Effect of installation angle on pull-out resistance of nails in soil slopes

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Abstract

In this study, the effect of the nailing angle on the pull-out capacity of nails in soil slopes was investigated using the finite difference method with the help of FLAC^{3D} software. Initially, the geometric model was created at three different angles of the excavation slope (45°, 63°, and 80°). Considering the Mohr–Coulomb behavioral model and applying the physical and geometric parameters of the model in order to model the nail in the nailing system, five rows of nails at different angles, relative to the horizon, which included 5°, 10°, 15°, 20°, 25°, 30°, and 35° were used to evaluate the effect of change in the angle of the nail and the different angles of the excavation slope on the pull-out capacity of the nails. The results showed that the magnitude of the nail pull-out force, at slopes of the same level, increases as the angle of the excavation slope increases. Also, the maximum force is generated at the level range of 0.7 of the height from the upper edge of the slope and the nails situated at an angle of about 30° relative to the horizon. Therefore, according to the soil conditions, the angle of nail, and the factor of safety, the optimal implementation angle of the nail on the slope can be calculated in different designs.

Keywords Soil nailing · Pull-out resistance · Nail angle · Numerical modeling · FLAC^{3D}

1 Introduction

Excavation in soft soils to execute the basements and underground structures requires keeping the excavation slope stable. The high cost of implementing rigid retaining walls, and in general, the disadvantages of conventional methods have led design engineers to use other stabilization methods so that gradually, more flexible systems with more relative durability have replaced conventional retaining structures. One of these important and new methods is the use of soil nailing as a reinforced soil system. The basis of the nailing system is based on the application of tensile reinforcement materials in the resistant area of the soil, which are located in close proximity to each other. The nailing systems are capable of withstanding static and

dynamic vertical loads. This system can also be used to stabilize and repair the existing soil structures.

The pull-out resistance of soil nails is a vital factor in the design, which is a function of soil conditions, nail length, nail surface conditions, and nail installation method [1, 2]. It is also difficult to estimate that with high accuracy due to the uncertainty associated with the interactive behavior of nail and soil during pull-out [3]. Jewell and Pedley [4] conducted a long-term experiment on a 15-m nailed wall in cohesive soil. They found that: (1) Upper nail does not play a significant role in maintaining and stabilizing the slope system. (2) The force of the nail increases for a short period and remains constant almost after that. (3) Maximum deformation occurs at the top of the slope. Morris [5] stated that the loading rate has a significant effect on pull-out resistance. In addition, he concluded that at the

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maximum point and before that, the cohesive strength of the nails had increased with the in-situ stress. The studies of Johnson et al. [6] show that the shear strength of the entire reinforced soil depends on the orientation of the reinforced elements. By changing the orientation of the reinforced elements, reinforcement can either increase or decrease the shear strength. Chu et al. [7] conducted a series of laboratory experiments on the pull-out of a completely decomposed granite soil. The results showed that in the pull-out tests, in the load–displacement curves, the shear strength is significant at the maximum value of the curve and before that. Pradhan et al. [8] performed pull-out tests to determine the pull-out behavior of the nail in the loose sand materials (completely decomposed granite). They stated that the pull-out resistance of the soil nails is related to the surcharge pressure. Su et al. [9] conducted a series of pull-out tests using a model box with the dimensions of 1000 mm × 600 mm × 800 mm. They concluded that the choice of nail installation methods depended on vertical stress changes in the soil around the nail and that the shear strength of the nail pull-out relies upon the surcharge pressure. Meenal et al. [10], in a study, presented a pseudo-static analysis to evaluate the stability of nails reinforced with vertical or almost vertical excavation. The failure surface was assumed to be the arc of a logarithmic spiral that passes through the excavation toe and intersects the ground at right angles. Moreover, horizontal and vertical seismic forces were considered as horizontal and vertical seismic coefficients. The mode of internal failure of the nailing cut is expressed as rupture or pull-out or excessive bending (whichever is more critical). The analytical results were compared with the model experiments' findings, and good accordance was observed between them. Laboratory and numerical studies conducted by Su et al. [11] and Zhou et al. [12] revealed that with the increase in the surcharge pressure, the pull-out resistance increases. This is also true for the pumping pressure of the injected concrete grout, while the depth and the slope of trenches remain constant, which by increasing it, the magnitude of pull-out resistance rises. They also found that the pull-out resistance increased significantly before and after the maximum value as the angle of dilation in the shear area increased. Garg et al. [13] conducted experimental studies and numerical analyzes to understand the behavior of nailed soil slopes better. They observed that in addition to the geometry of the slope and the soil characteristics, other factors such as the angle of the cables, the characteristics of cables, their length, and also the spacing between the cables have a great impact on the stability of the nailed slopes. Askari and Gholami [14] studied the optimal layers of nailing numerically under different conditions. In their study, the nailed wall examination was done in three geometries and two

