

# Evaluating of optimal length and spacing of nails in stabilization of soil pits using finite element and limit equilibrium methods

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**Abstract.** Nowadays, nailed retaining structures are one of the most practical methods of stabilizing pit walls in urban environments and slopes. This study evaluates the optimal distance and placement length of nails in various conditions using Plaxis and GeoSlope software, taking advantage of the findings of other studies to increase the reliability and stability of the pits. In this study, three examples of common urban pits with a height of 4, 8, and 12 meters were selected, and the variable distances of the nails were evaluated as 0.5, 1, 1.5, 2, and 2.5 meters in each pit. The results of various modeling are presented in 3-dimensional forms, taking into account the state of stability and the maximum displacement, to achieve the minimum amount of the total length of nails used (economic efficiency) in different conditions. For example, the three-dimensional results of the simultaneous investigation of safety factor and displacement along with the total length of nails in an 8-meter pit show that the most suitable safety factor is 1.4 for nails with a distance of 1.5 meters (5 rows of nails with lengths of 10, 9, 8, 6, 4 meters) and with a maximum displacement of 10 mm. In the best case, the total length of nails is 37 meters. Also, the second priority is nails with a distance of 1 meter with a total length of nails of 45 meters, which is not economical. Although shorter distances of nails produce better results, special attention should be given to the parameter of the total length of used nails. In addition, there is a good agreement between the results of the finite element method (FEM - Plaxis) and Limit Equilibrium Method (LEM – GeoSlope/w). Furthermore, a relationship is proposed to relate the response parameters of the pit (i.e., maximum displacement, optimal length of nails, and factor of safety) to the input parameters, such as pit height and nails distance. The results show that the proposed formula has good accuracy and efficiency in predicting the response parameters and gives reliable estimates in comparison to finite element simulations.

**Keywords:** GeoSlope; nailing; optimum length and space; pit; plaxis; safety factor

## 1. Introduction

In many construction projects, it is necessary to excavate the ground in such a way that its walls are vertical or close to vertical. The lateral pressure on these walls is caused by soil drift due to its own weight and possible overloads acting on the soil next to the pit. These overloads can be caused by soil above the horizontal level at the edge

of the pit, nearby buildings, loads caused by the use of nearby roads, and other factors. The collapse of the pit wall and adjacent buildings during excavation is one of the main problems of construction projects, which unfortunately still causes many casualties and financial losses despite recent advances in civil engineering. Therefore, due to the increasing growth of new urban constructions and the need for safe stabilization of the pit, the presence of geotechnical engineers alongside civil and architectural engineers is highly required (Farokhzad *et al.* 2020).

In order to prevent the fall of the trench and the possible negative consequences of this excavation, temporary structures can be implemented to restrain the trench. In this regard, soil nailing method is one of well-known methods of stabilization of excavations. This method not only has high safety, but depending on the conditions, in most cases, it has lower costs than other methods and it can be implemented in much less time (Porterfield *et al.* 1994).

Soil materials usually have relatively high compressive strength and low tensile and shear strengths. Nailing reinforces the soil and increases its tensile and shear resistance. The construction of a nailing reinforced soil wall

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involves reinforcing the soil during excavation operations by a series of rebar called soil nails. The nails are practically worked in tension and are often parallel to each other and have a slight downward slope of about 15 degrees in most executive works. The nailing system is based on the transfer of tensile load from the soil to the nail through the shear stress of the interface between them (Lazarte *et al.* 2003).

Nailing is one of the types of soil reinforcement operations that has been common in the stabilization of slopes and excavations since the last three decades in the world, especially in France, Germany, and recently in the United States. The main hypothesis of this type of strengthening is to reinforce the ground in order to increase the shear resistance of the soil and limit its movement (Zhou 2008). The main assumption of the design is to transfer the tensile force produced from the nails to the ground using the friction generated between them. It is worth mentioning that this system allows engineers to use the ground to create guard structures. The nailing method has many advantages over other strengthening methods such as retaining walls. In addition, it has lower costs, which has made the use of this method very popular among engineers (Panah and Majidian 2013, Rajabian *et al.* 2013, Nicknejad and NorouzOliaei 2020, Rasoli *et al.* 2022).

