

Numerical Modeling of Soil-Nailed Slope Using Drucker–Prager Model



Sagar Jaiswal , Ananya Srivastava , and Vinay Bhushan Chauhan 

Abstract Soil nailing is an efficient in-situ ground improvement technique that is being used extensively in the field to stabilize the unstable artificial or natural soil slopes. In this paper, a parametric study is done by varying the soil nailing parameters, namely the length (L) and the inclination of soil nails (α), with respect to the horizontal for a steep soil slope ($\beta = 40^\circ$). A finite element method-based program (Optum G2) has been used to analyze the soil slope using the shear strength reduction method. The Drucker–Prager failure criterion is considered in this study to model the soil slope. A soil slope of height (H) 6 m is considered, and the nail inclination (α) is varied from 0° to 50° in 10° intervals from the horizontal to get the best orientation of nail arrangement and study their effects on the performance of the overall slope based on the calculated factor of safety of the soil slope. Findings of the present study indicate that the length and the inclination of the soil nail are the major governing parameters to control the stability of the slope and based on above-mentioned outcomes, optimum length, and the orientation of soil nail are recommended and the transition of possible modes of failure of the slope are discussed for reinforced and unreinforced slope.

Keywords Slope stability · Soil nail · Drucker–Prager criterion · Strength reduction · Factor of safety

1 Introduction

Analysis of soil slope stability has gained attention in the recent past due to an increase in construction near the slopes. The soil slopes are susceptible to collapse due to nearby excavation activities, rainfall infiltration, or natural calamities and ground surface failure owing to detachment of the soil layers. The extent and possibility of failure of soil slopes mainly depend upon the shear strength of soil, soil slope inclination, erosion due to precipitation, and other man-made activities near the site.

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Soil nailing is an in-situ ground improvement technique in which reinforcement of ground is done with the nails, which are generally made up of hollow steel tubes or high yielding strength deformed (HYSD) bars. In this technique, the reinforcement is generally needed to be installed horizontally or slightly inclined parallel to the direction of tensile strain to develop the maximum tensile force in the soil nails, which is passive structural inclusion to stabilize the unstable ground. This technique is often used as a permanent or temporary soil slope/earth-retention system for steep slopes. Usually, soil nails are installed in predrilled holes and grouted under pressure with a joint hose, and thus, the mortars transfer the load to the soil nails through friction which leads to soil stability [1].

There are many advantages associated with this ground improvement technique, which can be roughly divided into three major categories, i.e., cost, design, and performance [2]. The construction of the soil-nailed slope is relatively quick, inexpensive, and sustainable compared to many other practices to stabilize the slope because it is less disruptive to traffic. Soil nails are flexible in terms of performance, and their deflections are usually within the tolerable limit.

It has been previously reported that the force generated by soil nails can reduce the principal strain in soil by decreasing the displacement of soil layers and subsequently improve the slope stability by creating a bond between the surrounding soil or friction between the adjacent soil that is reinforced between two soil nails [3]. The slope reinforced with soil nail can be divided into two zones, i.e., active zone and passive zone. At the time of slope failure, an axial shift in soil nails is observed due to the deformation of the active zone. The displacement of the reinforced bars tends to develop pulling force in the soil nails present in the passive region, which in turn resist the deformation in the active region. The length of soil nails is considered in such a manner that they are embedded sufficiently in the passive zone to resist the pull-out generated in the soil nail due to the friction produced between the surrounding soil and the nails.

Several methods of soil nailing are currently available for slope stabilization, such as the German method [4], the French method [5], the Davis method [6], and the finite element method [7], of which the first three methods are based on limit equilibrium approach, whereas the latter one is based on the limit analysis. However, an upper bound and lower bound solutions give an exact idea of the range of the factor of safety which can be certainly used to design the slope with confidence, which is limited in the available literature.

Given above, in the present work, slope stability analysis has been carried out using a finite element program taking into account the Drucker–Prager criterion for the soil. Also, the effect of soil nailing technique has been analyzed by varying the length of soil nails ranging from 2 m to 8 m having an interval of 2 m to get the optimum length by considering the spacing between soil nail, $s = 1$ m, for each simulation. Moreover, the effect of the soil nail inclination with the horizontal (α) on the stability of the slope is studied by varying α as shown in Fig. 1. The upper bound and lower bound strength reduction analysis is performed to examine the factor of safety (FOS) of a slope with a height, $H = 6$ m, and a slope angle (β) of 40° .

