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Optimum Design for Soil Nailing to Stabilize Retaining Walls Using FLAC3D

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Abstract. *The behavior of a reinforced soil system depends on parameters such as the structural geometry, execution steps, density and mechanical properties of the soil, density of reinforcement materials, deformation, and flexural stiffness of reinforcement materials. A critical parameter in the design of a soil-nailed system is the optimal use of materials with respect to cost. It is necessary to find an optimal design that is cost-effective within the parameters affecting the behavior of the nailed system. A common problem in nailed excavations is an increase in the excavation depth beyond the initial design of the wall, which will require more reinforcements. In this research, we used one approach not used before the method is placing one and two rows of long nails placed at the appropriate depth. In this study, a comparison between safety factor, horizontal displacement, and lateral pressure behind the wall has been made at two nail placement depths using FLAC3D finite difference software that reveals the optimal depth for efficiency is approximately at the middle of the finished wall height. When the number of reinforcement nails with the same lengths was considered, the installation of two rows of nails in comparison with 5 or 3 rows of nails reduced the maximum wall displacement to a greater extent. A greater factor of safety was achieved.*

Keywords

Nailing, retaining structure, optimal arrangement, efficiency.

1. Introduction

One of the main concerns in constructing underground facilities in urban areas is the effect on adjacent buildings of deformation caused by excavation. The excavation design also should be cost-effective in addition to preventing excessive deformation of the ground. In recent years, soil-nailing has received more attention as an economical method of stabilizing excavation walls [1]. The implementation of this method has been described in detail in the references and standards and briefly includes reinforcement with steel elements (nails) of a specific arrangement and length. Soil nailing increases the tensile strength and shear strength from friction at the contact surface of the soil and nails. Soil-nailed walls offer flexibility, speed and ease of execution, and are more cost-effective under certain conditions than other stabilization systems [2]. The main components of a nailing system include the site soil, tensile nails, and retaining structural elements. The behavior of nailed walls is affected by parameters such as soil resistance [3-5], type of nail, wall execution stages, and geometric characteristics.

Sabhahit et al. (1995) [6] proposed an optimal design method for nailed slopes. They used an accurate method of stability analysis (Janbo method), which modified limit equilibrium analysis. In this method, only the tensile strength is investigated, and shear and bending effects are not considered. The total reinforcement force required to bring the safety factor to the required value relative to the direction of the reinforcement factors and the distribution of the reinforcement force factors as decision variables is minimized. Overall, the proposed method states that the number of reinforcement layers has a marked effect on the amount of reinforcement required. The total length of nails required would be less if the nails are placed in the lower part of the slope. The close horizontal placement of the reinforcement factors and long nails in the middle of the slope height produce an optimal design for soil-nailed slopes. However, in their study, the position, length, diameter, and direction of the optimal nails were not investigated or presented.

Yuan et al. (2003) [7] developed a new method of limit equilibrium analysis and used it to analyze soil-nailed walls. The basis of their method was to calculate the force between the pieces recursively and supplement the deficits of the balance of forces between the pieces of the last boundary section by trial and error. A parametric study was conducted to investigate the effect of soil behavior and nail arrangement patterns on the safety factor. Finally, they presented an optimal technique for obtaining the design with the lowest cost with a target function based on the total length of the nails, which is a good estimate of the total cost of the soil-nailed wall.

Patra and Basudar (2005) [8] developed a general computational method for optimally designing soil-nailed slopes. Their approach provides a formulation for limit equilibrium that satisfies the overall and internal equilibrium and considers the effect of the tensile strength of the reinforcement components on the calculation of the strength of the nailed slopes. The amount of steel required to increase the safety factor to the desired value is estimated. The location, size (length and diameter), the orientation of the nails, location, and shape of the critical shear surface are considered variables. They obtained the ratio of the total volume of nails required in terms of length in the active region and length and diameter in the resistant region because the required volume depends on the diameter, direction and location of the nails, the shape and position of the critical surface and the resistance length of the nails. Their results showed that upwardly oriented nails with longer lengths at the top of the slope produced the optimal design. However, the upward inclination of the nails was small and ranged from 0° to 6°. The optimal design used unequal distances between the nails and reduced the length of the nails from the top to the bottom of the slope.

Fan and Lou (2008) [9] performed a numerical analysis of the optimal arrangement of soil-nailed slopes. They showed that if the construction cost is taken into account, nails having a uniform arrangement may not be the optimal design. In addition to the slope geometry and soil parameters, the main factors that affect the stability of a soil-nailed slope were the arrangement, properties, length, and direction of the nails. Their results showed that if the wall is divided into upper and lower halves, the nail spacing in the upper half of the wall should be shorter than in the lower half.

Halabian et al. (2012) [10] used the 3D finite difference method to investigate the behavior of nailed structures under static conditions. They examined the effects of the nail angle, nail length, length arrangement, slope angle, nail arrangement, and soil strength parameters. Their results showed that experimental methods for estimating lateral pressure lead to conservative predictions, and an increase in soil cohesion improved the shear strength of the soil and as a result, the nailed structure performed better to withstand lateral loads and the horizontal, and vertical settlements at the top of the wall decreased. They also found that an increase in the nail length increased the stability of the nailed structures and decreased displacement of the wall. Halabian et al. (2012) demonstrated that nail inclination angles of up to 15° reduced the lateral pressure on the nailed wall and increasing the length of the nails to 9 m decreased the lateral pressure on the wall, but longer lengths had little effect.

Singh and Babu (2010) [11] used a 2D numerical method to analyze the behavior of soil-nailed walls. They studied advanced soil models such as the soil hardening model and the low-strain hardening soil model to simulate in-situ soil behavior on the overall response of a soil-nailed wall. They then compared the results of the advanced soil models and the simple Mohr-Coulomb model. They concluded that advanced soil models significantly affect the overall balance of a nailed wall and the distribution of stress elements such as the tensile forces, bending moment, and shear forces on the nails, which are sensitive to small deformations. They recommended using advanced soil models and concluded that considering the flexural stiffness of the nails in numerical modeling produces more accurate results for the failure mode. They also investigated the effect of mesh density on the responses and selected the appropriate mesh density.

Cheuk et al. (2013) [12] proposed a combined method of placing the nails at different angles. They investigated the mechanism of stability of soil-nailed walls on embankment slopes using FLAC2D. The goal was to investigate the mechanism of the force of steeply sloping nails and optimize the nails' angle. Based on the analysis results, they presented new design recommendations to enhance the reinforcement of loose embankment slopes by soil nailing. The numerical model studied had a height of 10 m, a slope of 34°, and a loose embankment with a depth of 3 m that was located on completely decomposed granite (CDG). Three nail arrangement models were investigated. The first arrangement consisted of sharply inclined nails that were perpendicular to the slope surface. In the second case, the nails were inclined at an angle of 20° below the horizontal surface, which is a common orientation on conventional excavation slopes. The third model was a combined mode that included nails with a slope below the horizon and nails with a steep slope. In their study, the loose embankment and CDG were modeled as elastic perfectly plastic continuous soil with a Mohr-Coulomb failure criterion. The nails were modeled as elastic cable elements that could withstand axial tensile and compressive forces with a center-to-center distance of 1.5 m.

The analysis results showed that for the conventional behavior of the loose embankment slopes with sharply angled nails, when the entire embankment body reached full liquefaction, sufficient nail force can be mobilized to achieve full stability. The nails at angles below the horizon were effective in preventing slippage of the excavated slopes. The most effective direction for soil reinforcement is in the direction of the tensile strain of the soil. An angle of 10° to 20° is suitable for normal slopes. Numerical analysis showed that if nails at angles below the horizon are used for loose embankment slopes, the system will not be effective against uplift resistance of the lattice front and therefore cannot provide overall stability against full liquefaction.