The soil nailing technique is mostly used to stabilize the excavations or vertical cuts, the slope of the reservoir and underpass (Babu 2009). Numerical modeling was conducted on soil slope using PLAXIS-2D software and concluded that up to 60% of the construction of a soil-nailed wall, the lateral displacement of wall more predicted by the Mohr-Coulomb material model (Singh and Sivakumar Babu 2010). Soil nailing is an innovative technique that can be adopted to strengthen the facing of the tunnel (Sterpi *et al.* 2013). Farokhzad *et al.* investigated the performance of excavation under the effects of behavioral models and soil resistance properties and the value of surcharge, using numerical analysis. They indicated that under certain designing conditions, the lateral deformation of the soil nail wall and ground settlement decrease as soil resistance specifications increase (Farokhzad *et al.* 2020). Various numerical methods such as the traditional limit equilibrium method, finite element method and finite difference method have been used to evaluate the performance of soil slope nailing. The limit equilibrium method is adopted by various researchers for assessing the performance of a nailed slope (Zhu *et al.* 2003, Cheng and Zhu 2004, Alejano *et al.* 2011, Zhou and Cheng 2013, Ardakani *et al.* 2014). Traditional designs based on LEM is adequate, but is the efficiency questionable due to the lack of knowledge in soil-structure interaction. Such limitations can be overcome using numerical methods such as finite element (FE) analysis (Chen *et al.* 2001, Loukidis *et al.* 2003, Rawat *et al.* 2014). Many researchers have used 2D FE or finite difference methods for the analysis of nailed slopes (Unterreiner *et al.* 1997, Sivakumar Babu *et al.* 2002, Cheuk *et al.* 2005), undrained capacity and stability of footing lying on layered slopes as well (Xiao *et al.* 2019, Wu *et al.* 2020, Wu *et al.* 2020, Wu *et al.* 2021, Wu *et al.* 2021).

Hong and Chen studied the effect of bending stiffness and nail inclination on the performance of nailed walls using a two-dimensional finite difference software program. They evaluated the behavior of a 7 m high nailed pit in three models including loose, relatively compact and compact granular soil. The results of their research showed that with the increase in bending stiffness, the normalized tensile force does not increase significantly, and by decreasing the slope of the nails, the force produced inside the nails increases. This increase in loose and relatively dense soil has been less than dense soil, and with the increase in the slope of the nails, the horizontal deformation of the wall has also increased (Foroudian *et al.* 2020). Rashid *et al.* evaluated the performance of nailing using finite element and finite difference methods. Based on the modeling of a 12-meter pit with a nail angle of 7 degrees and a length of 8 to 10 meters, they showed that the finite element method is more powerful and, as a result, has shown better results comparing to the finite difference method (Rashid *et al.* 2013).

Based on the performed numerical modeling, it was determined that with the increase of the angle of the nailed slope - with the constant angle of the embankment above it - the optimal angle of nailing decreases. The maximum tensile force in the nails - which are executed at a lower level compared to the canopy - is higher than the nails that are at a higher level; and the maximum tensile force is created in the nails that are applied at the level of one-third of slope crest.

In the CLOUTERRE project, the pit wall was built using rebars in the soil, so that its height and width were 7 and 5.7 meters, respectively. The resistant element of the facade consists of reinforced shotcrete, and the angle of the nails compared to the horizon is 10 degrees and their horizontal and vertical distances are 1.15 and 1 meters, respectively. The results showed that increasing the angle of the nail in the pits with slopes close to 90 degrees to the horizon level, the amount of factor of safety decreases, and increases with the decrease of the nail angle. On the other hand, in the slopes with angles less than 90 degrees, the influence of the placement angles of the nails on the factor of safety has variable peaks (Fan and Luo 2008).

Kaotho *et al.* (2021) conducted a numerical evaluation on the soil-nailed slope with flexible facing based on the finite element method in order to investigate the range of those two parameters with any size of nail head in various slope angles. The numerical results indicated the optimum nail inclination in a range between 10° and 20° for slope angle of 45° and 55° (Kaotho *et al.* 2021). In another research, the stabilization of the pit wall in Tehran was investigated using nailing technique in FLAC2D software.

The results showed that the best factor of safety is achieved when the angle of the nails is slightly above the horizon level; and as the angle of the nails increases with respect to the horizon, the value of factor of safety decreases (Zamiran *et al.* 2012). Elahi *et al.* (2022) evaluated the effect of angle, length and distance of nails on the stability of soil slopes. They showed that the optimal angle of the nails according to the different geometries of the slope is between 0 and 25 degrees and increasing the