surcharges in terms of safety factor and displacement of the slope tip. Also, it was evaluated how different height sections affected the safety factor and displacement of the slope tip. They found that the highest safety factor is at the nail slopes between 0° and 10° in the vertical nailed wall. Also, after a certain point in terms of nail length, in all nail slopes, increasing nail length does not have much effect on nail length reducing lateral slope displacement. Rawat and Gupta [15] performed experiments and numerical modeling of screw nails reinforced soil slopes. They stabilized two soil slope models at 45° and 90° to the horizon by placing six nails with a zero angle deviation from the horizon. Generalized finite element analysis was also used by the strength reduction method to determine the slip surface safety factor. Moreover, using the generalized finite element analysis method, they studied the slope displacement, failure load, and volumetric deformation of these two slopes reinforced with screw nails. In this study, it was concluded that comparably, between the experiment and modeling, the factor of safety, slip surfaces, and load–displacement were slightly different. A comparative study was also performed using smooth nails and screw nails between the factor of safety and slope load–displacement relationship. As a result, it was seen that slopes reinforced with screw nails have a higher factor of safety and a lower slope displacement. Ye et al. [16] introduced a new type of nail called compaction-grouted soil nail and also presented a physical model to study the pull-out behavior with different grouting pressures. In addition, the newly introduced soil nail and a conventional type of soil nail were compared based on their pull-out resistance. Furthermore, comparing these two types of soil nails showed that regarding improving the pull-out strength, the conventional soil nail is less sensitive to grouting pressure than the compaction grouted soil nail. Sharma et al. [17] discussed soil nailing techniques using laboratory, field, and numerical methods to determine the pull-out capacity of the nail. The effect of various parameters on the pull-out capacity of the soil was investigated. These parameters comprised grouting pressure, overburden pressure, soil dilation, saturation degree, the roughness of nail surface and borehole. They found that the response of soil nail pull-out is an essential parameter for soil nail design. Sharma et al. [18] investigated the behavior of helical nailing of soil installed in cohesionless soils under pull-out force under varying parameters such as nail configuration (helix diameter, helix depth, number of helices, shaft diameter, and etcetera), type of nail shaft (stiffness and roughness), overburden pressure, and installation torque were examined. From the result of the pull-out test, they found that the amount of pitch in the range between 24.5 and 35.5 mm shows a better pull-out capacity. It was also shown that extra helices can only affect the pull-out

capacity if they are outside the mobilized area of the soil in the failure mechanism at the lower end of the helix. Their results showed that there is a linear correlation between maximum pull-out shear stress and overburden stress on Mohr–Coulomb failure for different types of helical nails. Yang et al. [19] investigated the seismic stability of traditionally soil nail reinforced slopes using a two-dimensional limit equilibrium method. In addition, the combined strength reduction method with kinetic approach of limit analysis was used to evaluate the factor of safety of nail reinforced slopes using a three-dimensional rotational failure mechanism. Both tensile failure and pull-out failure of soil nails are considered in internal energy dissipation calculations and computations. Also, parametric analysis was performed to investigate the effect of model parameters comprising nail length, nail density, soil shear strength, and seismic forces on slope stability. Finally, in order to validate the proposed approach, a comparison was made, which showed that the adopted approach is a powerful and effective design tool for assessing the factor of safety of slopes reinforced with soil nails. Sharma et al. [20] investigated the behavior between shear stress and displacement of helical nails under different overhead pressures and different pull-out loads in a study. Moreover, two types of helical nails (ribbed solid and hollow plain) and a group of nine ribbed solid shafts helical soil nails installed with uniform spacing were also examined experimentally. The axial strain results for both types of helical soil nailing show the strain softening in the post-peak stage, which in the case of group nailing, it disappears. Overall, it was concluded that the truncated cone rupture failure in the case of group nailing could significantly affect the stress–displacement response, which is more evident in bearing than the shear resistance of the interface of soil plugging in hollow shafts.