Seo et al. (2014) [13] examined the behavior of soil-nailed walls. In addition to shear and tensile failure, they also considered the fracture structure of the front wall. The boundary conditions for the failure modes were defined, and the optimal design was presented accordingly. The design variables for all three failure modes were nail cohesion length, number of nails, and pre-stressing. These design variables were estimated from the proposed optimal design process according to the boundary conditions. Because their proposed optimal nail design process considers front failure in addition to tensile and shear fractures, it can provide a more satisfactory design process in the field. They used Rankin's ground pressure theory and assumed that the angle of the fracture face is at the vertical slope; however, the wedge rupture mechanism could be transformed into mechanisms such as the logarithmic curve mechanism. The purpose of their research was to propose a general layout for optimizing soil-nail design. Thus, the wedge plate mechanism, a relatively simple model, was used (15).

Yazdi et al. (2014) [14] studied the effect of nail arrangement on the analysis of soil-nailed walls. Their goal was to develop a program with a fast search algorithm that could find the critical slip level of the soil nails by using different nail arrangements.

Lin et al. (2013) [15] investigated the effect of nail reinforcement on slope stability using numerical analysis and a resistance reduction method in which the stability of the nailed slopes was estimated using the safety factor and slip potential levels in FLAC3D software. They examined the effect of length, direction, and location of the nails and the horizontal distance of the nails on the safety factor and slip level. They showed that the safety factor increases linearly with an increase in nail length to reach the effective reinforcement length, and the force of the nails was symmetrical, with the highest at the center and the lowest at the ends. Lin et al. (2013) found that the direction of the nails had a strong effect on the safety factor of wall stability, and the optimal angle resulted in optimal wall stability, and this optimal angle decreased with an increase in the nail length. They demonstrated that the safety factor increases with an increase in the angle of placement of the nails to the optimal angle and then decreased linearly and when the nail placement angle was small, the potential slip surface moved backward relative to the slope surface as the placement angle increased. They also demonstrated when the placement angle was sufficiently large, increasing the length of the nails had little effect on the yield surface potential and as the angle of the nails increased, the force on the reinforcing elements decreased and the maximum force of the reinforcing elements was approximately the same for angles from $0°$ to $20°$. They also reported that the optimal location for the nail was in the middle of the slope and the horizontal distance between nails had a strong effect on the strength characteristic of the nails, which determines the upper and lower limits of the safety factor and can be increased according to S/D from one to infinity.

According to the researches presented above on the arrangement of soil-nailed walls, it can be concluded that the creation of an uneven distance between nails by reducing the length of the nails from the top to the bottom of the slope will produce the optimal design and as the drilling depth increases, the horizontal and vertical displacement increases and the vertical settlement corresponds to the horizontal displacement. It can also be shown that as the length of the nails increases, horizontal displacement decreases, and as the horizontal distance between the nails decreases, the horizontal displacement and settling decreases. The above-mentioned researches also demonstrated that experimental methods for estimating lateral pressure would lead to conservative predictions, and nails with angles from $0°$ to $15°$ below the horizon are effective in preventing slippage on excavated slopes.

By 3D modeling of geotechnical problems, their behavior can be better modeled and predicted. FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is numerical modeling software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support. Such analyses include engineering design, the factor of safety prediction, research and testing, and back-analysis of failure. FLAC3D utilizes an explicit finite volume formulation that captures the complex behaviors of models that consist of several stages, show large displacements and strains, exhibit non-linear material behavior, or are unstable. Most studies used 2D analysis and were approximate; therefore, 3D research is required to understand the problem better. Also, the models used in previous studies are not complete for considering the increase of depth after excavation using 3D modeling, so the need for more behavioral models can be felt. In the present research, a very detailed model of FLAC3D finite difference software and 3D modeling was used to compare the different depths of nail placement and obtain the optimal depth under different excavation conditions. To do so, two types of models were considered 9 meters primary + 4.5 meters secondary and 12 meters primary + 9 meters secondary, and the effects of the placements of their nails on their forces and horizontal displacements have been investigated.

2. Modeling and validation

Because performing laboratory tests or in-situ testing is costly and time-consuming [1], numerical modeling has been used in this study. Static-dynamic FLAC3D (Fast Lagrangian analysis of continua 3D) performs fast and continuous Lagrangian analysis using the finite difference method. This program has the ability to simulate the behavior of structures built in soil, rock [16-18], and other geotechnical materials. Several behavioral models are embedded in the software that allows simulation of the nonlinear behavior of materials.

Using these models, the user can define the desired behavioral mode. In the present study, the Mohr-Coulomb model was used. Each cable element is defined by its geometry, material characteristics, and grout. The cable element is elastic, perfectly plastic, and gives in to tension and pressure but cannot withstand bending moments. A one-dimensional structural model is sufficient for simulating the axial behavior of the reinforcement components. Axial stiffness can be obtained using the following formula:

$$K = \frac{EA}{L} \tag{1}$$

where L is the length of the element, A is the cross-sectional area of the element, and E is the Young's modulus. The compressive and tensile strength of the cable must be set so that it is not exceeded by force in the cables. If a value is not set, it will be considered unlimited by default.

The liner element is used to model the shotcrete of the excavation walls, and its mechanical behavior is divided into two categories. The first is the independent behavior of the linear element. The other is how it interacts with the surrounding mesh.

The normal behavior of the contact surface with the spring-loaded coupling component is controlled using unit area k and tensile strength f. The shear behavior of the liner contact surface is frictional and cohesive and is controlled by the stiffness components using unit area k and cohesion resistance C.

Seattle Polyclinic wall was selected to validate the modeling in the software. This wall has a height of 16.5 m (55 ft). Its geometry is shown in Fig. 1 and the soil parameters are listed in Tab. 1. The cable and shotcrete elements have been defined and analyzed as described above and are similar to the reference model [19]. The results have been compared with the values obtained on-site and the results for displacement versus the depth of the wall is shown in Fig. 2. This difference was slight and validates the accuracy of the model.

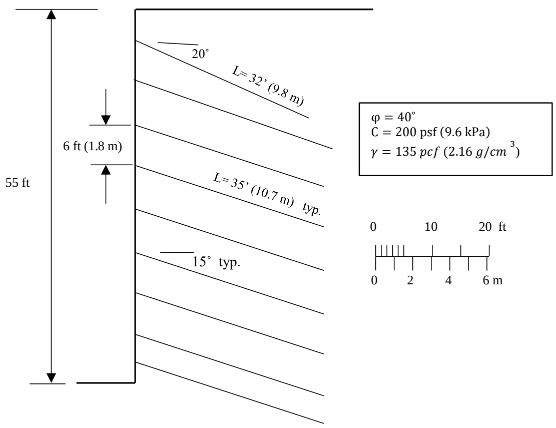

Fig. 1: The geometry of wall [19].

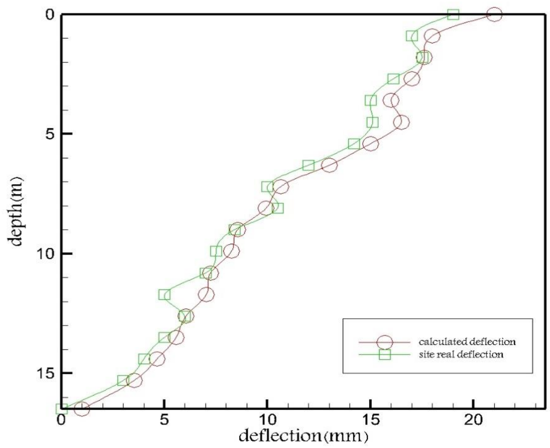

Fig. 2: Comparison of polyclinic wall displacement with software modeling.