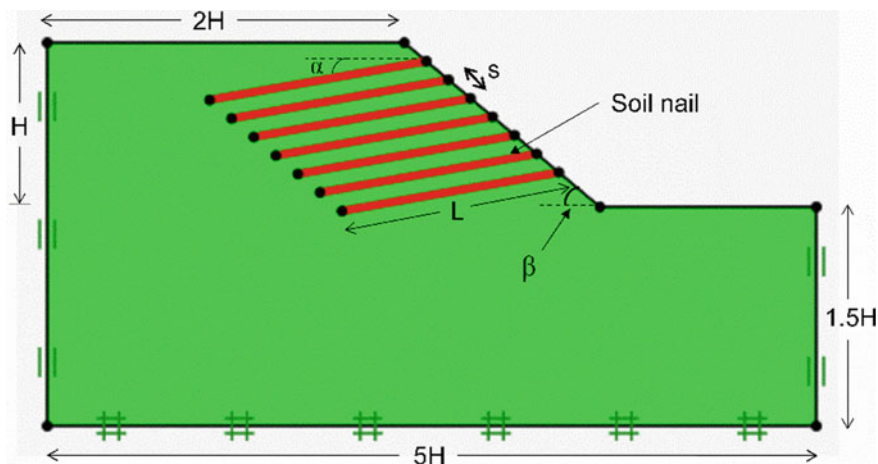


Fig. 1 Schematic diagram of slope reinforced with soil nails

2 Numerical Modeling

A slope stability analysis has been carried out for a soil slope with height, $H = 6$ m and a slope angle of $\beta = 40^\circ$ from the horizontal, using two-dimensional finite element method-based numerical tool Optum G2 [8]. The soil slope is reinforced with soil nails at six different inclinations from the horizontal, i.e., 0° , 10° , 20° , 30° , 40° , and 50° , respectively (as shown in Fig. 1), and their effects on the factor of safety (FOS) have been studied using shear strength reduction method. The Drucker–Prager model is chosen to represent the soil behavior in the numerical model for performing finite element analysis, and the plane strain condition with associated flow rule is considered in the present study. The boundary conditions considered in this study are roller support at the vertical ends of the boundary and fixed support at the bottom. A schematic representation of the geometric configuration of soil slope reinforced with soil nails is shown in Fig. 1.

The strength reduction in Optum G2 is analyzed by calculating a strength reduction factor in order to reduce the material parameters to attain the state of incipient collapse [9]. The strength parameters of the Drucker–Prager model are cohesion, k (kPa), and friction coefficient, M , and the factor of safety for the considered failure criterion is defined in Eq. 1 [9]:

$$\text{FOS} = \frac{k}{k_{\text{red}}} = \frac{M}{M_{\text{red}}} \quad (1)$$

The accuracy of a numerical model analyzed with finite elements simulations depends upon the selection of the total number of elements for a generated mesh as noted from the previous findings [10]. For a high precision of FOS, it is necessary to take a large number of elements, whereas taking a large number of elements for a

given mesh may elapse elongated computational time than usual. On account of the above, a sensitivity analysis is performed to find out an optimum number of elements for the mesh considered in this study. The number of elements has been increased from 1000 to 6000 at an interval of 1000 each, and FOS is observed in both the lower bound (LB) and upper bound (UB) analyses, and it is observed that 4000 elements are enough for the mesh considered in this analysis (Fig. 2). The typical properties considered in this study are shown in Table 1.

In the present study, a soil slope with angle $\beta = 40^\circ$ is considered and its FOS has been determined by strength reduction analysis. Furthermore, the soil slope is reinforced with soil nails at various inclinations from the horizontal, and again, the FOS has been determined. A parametric study is also performed to ascertain the FOS of the soil slope, the length of soil nails is varied from 2 to 8 m with an increment of 2 m each, and the best length is determined to carry out further study. The analysis

