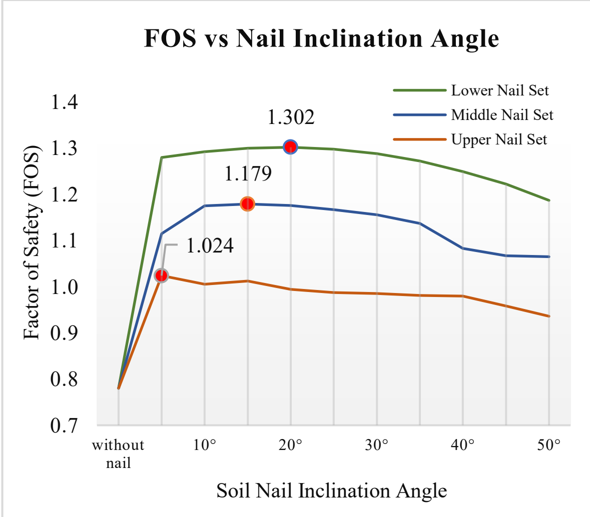
This study was conducted to determine the highest Factor of Safety (FOS) for used three sets of nails to evaluate the optimum nail inclination angle with respect to the position of the nails according to height. The FOS obtained its maximum value at the optimum angle and indicated the suitable nail inclination angle for this position of the slopes. For three sets of nails (upper, middle, and lower), three different nail inclination angles are obtained with the highest FOS for a given slope. Figure 4 shows the variation of Factor of Safety (FOS) with nail inclination angle for different nail sets on soil slopes.



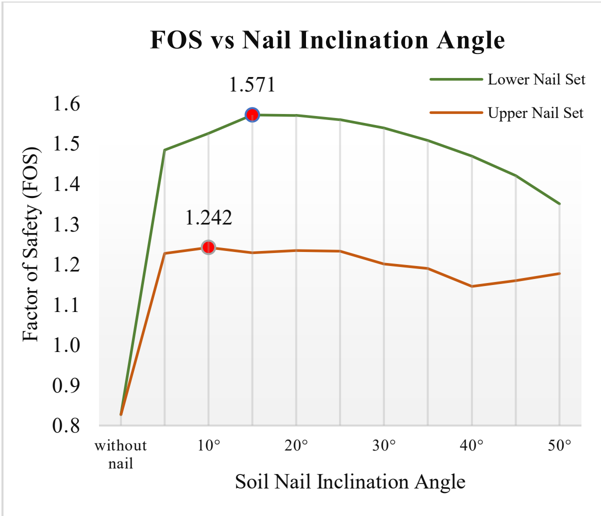
(a)



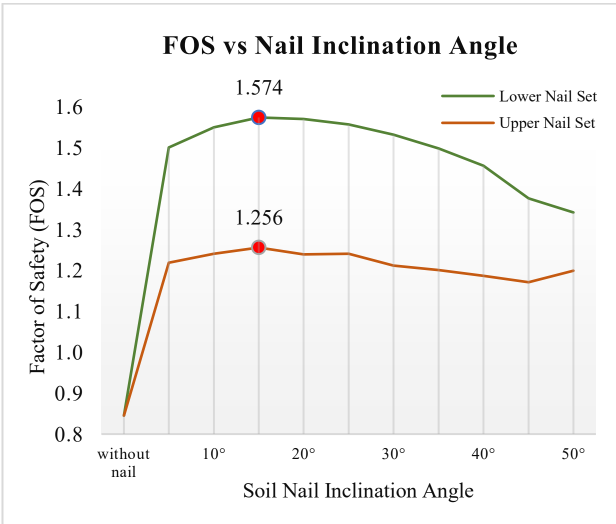
(b)



(c)



(d)



(e)

Fig 4: Shows the variations of FOS with respect to nail inclination angles for nail sets on the soil slopes of (a) 30°, (b) 45°, (c) 60°, (d) 75°, (e) 90°

The analysis determines the optimum nail inclination angle that yields the highest Factor of Safety (FOS). However, the optimum inclination angles varied for different nail sets on the same simulated soil slope. This variation occurs because of the shape of the critical slip surface generated during slope analysis, which governs the failure mechanism. At the optimum nail inclination angle, the soil nails provide better resistance against slope failure. The horizontal component of the nail force contributes to pullout resistance, thereby anchoring the nails firmly in position, while the vertical component resists the movement along the slip surface, enhancing overall slope stability.