length of the nails is effective in reducing the lateral movement of the slope (Elahi *et al.* 2022). Maleki *et al.* (2022) investigate the effects of mechanical and geometrical properties of the nails on the dynamic response and the amplification characteristics of a retained trench wall in both loose and dense soil conditions. It was found that the vertical spacing of the nails is more influential in the control of the settlement compared to the horizontal spacing (Maleki *et al.* 2022). In addition, a series of parametric studies are performed with some important factors, such as: the (1) soil nailing length, inclination, and horizontal spacing; (2) location of the groundwater level; (3) excavation depth and thickness of the clay layer; and (4) undrained shear strength of the soil (Lyman *et al.* 2022). In general, the safety factor was decreased by increasing the height of the soil nailed wall, and stability of the wall decreases as horizontal acceleration coefficient values increases (Naik and Savoikar). The stability of the slope decreased by increasing the spacing between the soil nails and increased by the inclination of the nail (Sarkar *et al.* 2017). The spacing of nails in a slope is an important parameter to be checked as the stability of the slope depends much on it (Villalobos and Villalobos 2021).

Considering the importance of stabilization of urban pits and the relevance of this topic based on recent research in this field (Mohamed *et al.* 2021, Bathini and Krishna 2022, Cheng *et al.* 2022, Imani Kalehsar *et al.* 2022), this paper evaluates the optimal distance and length of nails in common urban pits with heights of 4, 8, and 12 meters. To model and analyze different placement modes of the nails in the three considered pit samples, limit analysis methods using Geo-Studio software and the finite element method based on Plaxis are utilized. The optimal distance and length of the nails are then determined using the safety factor of pit stability and the displacement of the maximum pit. Next, the optimal distance and length of the nails are determined using the values of factor of safety of stability and maximum pit displacement. To achieve the optimal length and distance of the nails, the analysis and modeling process is carried out in accordance with the actual process of executing urban projects. Initially, based on the resulting failure level and the provided safety factor values, the initial optimal length and distance of the nails are determined. Then, the displacement values of the pit are recorded according to the stages of excavation and execution of nails and shotcrete. If the design rules and criteria are not met, this process is repeated again to provide acceptable values of safety factor and displacement. In this regard, for each of the pits, the variable distances of the nails have been considered as 2.5, 2, 1.5 and 1 meters. The results are presented in terms of displacement and safety factor, with the optimum length achieved in each case. Furthermore, based on the data provided by the finite element analysis used as a data bank, a practical formulation is proposed for calculating these parameters for pits that differ from the intended ones. The results, along with the accompanying details, are subsequently presented.

## 2. Modeling and validation

### 2.1 Modeling

Numerical modeling is one of the methods of solving engineering problems that provides the possibility of predicting the behavior and studying the effect of different parameters in less time, easier conditions and less financial cost compared to laboratory modeling (Rahnema *et al.* 2021, Dolatyari *et al.* 2024). In this paper, Geo-Studio and Plaxis 2-D software are used for numerical modeling, which is based on the finite element method and are common for analyzing geotechnical problems. In this article, Plaxis 2D version 8 is used to simulate common urban pits and nailing system (Brinkgreve *et al.* 2002, Farokhzad *et al.* 2020, Sreedevi *et al.* 2022). Numerical simulations using FE analysis can provide accurate results if the parameters representing soil characteristics are properly evaluated and interaction among different elements such as nails and soils are correctly considered (Pak *et al.* 2021, Islam *et al.* 2022).

FEM could complement conventional methods, in achieving economical and reliable design (Lin 2022). The most important features of this software are the possibility of modeling gradual drilling using the ability to remove elements, modeling elastoplastic behavior using the Mohr-Coulomb model, and using the method of reducing cohesion coefficients and internal friction angle to determine factor of safety in slope stability. Considering the fact that element dimension has a close relationship with the accuracy and resolution of the results, the automatic mesh generation method has been used in the modeling. Also, a finer mesh is used in areas where the density of nails and layers are high and closer to each other, or there is a need to collect data more accurately (Mirassi and Rahnema 2021). To perform limit analysis GeoSlope/w software (GeoStudio) is used. GeoSlope is one of the most useful two-dimensional software in geotechnical engineering which works based on numerical methods, as like as other specialized geotechnical software such as FLAC, Plaxis and Abaqus (Mirassi and Rahnema 2020). In this software, it is possible to analyze the stability of slopes and earthen dams, and the dynamic analysis of geotechnical structures. Modeling of nailing and liquefaction phenomenon in susceptible soils and simulation of settlement phenomenon are among other functionalities of GeoSlope software.