The studies conducted so far have been mainly on how and to what degree the angles can affect the failure resistance of nailed trenches and slopes, but the effects of these parameters on the pull-out resistance have been less considered. Given that the limit equilibrium method is used to assess the overall stability of the slope and determine the forces required by the nail to maintain the nailed wall, the finite difference method can be used to determine stresses and axial forces in the elements and displacement of the slope and subsidence in the nailed areas. Consequently, the effect of changes in the effective parameter of nailing angle on the pull-out capacity of nails in excavations and natural and artificial slopes was investigated in this study. By applying changes in the angle of the nails, it was attempted to obtain and suggest an adequate angle and investigate the changes of this parameter concerning the depth using three-dimensional numerical modeling.

2 Numerical modeling

In this paper, the finite difference method (FLAC^{3D} software [21]) was used as a numerical method to analyze the effect of the nail angle on the pull-out resistance of the nails. The three-dimensional geometric model is 28 m in length, 12 m in height, and one meter in width. The model consists of two parts: (1) slope angle (β) relative to the horizon, and (2) excavation area. Special attention has been paid to the dimensions and scales of the structure to model this structure. Therefore, the effects that may occur due to improper modeling of real boundaries (walls) can be prevented. The angle of the excavation slope was considered to be equal to β , which was considered for three angle degrees of 45°, 63°, and 80°, and the extension of the slope edge for three modes of 17 m, 19.5 m, and 21.12 m, respectively. Moreover, each of the models consists of 2688 elements and 4275 nodes, and meshing was hexahedral.

The Mohr–Coulomb model was used in this study, which is the prevailing model in soil and rock mechanics analysis, underground excavation stability analysis, and slope stability, especially trench excavation. In this model, the yield stress is a function of the maximum and minimum stresses, and the mean core stress does not affect failure. The soil parameters and specifications are presented in Table 1 [22].

In this paper, for modeling boundary and initial conditions, the side and the bottom borders were considered as fixed roller, and the upper border was deemed to be free so that the model could settle (Fig. 1).

In geotechnical and mining researches, before any drilling operations, the state of stresses is in-situ, which in FLAC software, this situation is possible by setting the initial conditions. For a uniform rock or soil layer that has a free surface, the vertical stresses are usually calculated as ρgz , which is the gravitational acceleration (g), density of the material (ρ), and depth from the ground (z). Due to the depth changes from the ground to the bottom of the model, the amount of in-situ stress at different heights is different. In the final depth of the model from the ground, which is equal to 12 m, considering the density of soil

Table 1 Model parameters [22]

Parameter	Value
Density, ρ (kg/m ³)	1900
Young's modulus (Elastic modulus), E_s (MPa)	15
Poisson's ratio, ν	0.42
Internal friction angle, ϕ (°)	30
Cohesion, C (kPa)	7

Fig. 1 Boundary conditions in different directions of x , y , and z

Fig. 2 Slope geometry after the trench excavation

mass 1900 kg/m^3 and gravitational acceleration 10 m/s^2 , the amount of vertical stress of σ_{zz} is equal to -0.228 MPa (negative sign means compressional stress), which has the highest value. The values of horizontal shear stresses are calculated from Eqs. 1 and 2.

$$\sigma_{xx} = \sigma_{yy} = k_0 \sigma_{zz} \quad (1)$$

$$k_0 = 1 - \sin \phi \quad (2)$$

where σ_{xx} is the horizontal in-situ stress in the direction of the x -axis, σ_{yy} is the horizontal in-situ stress in the direction of the y -axis, and σ_{zz} is the vertical in-situ stress in the direction of the z -axis. Also, k_0 is the stress coefficient, and ϕ is the internal friction angle of the soil. A series of disturbances in the state of stresses and displacements will be caused by trench excavation. Considering that up to this stage, the boundary conditions and in-situ stresses