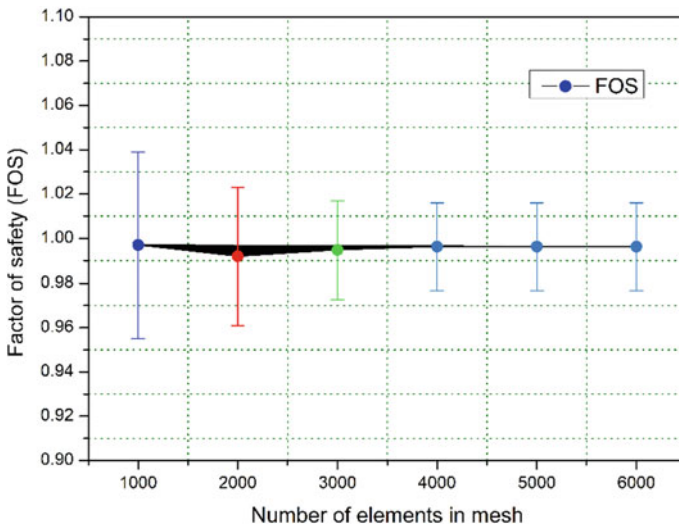


Fig. 2 Sensitivity analysis for the considered mesh in the present study

Table 1 Material properties used in this study

Properties	Soil	Soil nail
Lateral strength, $F_{L, \max}$ (kN/m) ^a	–	42
Axial strength, $F_{A, \max}$ (kN/m) ^a	–	415
Young’s modulus, E (MPa) ^{b, a}	30	2.6×10^4
Cohesion, k (kPa) ^b	12.33	–
Friction coefficient, M ^b	0.613	–
Poisson’s ratio, ν ^b	0.25	–
Dry unit weight, γ_{dry} (kN/m ³) ^b	22	–

^a Rawat and Gupta [11], ^b Abderrahmane and Abdelmadjid [12]

of failure plane obtained through numerical simulations for the unreinforced slope is performed, and the improvement in FOS is calculated after the reinforcement of the slope.

3 Results and Discussion

The stability of the unreinforced slope is examined, and the FOS is found to be 1.02 which is well compared with the results reported by Abderrahmane and Berga [12]. Figure 3 indicates the failure plane obtained without reinforcing the soil slope for $\beta = 40^\circ$ with horizontal. The current model is therefore validated, and it shows that the current model is suitable for carrying out further analysis. Furthermore, parametric studies were conducted using the parameters mentioned earlier.

Figure 4 shows the variation of the length of soil nail with FOS obtained from the numerical analysis for $\alpha = 10^\circ$ with horizontal. The obtained variation indicates that the smaller length of soil nails could not contribute toward the enhancement of the overall factor of safety of the slope system. However, the FOS of the slope tends to increase with the increase in the length of soil nail (L), and it is found to be 1.55 (>1.5) for $L = 8$ m.

It is observed that for the nail length (L) 2 m, 4 m, and 6 m, the reinforcement length could not reach to the passive region of the failure zone, due to which the utilization of tensile strength of the nails could not be realized by the soil slope and the FOS thus obtained is smaller than the criteria recommended by the FHWA [2]. The sliding circle formed by the respective reinforcement (2 m, 4 m, and 6 m) was also relatively smaller, which does not support the backfill. Global failure is observed in the case of failure plane obtained when the soil nail length does not reach to the passive region of the reinforced slope. It should be noted that the nail length of 8 m brings the FOS of the considered slope to the recommended minimum value of FOS, which is 1.5. Thus, a nail length of 8 m is found to be most suitable for the provision

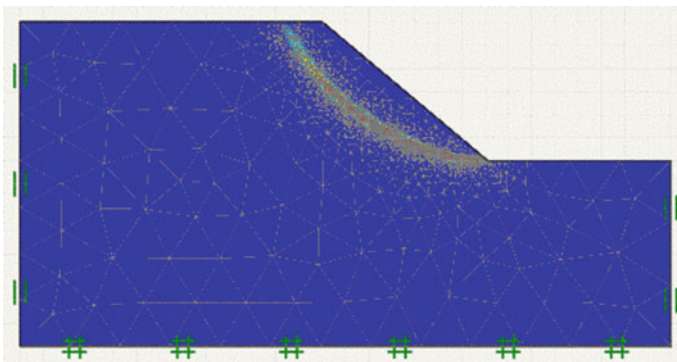
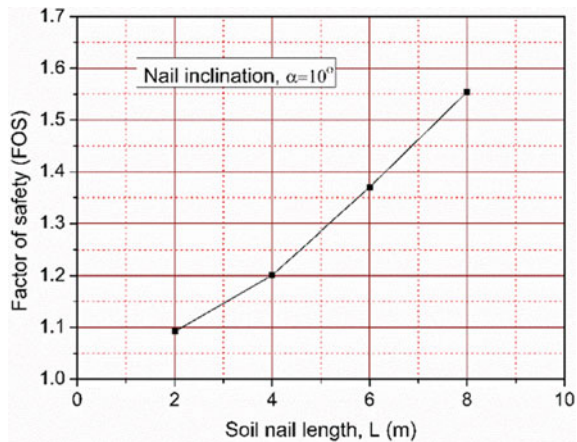