3. Modeling

The length of the nails and their arrangement were examined, and the effect of these parameters on the lateral pressure of the soil, the force created in the nails, and the lateral deformation of the wall surface were investigated. Soil lateral pressure diagrams are based on a dimensionless parameter (earth pressure/γH) relative to Z/H. The diagrams of the maximum force generated in the row of nails have been plotted according to the Newton unit and row number from top to bottom.

Tab. 1: Wall's parameters [19].

mc-Coulomb		1	2	3	4	5
Type		**SN_Soil1** Drained	**SN_Soil2** Drained	**SN_Soil3** Drained	**SN_Soil4** Drained	**SN_Soil5** Drained
γ_{unsat}	$[\text{lb}/\text{ft}^3]$	135.00	135.00	135.00	135.00	135.00
γ_{sat}	$[\text{lb}/\text{ft}^3]$	135.00	135.00	135.00	135.00	135.00
k_x	$[\text{ft}/\text{s}]$	0.001	0.001	0.001	0.001	0.001
k_y	$[\text{ft}/\text{s}]$	0.001	0.001	0.001	0.001	0.001
e_{init}	$[-]$	0.500	0.500	0.500	0.500	0.500
c_k	$[-]$	1E15	1E15	1E15	1E15	1E15
E_{ref}	$[\text{lb}/\text{ft}^2]$	850000.00	2000000.00	3000000.00	7500000.00	19300000.00
ν	$[-]$	0.340	0.320	0.290	0.234	0.200
G_{ref}	$[\text{lb}/\text{ft}^2]$	317164.18	757575.76	1162790.70	3038897.89	804666.67
E_{oed}	$[\text{lb}/\text{ft}^2]$	1308302.24	2861952.86	3931339.98	8751111.98	21444444.44
c_{ref}	$[\text{lb}/\text{ft}^2]$	200.00	200.00	200.00	200.00	200.00
φ	["]	40.00	40.00	40.00	40.00	40.00
ψ	["]	0.00	0.00	0.00	0.00	0.00
E_{ine}	$[\text{lb}/\text{ft}^2/\text{ft}]$	70000.00	150000.00	390000.00	980000.00	2350000.00
y_{ref}	$[\text{ft}]$	155.000	141.500	129.500	117.500	105.500
$c_{\text{increment}}$	$[\text{lb}/\text{ft}^2/\text{ft}]$	15.00	25.00	30.00	40.00	45.00
$T_{\text{str.}}$	$[\text{lb}/\text{ft}^2]$	0.00	0.00	0.00	0.00	0.00
$R_{\text{inter.}}$	$[-]$	0.80	0.80	0.80	0.80	0.80
Inter permeability		Neutral	Neutral	Neutral	Neutral	Neutral

At times, it is necessary to increase the depth of excavation; thus, the wall must be redesigned. This can be not easy, depending on the excavation depth and the likelihood of installing and digging holes again from the top of the wall. Therefore, an alternative arrangement has been used in place of rearranging the nails to strengthen the walls. Table 2 shows the results for two models having different primary and secondary heights. The models increase in height as they progress. Table 3 shows the parameters used to simulate the soil behavior in the Mohr-Coulomb model. The advantages of the MC failure criterion are its mathematical simplicity, the clear physical meaning of the material parameters, and general level of acceptance

Tab. 2: Models.

Model name	Description
Model 1	9 meters primary + 4.5 meters secondary
Model 2	12 meters primary + 9 meters secondary

Tab. 3: Sandy soil characteristics for model 1.

Mohr-Coulomb model parameters	Value
Density (kg/m^3)	1950
Friction angle	27.5
Cohesion (kPa)	1
Young Modulus	50
Poisson ratio	0.25
Bulk coefficient (MPa)	25
Shear coefficient (MPa)	21.4

3.1. Model 1

For the two-stage excavation, the model has 50 m length, 30 m height, and 2 m width; in the first stage, the wall was 9 m in height with 2 nails of length 13, 14 and 12 m with the angle of 12 below horizon and vertical space of 1.5 m, and then the excavation depth was increased to 13.5 m. The geometry of the model is shown in Fig. 3. To improve the performance of the wall, a row of nails of 25 m in length was used. The following diagrams compare the results of installing this row of nails at different depths and show that the function of the wall differed, and a noticeable difference was created in the rupture wedge.

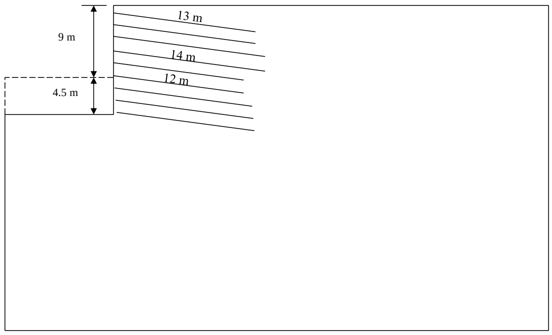

Fig. 3: Excavation and wall reinforcement elements with the length of 13.5 m for model 1.

The contour of x displacement without adding long nails is shown in Fig. 4, and contour of x displacement of wall adding long nails at a depth of 7.5 is shown in Fig. 5. For the installation of a long nail, the wedge was split and showed less displacement and damage. However, the focus of this research was to obtain the second type of wedge. In order to compare the performance of the wall, 25-m nails were installed at depths of 1.5, 3, 4.5, 6, 7.5, and 9 m. Figures 6 to 9 can be used to compare the behavior of each aspect of the model.

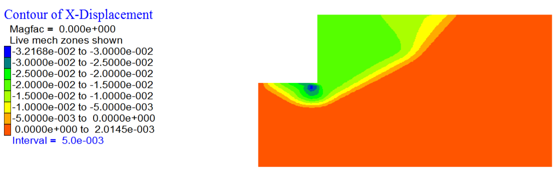

Fig. 4: Displacement contour for the case without long nail installation.

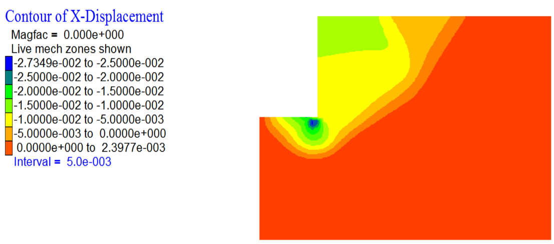

Fig. 5: Displacement contour for the installation of long nails at a depth of 7.5 meters.

1) Effect of reinforcement nail location on displacement in model 1

Figure 6 shows the horizontal displacement of the wall for the 25 m nail placement at different depths. As can be seen, by installing a row of long nails, the maximum wall displacement was halved. The smallest displacement was achieved by installing a row of nails at the top of the wall. The maximum displacement increased as the placement moved downward on the wall.