Table 2 Excavation steps

Stage	1	2	3	4	5
Amount of excavation (m)	1	1	1	1	1
Level excavation (m)	11	10	9	8	7

have been applied to the model, it is necessary to solve the numerical model before the trench excavation, so the initial stresses are generated. After reaching to the in-situ stresses and zeroing the displacements, the excavation is created with the corresponding geometry in the model. In Fig. 2, the slope geometry after the trench excavation is shown for the angle of the excavation slope of $\beta = 45^\circ$.

Table 2 shows the excavation steps where the soil nails are gradually placed inside the slope.

The shear behavior of the intersection of the cable-soil junction is due to cohesion and friction. Therefore, the loop

Fig. 3 Idealization of grouted-cable system

Table 3 Properties of the structural elements of the nail used in modeling

Parameter	Value
Young's modulus of the grouted nail, E (GPa)	45.44
Shear zone cohesive strength per unit length, C_g (kN/m)	3.25
Shear zone friction angle, ϕ_g (°)	23
Shear zone stiffness per unit length, k_g (MPa)	84.58
Shear zone exposed perimeter, p_g (m)	0.628
Cross-sectional area of the grouted nail, A (m ²)	0.0314
Compressive and tensile yield strength of the grouted nail (force), F_c, F_t (MN)	0.238

shear behavior of the grout during the relative shear displacement between the cable-grout and grout-soil junction can be modeled. Figure 3 shows the idealization of the grouted-cable system.

When it comes to modeling the nails as cable elements, there are many essential parameters to consider. These requisite parameters include the cross-sectional area of the nails, density, Young's modulus, the nails' compressive and tensile yield forces, and also four parameters concerning the grout, which consist of the friction angle, the cohesive bond strength, the bond stiffness, and the visible perimeter of the grout. The structural elements of the nail used in modeling are shown in Table 3.

Equations 3 and 4 were used to calculate k_g .

$$k_g \approx \frac{2\pi G_g}{10 \ln \left(1 + \frac{2t}{D}\right)}, \quad t = 0.004 \text{ m}, \quad D = 0.2 \text{ m} \quad (3)$$

$$G_g = \frac{E_s}{2(1 + \nu)} \quad (4)$$

where the shear modulus of the grout is G_g , the thickness of the grout ring is t , and the diameter of the steel nail is D .

Using the code of Federal Highway Administration [23, 24], the factor of safety (FOS) was set at 1.35. To calculate C_g and ϕ_g , we have Eqs. 5 and 6, respectively:

$$C_g = C\pi D / \text{FOS} \quad (5)$$

$$\phi_g = \arctan \left[(\tan \phi) / |rm\text{FOS}| \right] \quad (6)$$

Also, in the present study, in order to model the nails in the soil nailing system in the FLAC^{3D} software and stabilize the slope, five rows of 6-meter long nails were all installed at the angle of α in regard to the horizon. The spacing between the nails, horizontally and vertically, was considered to be one meter. Table 4 shows the number of nails in different slope levels, where the height of the slope is H and is equal to five meters.

In this paper, the effect of the nail angle on the pull-out resistance in the slope was the primary intention of the study. Therefore, the variables associated with this model are the angle of the nails (α), which ranges from 5° to 35° relative to the horizon, and the three slopes with different slope angles (β) relative to the horizon.

3 Results and analysis of data

The soil slopes with three different slopes of 45°, 63°, and 80° should be evaluated for overall stability before nailing. Figure 4 shows the failure circles in the different angles of the slope before nailing.