From this study, the optimum nail inclination angle was found to be 25° for the 30° and 45° soil slopes, 20° for the 60° soil slope, and 15° for the 75° and 90° soil slopes at the lower nail set. For the middle and upper nail sets, the optimum inclination angle ranged between 5° and 15° across all slopes.

Since the optimum nail inclination varies with the position of the nails along the slope height, an attempt was made to identify the most effective nailing pattern over the entire slope. It was observed that, for gentle to medium slopes (30° to 60°), installing the lower nails at their respective optimum inclination while keeping the middle and upper nails at inclinations between 5° and 15° yielded a higher Factor of Safety (FOS) compared to using a single optimum inclination angle throughout the slope. However, for steep slopes (75° to 90°), using a single optimum inclination angle (corresponding to the lower nail set) across the entire slope produced the highest FOS. The results found in these analyses were shown in Figure 5 and Table 5.

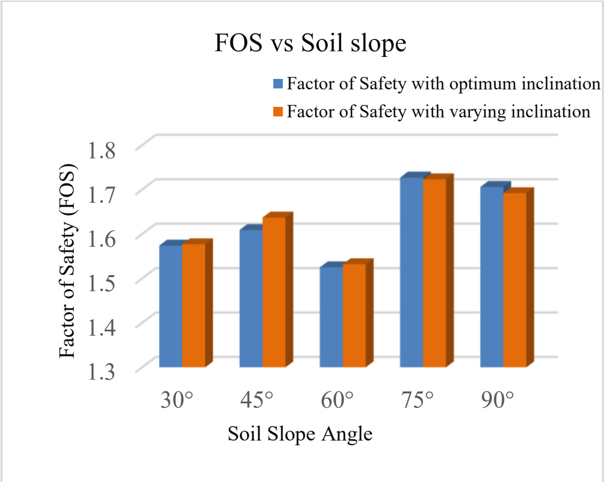
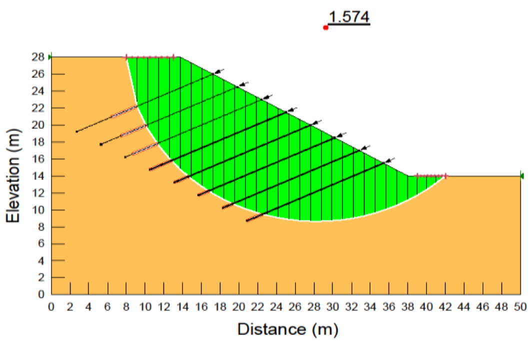
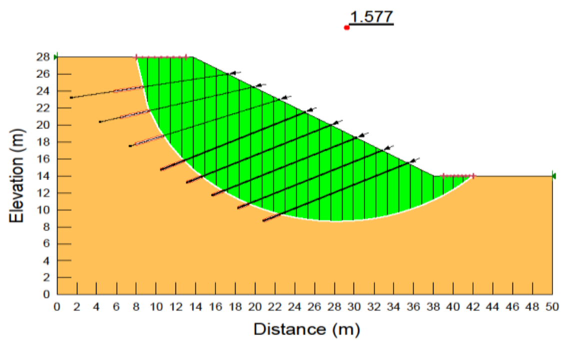
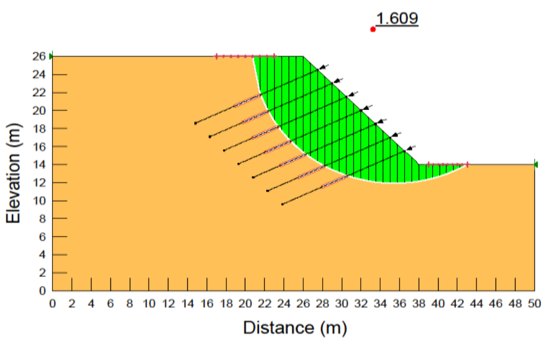
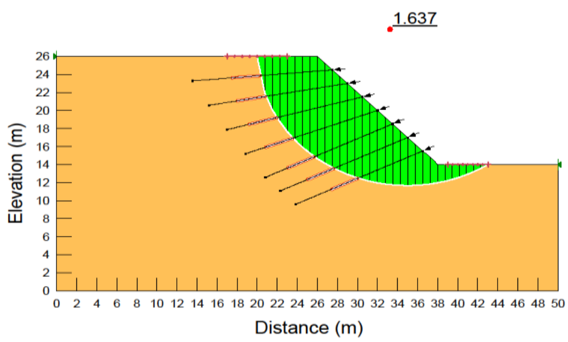
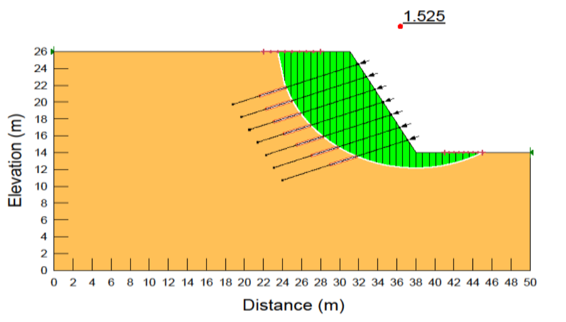
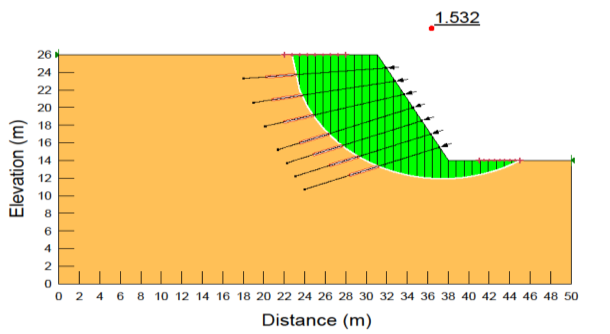
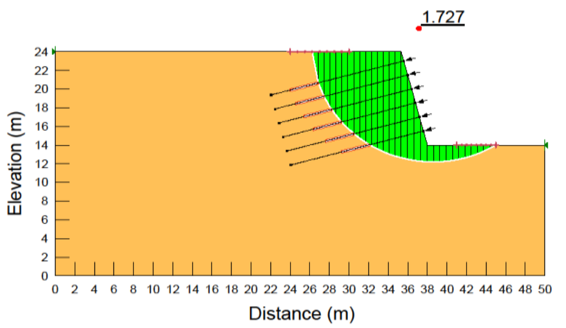
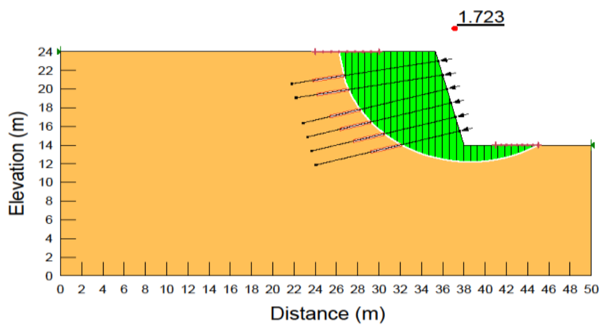
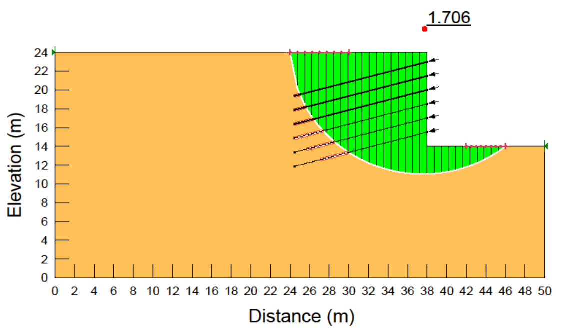
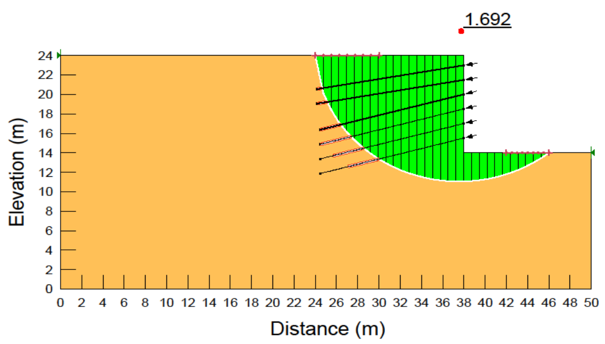


Fig 5: Shows Factor of Safety with respect to soil slope angle.