Fig. 3 Failure surface of unreinforced slope considered in the present study

Fig. 4 Variation of FOS with reinforcing soil nail length, L (m)

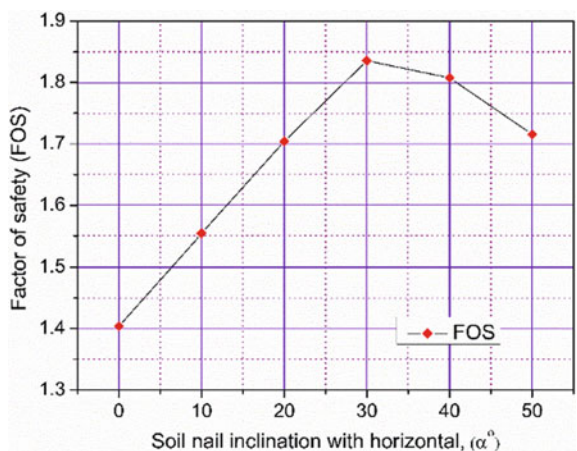


of the slope under consideration. Lin et al. [13] conducted a parametric study on the length of soil nails and reported similar results.

Furthermore, analysis is performed while keeping the nail length and spacing invariable, and the factor of safety is determined with the variation of nail inclination, $\alpha = 0^\circ$ to 50° with horizontal, to determine the best orientation of nail to maximize the FOS of the reinforced slope.

The variation of factor of safety and soil nail inclination (α) with horizontal is shown in Fig. 5, which indicates that initially the FOS increases with an increase in nail inclination (α) up to 30° , but any further increase in α decreases the FOS rapidly. This can be attributed to the fact that a too steep nail inclination (α) can cancel out the advantages since the direction of the nail is not optimal for stability. Nails that are steeper than 30° may be in compression, which can be the possible reason for a reduction in FOS.

Fig. 5 Variation of FOS with nail inclination (α) at soil slope, $\beta = 40^\circ$, and nail length, $L = 8$ m



It is also observed that if the nail orientation is kept parallel to the horizontal, the FOS only rises to 1.4 ± 0.01 (<1.5) (where the first term signifies the average of LB and UB values of FOS, whereas the latter one denotes the difference between the average value of FOS and the UB and LB values of FOS), which is not the recommended value for design. For this reason, a nail inclination of less than 10° should be avoided to prevent creating voids from forming, when grouting is to be carried out after reinforcement since voids can reduce the pull-out resistance and reduce corrosion protection. As α increased to 10° , 20° , and 30° , the FOS increased significantly to 1.55 ± 0.01 , 1.70 ± 0.02 , and 1.83 ± 0.03 , respectively. The maximum FOS was achieved at 30° inclination of the nail with horizontal. It is evident from Fig. 5, as α increases to 40° and 50° , a reduction of 1.7% and 7% in FOS is observed.

The potential failure curve obtained in the above study is also analyzed for the different inclinations of the soil nails for the same soil slope as shown in Fig. 6.