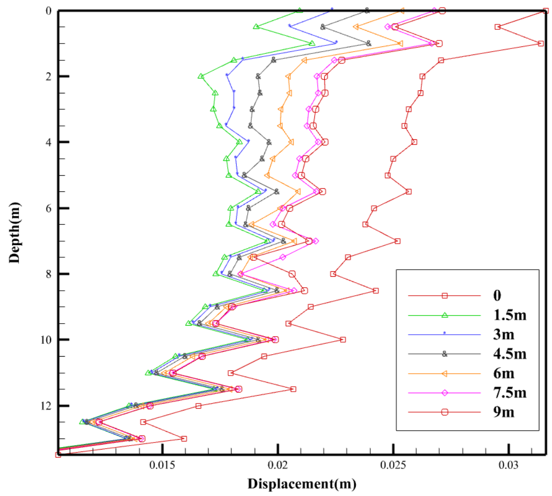

Fig. 6: Horizontal wall displacement for different depths 25-meter nail placement in model 1.

2) Effect of reinforcement nail location on force generated in row of nails in model 1

Figure 7 shows the maximum force in the row of nails from top to bottom. It can be seen that the greatest value of forces in the row of nails was in the wall without long nails. As shown in Fig. 7, when the nails are installed at any depth, the maximum force created in the row of nails decreases because the nails cut the rupture wedge sustain more forces.

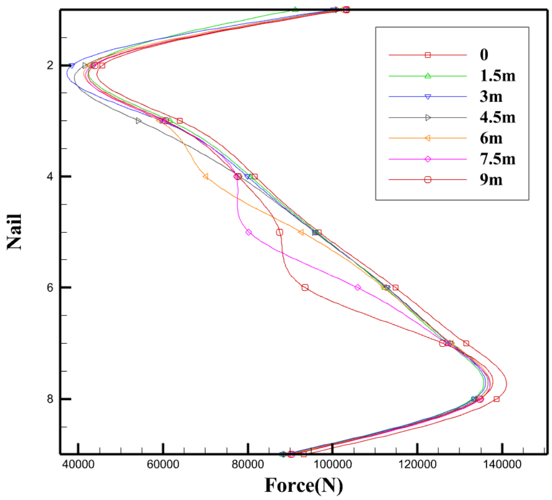

Fig. 7: Maximum Forces generated in the rows of nails for different depths of 25-meter nails in model 1.

3) Effect of reinforcement nail location on force generated along long nail in model 1

In this section, the Effect of reinforcement nail location on the force generated in a long nail in model 1 has been investigated. Figure 8 shows the force generated in the row of 25-m reinforcing nails. It can be seen that, as the placement moved downward on the wall, the maximum force created in the nail decreased.

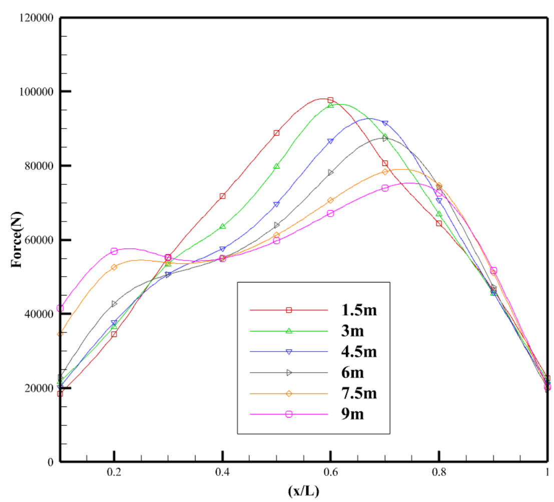

Fig. 8: Forces generated in the 25-meter reinforcement nail for different depths of placement in model 1.

4) Effect of reinforcement nail location on lateral soil pressure in model 1

Figure 9 shows the lateral pressure. As can be seen, there was no visibly significant effect on the lateral pressure behind the wall after the installation of the long nails.

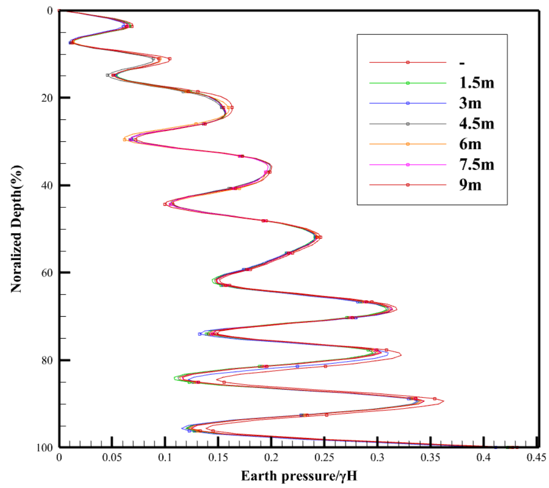

Fig. 9: Lateral pressure behind the wall for different depths of 25-meter nail.

Table 4 lists the safety factors for the nail-placement depths and shows that the highest reliability coefficient was at a depth of 7.5 m. The safety factor is the ratio of the calculated value under given conditions to that value, resulting in failure.

Tab. 4: Safety factor for model 1.

Reinforcement nail location (m)	Safety factor
-	1.6
1.5	1.68
3	1.7
4.5	1.71
6	1.73
7.5	1.77
9	1.76

5) Performance of 20, 25 and 30 m nails at depths of 1.5 and 7.5 m in model 1

Figures 10 and 11 show the horizontal displacement of the wall for nails of different lengths at depths of 1.5 and 7.5 m. Figures 12 and 13 show the maximum force generated in the nine rows of nails and Figs. 14 and 15 show the force generated along the length of the nail. Figures 16 and 17 show the lateral pressure behind the wall. An increase in the nail length at the top of the wall produced a higher safety factor and a greater decrease in displacement. As the length of the reinforcing nail increased, the maximum force created in the nail increased and occurred at a lower value of x/l. The difference between the lateral pressures of the models at the top of the wall showed the greatest value.

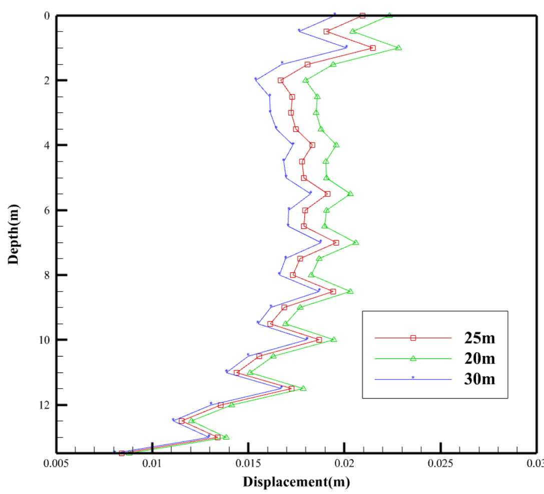

Fig. 10: The horizontal displacement of the wall for different lengths of long nails at a depth of 1.5 m in the Model 1.

Tables 5 and 6 show the safety factors for different nail lengths at two depths. At a depth of 1.5 m, the difference between the safety factors was greater than at a depth of 7.5 m.

3.2. Model 2

In this model of a two-stage excavation, the model has 70 m length, 80 m height, and 2 m width; in the first stage, the first stage of excavation began at 12 m with 2 nails of length 14 m

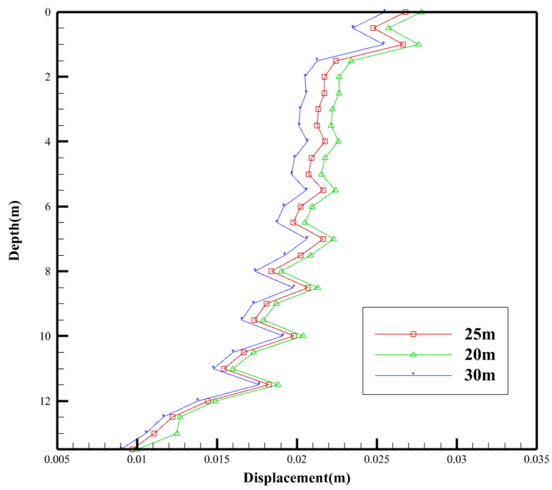

Fig. 11: The horizontal displacement of the wall for different lengths of long nails at a depth of 7.5 m in the Model 1.