Table 5. The soil slopes with nailing

Slope Angle	Nailing the slope with a single optimum nail inclination angle found at its lower nail set	Nailing the slope with varying nail inclination angle
30°		
45°		

60°		
75°		
90°		

4. CONCLUSION

This study was conducted to determine the effective nail inclination for reinforcing soil slopes. Reinforcing soil slopes using the soil nailing technique significantly improves slope stability in terms of the Factor of Safety (FOS). Based on the results of the investigation and the discussion presented above, the main conclusions can be summarized as follows:

- Installing nails at the lower portion of the slope is more effective than placing them at the middle or upper portions.
- To obtain greater stability in terms of FOS, the nail should be installed at its optimum inclination at the lower height and at the middle and upper heights with the inclination between 5° to 15° for gentle and medium soil slopes (30 ° to 60°).
- For the steep slopes (75° to 90°) of medium height, the nails should be installed at its optimum inclination angle (found at lower height) all over the slope height to obtain greater stability with higher FOS.

5. REFERENCES

[1] Bruce, D.A. and Jewell, R.A., 1986. Soil nailing: application and practice-part 1. *Ground engineering*, *19*(8), pp.10-15.

[2] Budania, R., Arora, R.P. and Ce, C., 2016. Soil nailing for slope stabilization: an overview. *International Journal of Engineering Science*, *3877*.

[3] Hossain, M.A. and Islam, A., 2016. Numerical analysis of the effects of soil nail on slope stability. *International Journal of Computer Applications*, *141*(8), pp.12-15.

[4] Hossain, M.A. and Rahman, M.N., Optimizing Soil Nail Configuration for Slope Stability using

GeoStudio. *International Journal of Computer Applications*, *975*, p.8887.

[5] Mandal, B. and Mandal, S., 2016. Assessment of mountain slope instability in the Lish River basin of Eastern Darjeeling Himalaya using frequency ratio model (FRM). *Modeling Earth Systems and Environment*, *2*(3), p.121.

[6] Deng, G., Xu, T., Chen, R., Lu, Z. and Liu, J., 2018. Numerical analysis on stabilizing mechanism of soil nails in steep fill slopes subjected to rainfall infiltration using a hypoplastic model. *Arabian Journal for Science and Engineering*, *43*(10), pp.5079-5090.

[7] Zewdu, A., 2020. Modeling the slope of embankment dam during static and dynamic stability analysis: a case study of Koga dam, Ethiopia. *Modeling Earth Systems and Environment*, *6*(4), pp.1963-1979.

[8] Patra, C.R. and Basudhar, P.K., 2005. Optimum design of nailed soil slopes. *Geotechnical & Geological Engineering*, *23*(3), pp.273-296.

[9] Fan, C.C. and Luo, J.H., 2008. Numerical study on the optimum layout of soil–nailed slopes. *Computers and Geotechnics*, *35*(4), pp.585-599.

[10] Garg, A., Garg, A., Tai, K. and Sreedeep, S., 2014. An integrated SRM-multi-gene genetic programming approach for prediction of factor of safety of 3-D soil nailed slopes. *Engineering Applications of Artificial Intelligence*, *30*, pp.30-40.

[11] Zhou, X.P. and Cheng, H.J.E.G., 2013. Analysis of stability of three-dimensional slopes using the rigorous limit equilibrium method. *Engineering Geology*, *160*, pp.21-33.

[12] Alejano, L.R., Ferrero, A.M., Ramírez-Oyanguren, P. and Fernández, M.Á., 2011. Comparison of limit-equilibrium, numerical and physical models of wall slope stability. *International Journal of Rock Mechanics and Mining Sciences*, *48*(1), pp.16-26.

[13] Rotte, V., Viswanadham, B. and Chourasia, D., 2011. Influence of slope geometry and nail parameters on the stability of soil-nailed slopes. *International Journal of Geotechnical Engineering*, *5*(3), pp.267-281.

[14] Marwane, H., Mohamed, E.H., Mohammed, M., Bensaid, M., Kamal, B., Mohammed, A. and Morabit, A., 2024. Soil nailing for slope stabilization: an overview. *Interactions*, *246*(1), p.14.

[15] Alsubal, S., Harahap, I.S. and Babangida, N.M., 2017. A typical design of soil nailing system for stabilizing a soil slope: case study. *Indian J Sci Technol*, *10*(4), pp.1-7.

[16] Singh, S. and Shrivastava, A.K., 2017. Effect of soil nailing on stability of slopes. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, *1*.

[17] Mangnejo, D.A., Oad, S.J., Kalhoro, S.A., Ahmed, S., Laghari, F.H. and Siyal, Z.A., 2019. Numerical analysis of soil slope stabilization by soil nailing technique. *Engineering, Technology & Applied Science Research*, *9*(4), pp.4469-4473.