Figure 6a shows potential failure curve of soil slope reinforced with nails that are kept parallel to the horizontal (i.e., $\alpha = 0^\circ$) and noted that the slip surface form during failure of a soil slope is larger in this case than the unreinforced case (Fig. 3). It is evident that as α increases from 0° , the slip surface tends to enlarge (as shown in Fig. 6b and c). However, the slip surface formed by the soil nail inclined at 30° (Fig. 6d) is the largest than all the cases considered in this study, and this can be

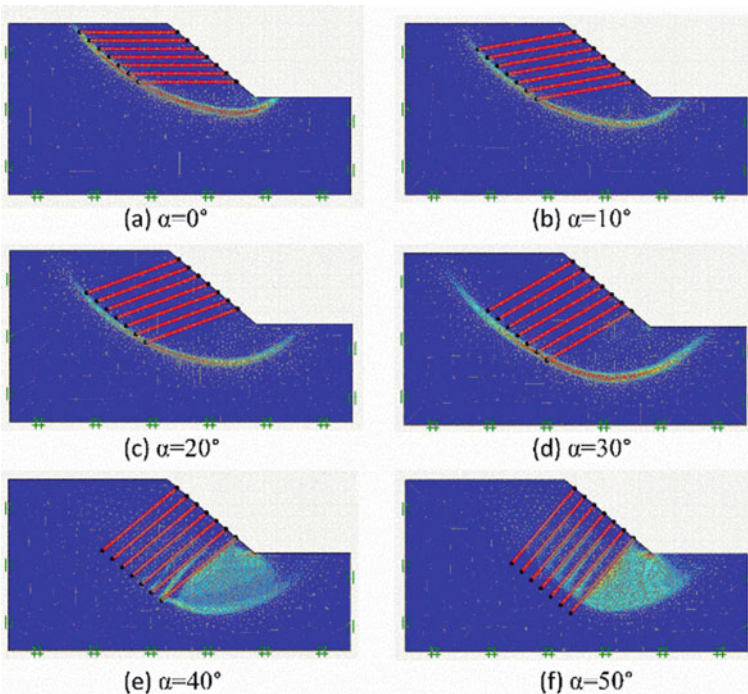


Fig. 6 Potential failure curve for soil slope ($\beta = 40^\circ$) reinforced with soil nail at inclination **a** $\alpha = 0^\circ$; **b** $\alpha = 10^\circ$; **c** $\alpha = 20^\circ$; **d** $\alpha = 30^\circ$; **e** $\alpha = 40^\circ$; and **f** $\alpha = 50^\circ$

attributed that maximum nail length is utilized to resist the shearing action. It can be also seen that no nail breakage has occurred, and this means that the load transfer mechanism is driven by the pull-out capacity of the soil nail.

A complex failure pattern is observed at $\alpha = 40^\circ$ and 50° (Fig. 6e and f). The soil mass tends to move with the mobilization of the toe of soil slope and also the upper tension bearing member does not seem to take any load on it, which is why the failure surface originates at the bottom-most nail and a global failure is observed in both the cases. This could be the reason for the reduction in the factor of safety of reinforced slope when the soil inclination is increased at 40° and 50° , respectively.

4 Conclusion

A parametric study is carried out on a 6 m high slope to determine the behavior of soil slope when reinforced with soil nails at various nail length (L) and inclination with the horizontal (α), using Drucker–Prager criterion for the soil under plane strain condition by a finite element numerical tool. A parametric study is done by varying the length (L) of soil nails from 2 m to 8 m in 2 m intervals and the inclination of soil nails (α) from 0° to 50° in 10° intervals, with respect to the horizontal for a steep soil slope ($\beta = 40^\circ$). The significant conclusions obtained in this study are as follows:

1. The factor of safety increases with an increase in nail length and the maximum value is achieved at nail length, $L = 8$ m and $s = 1$ m, for a given slope 6 m high and $\beta = 40^\circ$. This may be attributed to the fact that the slope surface holds an elongated path in order to form a deeper sliding surface with the increasing nail length, which in turn leads to an increase in factor of safety.
2. It is noted that as α increases from 0° , the factor of safety (FOS) increases up to 30° , but as soon as it reaches 40° , the FOS slightly decreased, and for $\alpha > \beta$, the value of FOS is decreased by 7%, which shows that soil nails are in compression when the inclination is too steep that is why too steep nails ($>30^\circ$) must be avoided while reinforcing the soil slope with soil nails. The failure plane observed in too steep nail inclination ($>30^\circ$) is not optimal for stability and can cancel out the advantages of soil nailing.
3. It is observed that the maximum factor of safety is obtained at $L = 8$ m and $\alpha = 30^\circ$, i.e., 1.83 ± 0.026 , for the slope $\beta = 40^\circ$; also, the result demonstrates that for a 6 m high slope, the factor of safety to be greater than the recommended value (i.e., 1.5), the L/H ratio must be greater than 1.

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