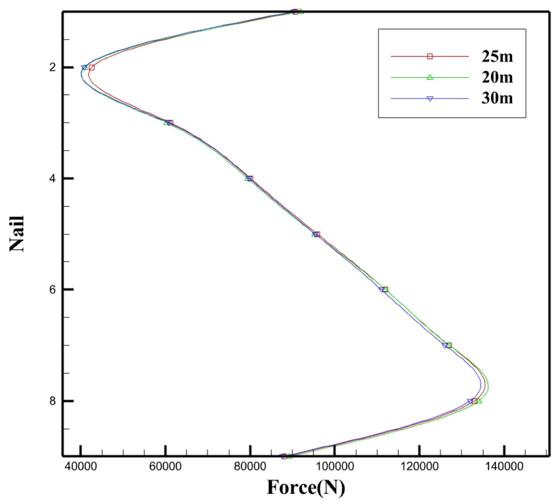

Fig. 12: Maximum Forces generated in the rows of nails for different lengths of long nails at the depth of 1.5 m in the Model 1.

Tab. 5: Safety factors for different nail lengths at a depth of 1.5 m in model 1.

Reinforcement nail length at the depth of 1.5 m	Safety factors
20	1.63
25	1.68
30	1.73

and 6 nails of length 12 with the angle of 10 degrees below horizon and vertical space of 1.5

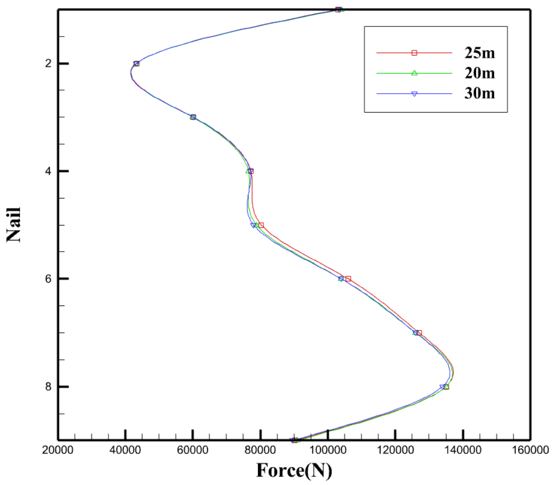

Fig. 13: Maximum Forces generated in the rows of nails for different lengths of long nails at the depth of 7.5 m in Model 1.

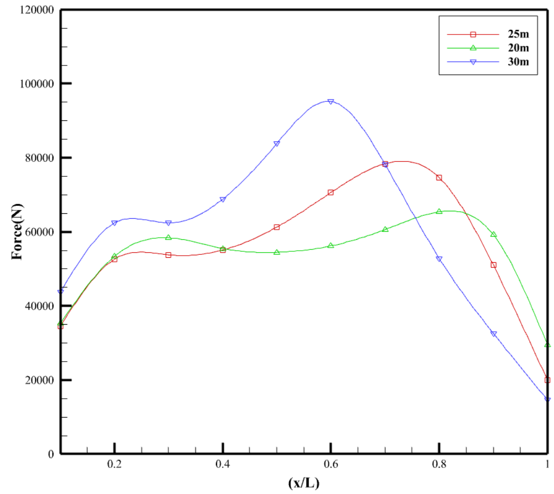

Fig. 15: Forces generated in reinforcing nails for different lengths of long nails at the depth of 7.5 m in Model 1.

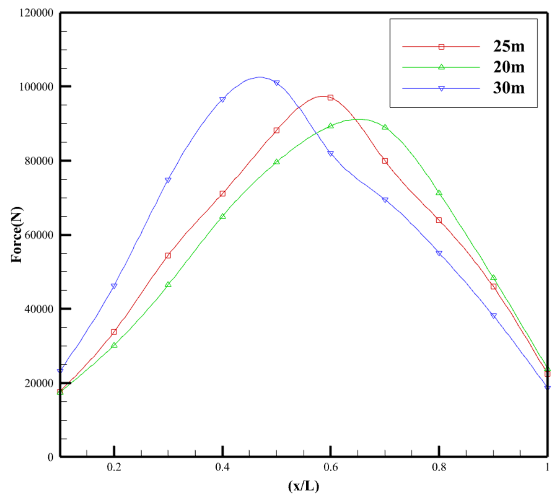

Fig. 14: Forces generated along the nails for different lengths of long nails at the depth of 1.5 m in Model 1.

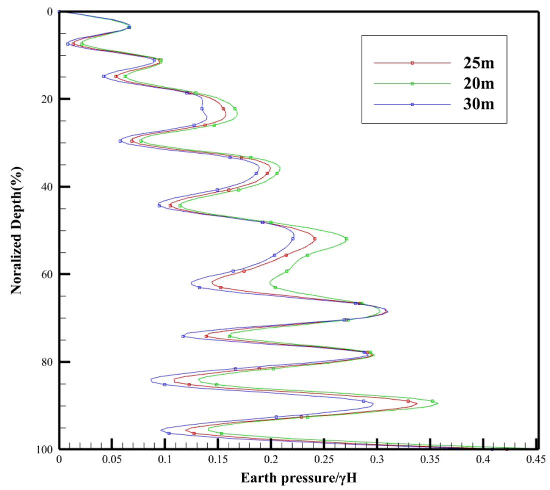

Fig. 16: Lateral pressure behind the wall for different lengths of long nails at the depth of 1.5 m in Model 1.

Tab. 6: Safety factors for different nail lengths at a depth of 7.5 m in model 1.

Reinforcement nail length at the depth of 7.5 m	Safety factors
20	1.75
25	1.77
30	1.78

m, and then the excavation depth was increased to 21 m. The geometry of the model is plotted in Fig. 18. Three arrangements were used to improve the performance of the wall by adding more rows of nailing to the wall:

- Two rows of nails of 26 m in length
- Three rows of nails of 17.5 m in length
- Five rows of nails of 10.5 m in length

A comparison has been made between the location and formation of reinforcement. The fig-

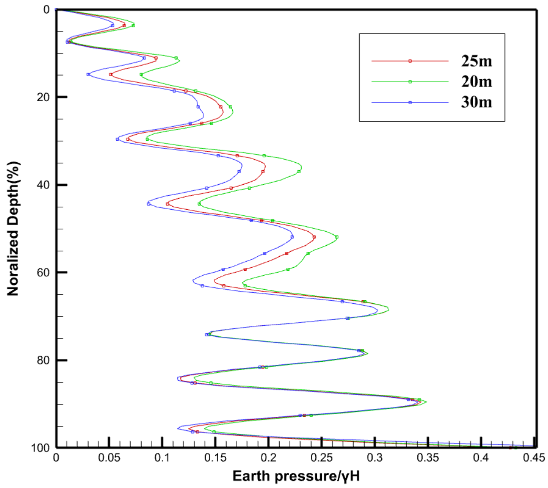

Fig. 17: Lateral pressure behind the wall for different lengths of long nails at the depth of 1.5 m in Model 1.