Table 5 shows the values of the factor of safety at different slope angles before (unreinforced slope) and after the nailing operation (reinforced slope in nails installed at different angles). According to the table, in the unreinforced state, it is observed that with increasing the slope angle (β), the factor of safety (FOS) decreases. Due to the fact that the reliability coefficient of stability in all of them is less than one, so nailing operation is necessary for their stabilization. Moreover, in the reinforced state, at a fixed slope angle ($\beta = \text{cte}$), the values of the factor of safety decrease with increasing the angle of the installed nails (α). Figure 5 shows the geometry of the nail model and distribution of tension force along the

Table 4 Number of nails in different levels of slope

Nail number	Nail 1	Nail 2	Nail 3	Nail 4	Nail 5
Installation height from the top of the slope	0.1 H (0.5 m)	0.3 H (1.5 m)	0.5 H (2.5 m)	0.7 H (3.5 m)	0.9 H (4.5 m)

Fig. 4 The failure circles in the different angles of the slope before nailing

Table 5 The value of the factor of safety in the reinforced and unreinforced states

β	Unreinforced state FOS	Reinforced state	
		α	FOS
45°	0.77	5°	1.68
		10°	1.66
		15°	1.63
		20°	1.56
		25°	1.53
		30°	1.49
		35°	1.46
63°	0.58	5°	1.31
		10°	1.28
		15°	1.25
		20°	1.23
		25°	1.21
		30°	1.19
		35°	1.15
80°	0.45	5°	1.11
		10°	1.09
		15°	1.07
		20°	1.06
		25°	1.04
		30°	1.02
		35°	1.01

nail. Moreover, Fig. 6 shows the installation of the nail at different angles ($\alpha = 5^\circ$ to $\alpha = 35^\circ$) and the distribution of tension force across the nail for a specific angle of the excavation slope ($\beta = 45^\circ$), as an example.

In Figs. 7 and 8, and 9, the results of the analysis of maximum pull-out forces in the slope with angles of $\beta = 45^\circ$, $\beta = 63^\circ$, and $\beta = 80^\circ$ and with nails installed at different angles are presented, respectively. By examining the figures, it is evident that the pattern of force propagation along the nail follows an orderly trend. The propagation of the force along the nails installed at different levels of each slope starts from the beginning of the nail (nail head), increases upwards to the middle of the nail, and then continues downwards to the end of the nail (nail tip).

Furthermore, by examining the plots in Figs. 7 and 8, and 9, it can be seen that the highest force of nail pull-out in all cases of slope angle is related to the fourth nail (Nail 4), which is installed at the level range of 0.7 of the height from the upper edge of the slope. Figure 10 illustrates the pull-out force along the length of the fourth nail at different angles of installation in the three different angles of the slope (45° , 63° , and 80°).

At the angle of the excavation slope of $\beta = 45^\circ$, the maximum force applied to the nail installed at the angle of $\alpha = 35^\circ$ is at the distance of 0.54 of the nail length from its head, and in other cases, at 0.58 nail length from its head.

Moreover, for the angle of the excavation slope of $\beta = 63^\circ$, the maximum amount of force applied to the nail installed at most angles is at 0.54 of the length of the nail from its head, with the exception of two cases. Firstly, for the angle of $\alpha = 30^\circ$ is at the distance of 0.54 of the nail length from its head, and secondly, for the nail angle of $\alpha = 35^\circ$, the maximum force is at 0.5 of the nail length from its head.

Ultimately, for the angle of the excavation slope of $\beta = 80^\circ$, when the nail is installed at the angle of $\alpha = 35^\circ$, the maximum amount of force is applied to the nail at the distance of 0.5 of the nail length from its head. Subsequently, for the nails installed at the two angles of $\alpha = 5^\circ$ and $\alpha = 10^\circ$, it is at the 0.54 of the nail length from the head. Also, for all of the angles from $\alpha = 15^\circ$ to $\alpha = 30^\circ$, it is applied at the distance of 0.5 of nail length from its head.

Table 6 presents the ratio of the maximum force's distance to the nail head to the total length and the nail's maximum force (Nail 4) at different angles of the nail installation and the excavation of slope. Table 6 shows that by increasing the angle of the slope at a specific level, in all of the present angles of the nail installation, the pull-out forces increase. The ratio of increase in the slope of 63° – 45° is more, opposed to the slope of 80° – 63° .

Figure 11a shows that the angle ranges of 5° and 35° for nail installation have the highest and lowest FOS values, respectively. Also, according to Fig. 11b, the maximum and

Fig. 5 The geometry of the nail model and distribution of tension force along the nail

minimum values of pull-out force created are in the installation range of 30° – 35° and 5° , respectively.