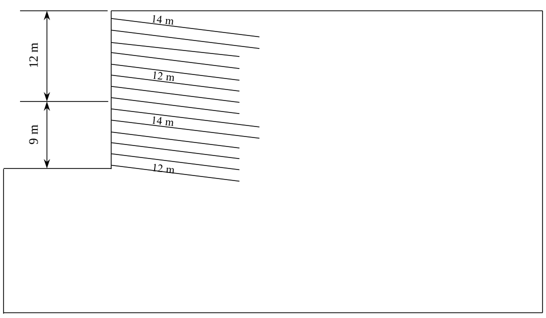

Fig. 18: Excavation and the 21-meter wall reinforcement elements.

ures compare the results of the installation of this row of nails at different depths. The soil parameters simulated in model 2 are shown in Tab. 7.

Tab. 7: Modeling parameters for model 2 (sand).

Mohr-Coulomb Parameter	Value
Density (kg/m^3)	1900
Friction angle	30
Cohesion (kPa)	5
Young Modulus (MPa)	39
Poisson ratio	0.3
Bulk Coefficient (MPa)	33
Shear Coefficient (MPa)	15

Figures 19 to 21 show the horizontal displacement of the wall for different depths of placement of the row of nails with three arrangements. The nails were installed at different depths in order to compare the displacement of the wall. The displacement of each model is plotted separately in the figures.

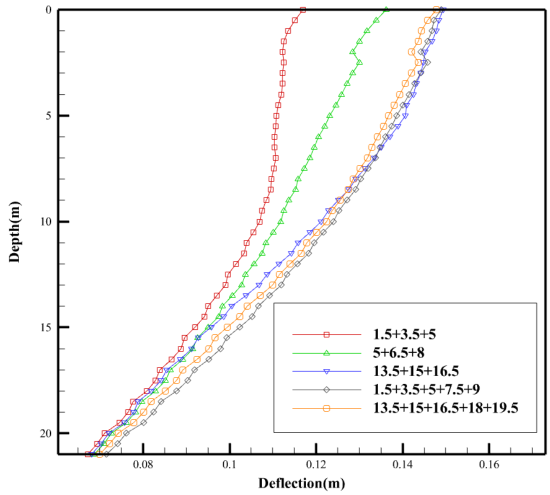

Fig. 19: Horizontal displacement of the wall for different depths Placement of 21-meter wall reinforcement nails in sandy soil- arrangement 1.

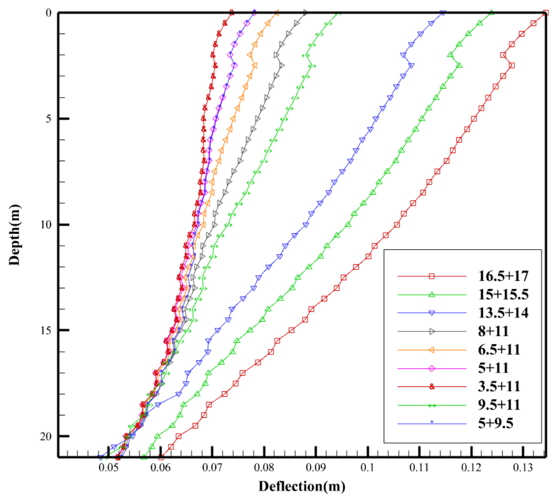

Fig. 20: Horizontal displacement of the wall for different depths Placement of 21-meter wall reinforcement nails Sandy soil arrangement 2.

1) Effect of location of reinforcement nails on displacement in model 2

Figure 19 shows that installing three rows of nails compared to five rows of nails caused a

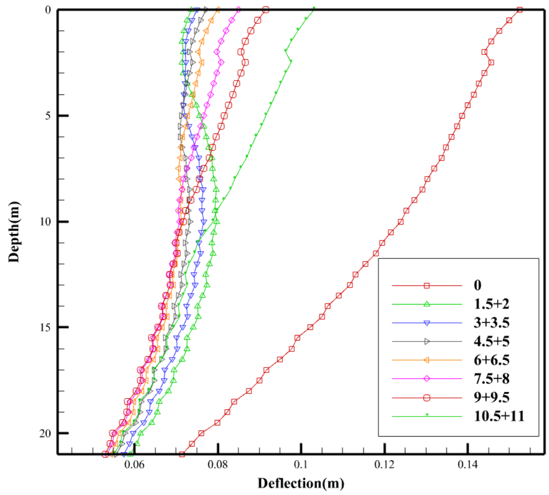

Fig. 21: Horizontal displacement of the wall for different depths Placement of 21-meter wall reinforcing nails Sandy soil arrangement 3.

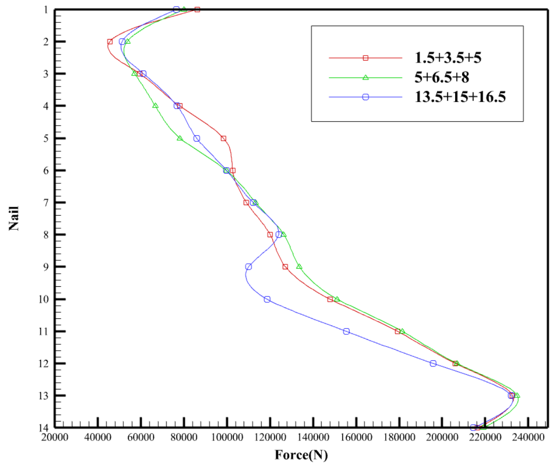

Fig. 22: Maximum Forces generated in the row of nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

more significant decrease in the maximum displacement of the wall. The smallest displacement of three rows value was achieved by installing three rows of nails at the top of the wall, and the maximum displacement increased as installation moved downward. The largest displacement is at the top of the wall, and the length outside of the rupture wedge has more effect, so a comparison of the three methods shows that minimum displacement was obtained when two rows of 26-m nails were installed at depths of 3.5 and 11 m. Installing a row of reinforcing nails in the lower half of the wall did not produce as much change as the case without reinforcing nails. Figures 22 to 25 show the maximum force generated in nine rows of nails.

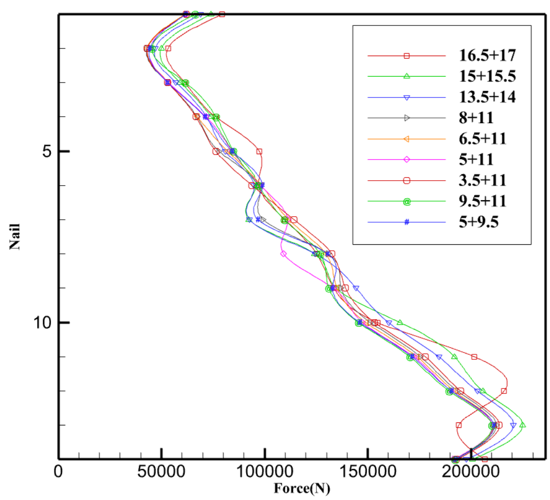

Fig. 23: Maximum Forces generated in the row of nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

2) Effect of location of reinforcing nails on force generated in row of nails in model 2

It can be seen that the biggest value of the forces in the row of nails was for the wall without long nails. The installation of nails at any depth reduced the maximum force in the nail row. In general, the minimum force generated in the rows of nails was obtained by installing two rows of nails at depths of 10.5 and 11 m. The maximum forces were obtained by installing five rows of equivalent nails. The maximum force generated in the reinforcing nails was for the installation of two rows of long nails at depths of 6.5 m and 11 m. The nails at a depth of 6.5 m experienced the most force. Figures 26 to 29 show the force generated along the length of the reinforcing nails according to the placement depth.

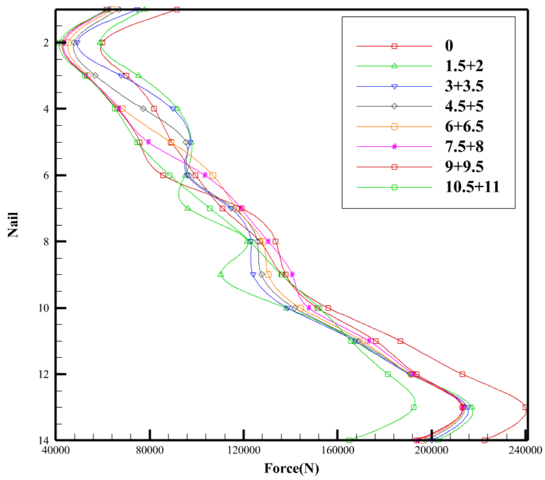

Fig. 24: Maximum Forces generated in the row of nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

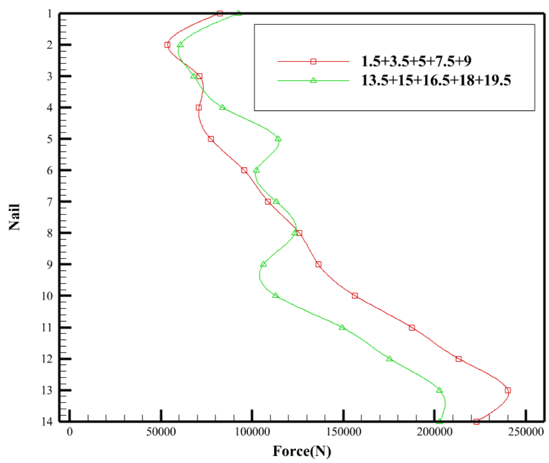

Fig. 25: Maximum Forces generated in the row of nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

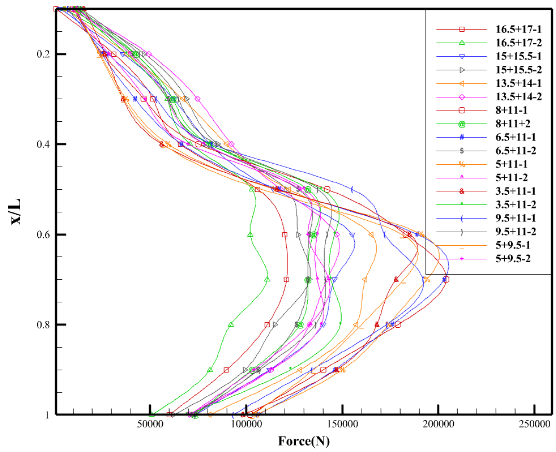

Fig. 26: Forces generated in the adding nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

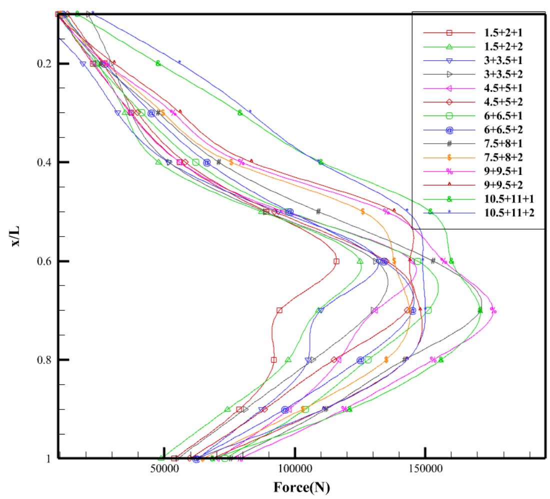

Fig. 27: Forces generated in the adding nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

3) Effect of location of reinforcing nails on force generated along long nails in model 2

The maximum forces generated in a nail at a depth of 6.5 m with the formation of two nails at a depth of 6.5, and 11 m with the longer length of nails the resistance out of rupture wedge is bigger, and the force generated in the nail is bigger. Figures 30 to 32 show the lateral pressure behind the wall.

4) Effect of long nail location on lateral soil pressure in model 2

The lowest lateral pressure behind the wall was for the case with two rows of long nails installed at depths of 3.5 and 11 m. Table 8 shows the safety factors of the different models at different reinforcement nail placement depths. The highest safety factor was obtained when two rows of long nails were used at depths of 13.5 and 14 m.

Table 8 shows the safety factor of different nailing arrangements. The biggest safety fac-

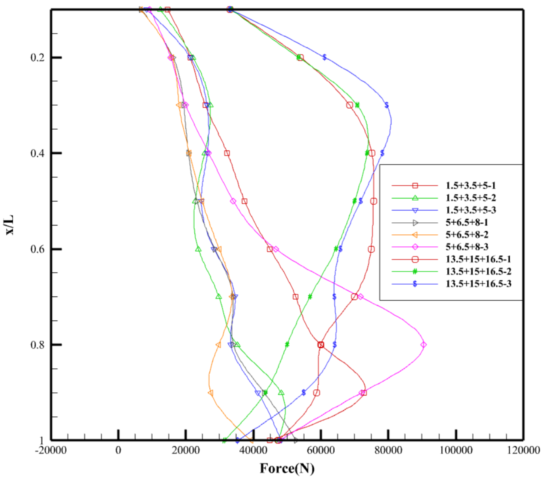

Fig. 28: Forces generated in the adding nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

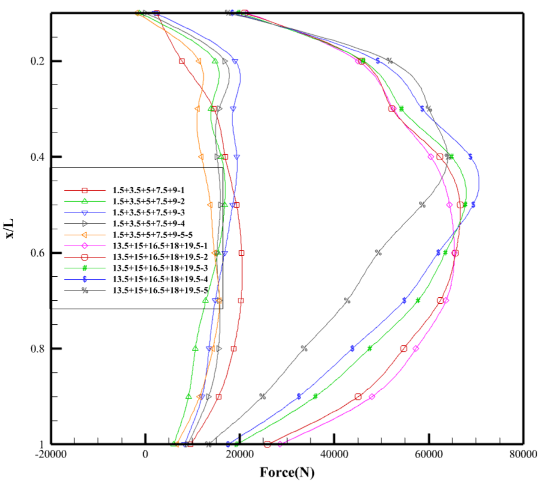

Fig. 29: Forces generated in the adding nails for different depths. Placement of reinforcing nails in a 21-meter wall of sandy soil.

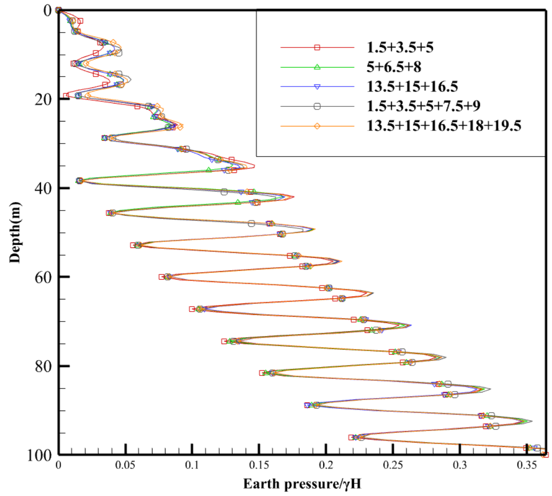

Fig. 30: Lateral wall pressure for different depths Placement of 21-meter wall reinforcing nails in sandy soil.