One of the study's limitations is the inadequacy of the nailing method in places where there is water flow. The nailing method is also unsuitable for soils such as organic soils, aerated rocks, soils with high corrosion, and cohesionless dry soils. One of the limitations of using FLAC software as a continuum model is the long time required by the software to perform calculations, especially on large scales.

4 Conclusions

The most important results concluded from this study are as follows:

- In all slope angles, in order to achieve maximum efficiency by nails in non-stick granular soil, the most proper angle of the nail can be within the installation angle of 5° to the horizon because the reliability coefficient, in this case, is the highest and also in this range, less pull-out force is created.
- As the angle of the soil slopes increases, the system becomes more unstable, the lateral force on the sup-

porting system increases, and therefore, the installation angle of the nails rises.

- The behavioral pattern and distribution of forces, along the length of all nails, are quite similar.
- The maximum force is applied at a section about 0.5 to 0.58 of the nail length from the nail head (installed to the shotcrete). As the angle of the slope increases, this ratio decreases to 0.5 of the length of the nail.
- By increasing the depth, the magnitude of the force generated in the nails increases, and maximum force between all of the slopes is generated in the nail located at the level range of about 0.7 of the height of the slope from its upper edge, and afterward, as depth increases further, it decreases.
- As the angle of the nail relative to the horizon increases, the magnitude of the pull-out force increases. The maximum amount of force for the nails in the slopes of $\beta = 45^\circ$ and $\beta = 63^\circ$ is when installed at the angle of 30° , and also, for the slopes of $\beta = 80^\circ$, the maximum force is generated when the nail is installed at an angle of 35° .
- In the same level range of the slopes with different angles, the magnitude of the force in the nails increases as the angle of the slopes rises.

Fig. 6 The installation of the nail at different angles ($\alpha = 5^\circ$ to $\alpha = 35^\circ$) and the distribution of tension force across the nail for a specific angle of the excavation slope ($\beta = 45^\circ$)

Fig. 7 Plots of the maximum pull-out force of nails in terms of the nail length with nails installed in the slope which has an angle of $\beta = 45^\circ$, and at different angles ($\alpha = 5^\circ$ to $\alpha = 35^\circ$)

Fig. 8 Plots of the maximum pull-out force of nails in terms of the nail length with nails installed in the slope which has an angle of $\beta = 63^\circ$, and at different angles ($\alpha = 5^\circ$ to $\alpha = 35^\circ$)

Fig. 9 Plots of the maximum pull-out force of nails in terms of the nail length with nails installed in the slope which has an angle of $\beta = 80^\circ$, and at different angles ($\alpha = 5^\circ$ to $\alpha = 35^\circ$)

Fig. 10 Plot of the pull-out force along the length of the fourth nail at different angles of installation of slopes (45°, 63°, and 80°)

Table 6 The ratio of the maximum force's distance to the nail head to the total length and the maximum nail force at various angles and slopes

		$\alpha = 5^\circ$	$\alpha = 10^\circ$	$\alpha = 15^\circ$	$\alpha = 20^\circ$	$\alpha = 25^\circ$	$\alpha = 30^\circ$	$\alpha = 35^\circ$
$\beta = 45^\circ$	The ratio of the maximum force's distance to the nail head to the total length	0.58	0.58	0.58	0.58	0.58	0.54	0.58
	maximum pull-out force of the nail	14.06	14.63	15.74	16.01	16.48	16.85	16.61
$\beta = 63^\circ$	The ratio of the maximum force's distance to the nail head to the total length	0.54	0.54	0.54	0.54	0.54	0.54	0.50
	maximum pull-out force of the nail	17.88	18.13	19.06	19.14	19.32	19.64	19.14
$\beta = 80^\circ$	The ratio of the maximum force's distance to the nail head to the total length	0.54	0.54	0.50	0.50	0.50	0.50	0.50
	maximum pull-out force of the nail	20.68	21.1	21.16	21.21	21.5	21.72	21.88

Fig. 11 The values of the factor of safety and the pull-out force at different angles of the nail

Declaration

Conflict of interest The author(s) declare that they have no competing interests.

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