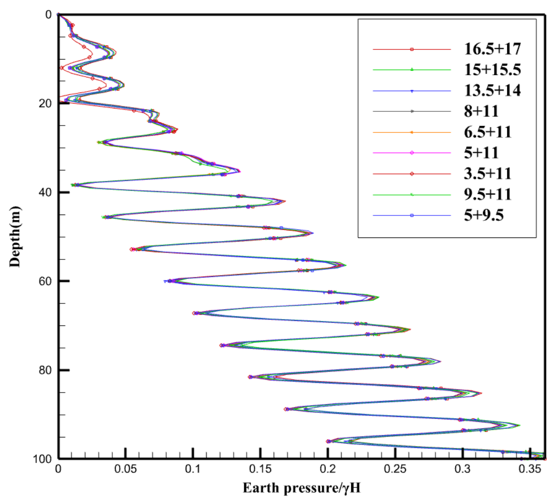

Fig. 31: Lateral wall pressure for different depths Placement of 21-meter wall reinforcing nails in sandy soil.

tor was achieved at a depth of 10.5 and 11 m, according to the involvement of nails in soil and rupture wedge.

4. Conclusion

With the advent of large construction projects and changes in design, it may be necessary to change the excavation depth after the onset of construction of larger buildings. This means that an optimal solution is required for increasing the excavation depth. By 3D modeling geotechnical problems, their behavior can be better modeled and predicted, and FLACE 3D is one of the best software to simulate geotechnical problems. In this research, according to the adopted method, the following results were obtained:

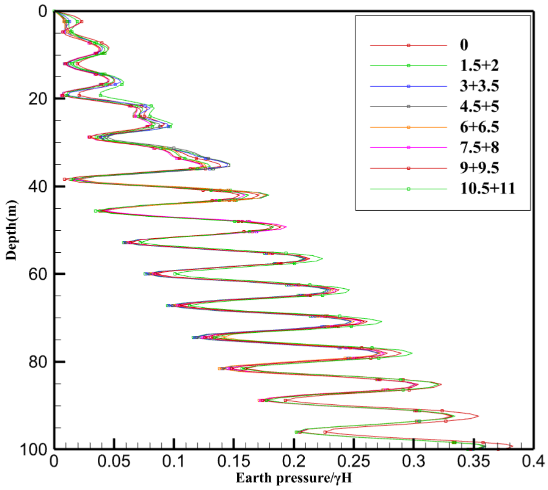

Fig. 32: Lateral wall pressure for different depths Placement of 21-meter wall reinforcing nails in sandy soil.

Tab. 8: Safety factor for model 2 (sand).

The location of the reinforcement nail (m)	Safety factor
-	1.3
5 + 3.5 + 1.5	1.35
8 + 6.5 + 5	1.45
16.5 + 15 + 13.5	1.42
9 + 7.5 + 5 + 3.5 + 1.5	1.4
19.5 + 18 + 16.5 + 15 + 13.5	1.4
1.5 + 2	1.32
3 + 3.5	1.36
4.5 + 5	1.37
6 + 6.5	1.45
7.5 + 8	1.47
9 + 9.5	1.49
10.5 + 11	1.54
13.5 + 14	1.6
15 + 15.5	1.53
16.5 + 17	1.5
8 + 11	1.48
6.5 + 11	1.45
5 + 11	1.41
3.5 + 11	1.4
9.5 + 11	1.39
5 + 9.5	1.38

- The installation of a row of nails in the upper half of the wall to strengthen the wall decreased displacement. When they were installed in the middle of the wall, the highest safety factor was obtained.

- By installing a row of long nails with a ratio of 0.2 to the total length of the reinforcement nails, a 10% increase in safety factor was obtained.

- When the number of reinforcement nails was increased to 3 and 5, it can be seen that the installation of three rows of nails compared to five rows of nails reduced the maximum displacement of the wall to a greater extent. It also can be seen that the smallest displacement was achieved by installing three rows of nails at the top of the wall and that the maximum displacement at the bottom of the wall increased.

- The smallest displacement was achieved when two rows of nails were installed, one at the top of the wall and one in the middle of the wall.

- When the number of reinforcement nails with the same lengths was considered, installing two rows of nails in comparison with 5 or 3 rows of nails reduced the maximum wall displacement to a greater extent, and a greater factor of safety was achieved.

Further research could usefully explore Seismic analysis of new arrangements, and analysis of this arrangement in soil with liquefaction potential.

References

[1] Rouhanifar, S., & Afrazi, M. (2019). Experimental study on mechanical behavior of sand-rubber mixtures. *Modares Civil Engineering journal, 19*(4), 83-96.

[2] Afrazi, M. (2018). Numerical simulation of soil lateral pressure on flexible retaining walls using a hybrid discrete-finite element method. *Tarbiat Modares University.*

[3] Afrazi, M., et al. (2018). Numerical analysis of effective parameters in direct shear test by hybrid discrete – finite element method. *Modares Civil Engineering journal, 18*(3), 13-24.

[4] Rouhanifar, S., et al. (2020). Strength and deformation behaviour of sand-rubber mixture. *International Journal of Geotechnical Engineering*, 1-15.

[5] Afrazi, M., Yazdani, M., & Fakhimi, A. (2017). The numerical study of effect of an oversize particle on the shear strength of sand in Triaxial test. *4th international conference on recent innovations in civil engineering, architecture, and urban palnning.*

[6] Sabhahit, N., Basudhar, P., & Madhav, M.R. (1995). A generalized procedure for the optimum design of nailed soil slopes. *International journal for numerical and analytical methods in geomechanics, 19*(6), 437-452.

[7] Yuan, J.-X., et al. (2003). New approach to limit equilibrium and reliability analysis of soil nailed walls. *International Journal of Geomechanics, 3*(2), 145-151.

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

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

[10] Halabian, A., Sheikhbahaei, A., & Hashemolhosseini, S. (2012). Three dimensional finite difference analysis of soil-nailed walls under static conditions. *Geomechanics and Geoengineering, 7*(3), 183-196.

[11] Singh, V.P., & Babu, G.S. (2010). 2D numerical simulations of soil nail walls. *Geotechnical and Geological Engineering, 28*(4), 299-309.

[12] Cheuk, C., Ho, K., & Lam, A. (2013). Influence of soil nail orientations on stabilizing mechanisms of loose fill slopes. *Canadian Geotechnical Journal, 50*(12), 1236-1249.

[13] Seo, H.-J., Lee, I.-M., & Lee, S.-W. (2014). Optimization of soil nailing design considering three failure modes. *KSCE Journal of Civil Engineering, 18*(2), 488-496.

[14] Yazdi, J.S., Rahman, M., & Cameron, D. (2014). Effect of Nail Layout Variability on Soil Nailed Wall Analysis. *Geo-Congress 2014: Geo-characterization and Modeling for Sustainability.*

[15] Lin, H., Xiong, W., & Cao, P. (2013). Stability of soil nailed slope using strength reduction method. *European Journal of Environmental Civil Engineering, 17*(9), 872-885.

[16] Bakyani, A.E., et al. (2018). Three-dimensional and two-phase numerical simulation of fractured dry gas reservoirs. *Journal of Petroleum Exploration and Production Technology, 8*(4), 1425-1441.

[17] Majedi, M.R., Afrazi, M., & Fakhimi, A. (2021). A micromechanical model for simulation of rock failure under high strain rate loading. *International Journal of Civil Engineering, 19*(5), 1-15.

[18] Majedi, M., Afrazi, M., & Fakhimi, A. (2020). FEM-BPM simulation of SHPB testing for measurement of rock tensile strength. *54th US Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association.*

[19] Abdulrahman, A. (2006). Finite Element Based Design Procedures For MSE Soil-Nail Hybrid Retaining Wall Systems. *Doctoral Thesis Submitted to the Graduate Faculty of Texas Tech University.*

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