### 2.2 Validation #1

To verify the performance of software and numerical modeling, a reinforced nailed earthen pit provided by Babu and Singh (2007) in Plaxis Bulletin has been used (Babu and Singh 2007, Ashrafi and Basharat 2015). The reinforced nailed slope has a height of 6.8 meters and is completely vertical. The specifications of the model include Poisson's ratio of 0.3, internal friction angle of 25 degrees, cohesion of 10 kPa, and Mohr Coulomb model is adapted for soil behavior. The physical model of the pit, nail and examined wall for validation is shown in Fig. 1(a). As can be seen, the model consists of 13 layers of nails. The model built in this paper is presented in Figs. 1(b) and 1(c) in terms of general deformation and color contours of the deformation after the analysis.

Modeling was done step by step and at each step, soil removal, nail installation and shotcrete activation were

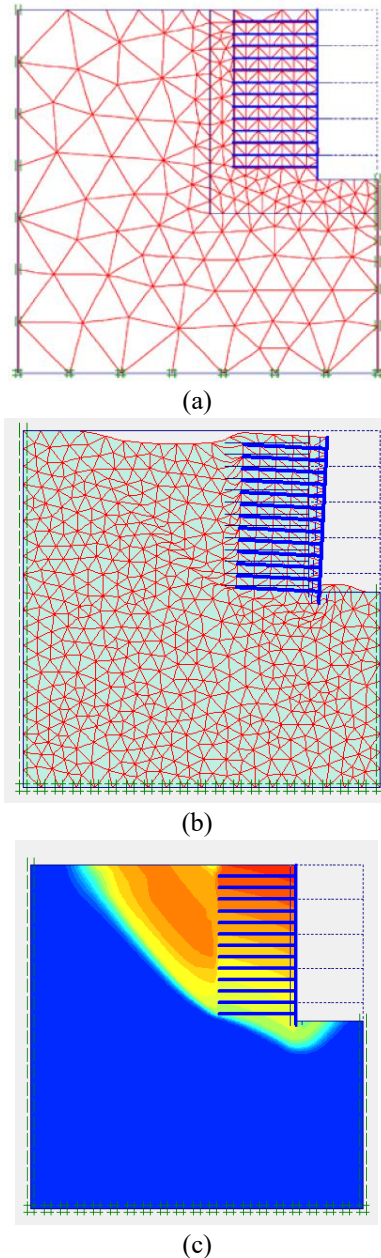


Fig. 1 Plaxis models: (a) selected model sample for validation, (b) general deformation of the meshed model in Plaxis and (c) contour of the general deformation of the model in Plaxis

done. In this way, in the first stage, the surface layer with a thickness of 1.5 meters was removed, and then the nail and wall system were placed, which after analyzing the safety factor of 3.19 was obtained. In the second stage, after excavating the soil to a thickness of 1.5 meters and activating the nails and the wall, the safety factor was obtained as 2.32. In the same way, the next steps have been carried out and in the final step, by removing the last layer and activating the nail and wall system, the safety factor of 1.235 has been obtained. The results of modeling in Plaxis software by Ashrafi and Basharat (Ashrafi and Basharat 2015) are compared with Babu and Singh (2007) diagram and shown in Fig. 2, which are in good agreement (Ashrafi

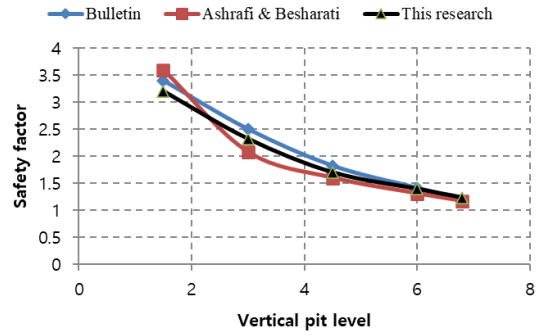


Fig. 2 Comparison of the results of this study with the results of Ashrafi and Basharat (2015) Babu and Singh (2007)

and Basharat 2015). In this study, for the purpose of validation, the results obtained from modeling in Plaxis software have been evaluated with the results of Babu and Singh (2007) and the results of Ashrafi and Basharat (Babu and Singh 2007). All the results are presented in Fig. 2. As can be seen, the results of this research are in good agreement with the results of other researchers.

### 2.3 Validation #2

In order to further calibrate the accuracy of numerical simulations, another validation has been done in this part (Fan and Luo 2008). For this purpose, the results of the French CLOUTERRE project and the modeling results of Fan and Luo (2008) have been used (Fan and Luo 2008). The specifications of the nailed wall in the CLOUTERRE project are shown in Fig. 3. The angle of the nails is 10 degrees with respect to the horizon and their horizontal and vertical distances are 1.15 and 1.0 meters, respectively. In front of this wall, there is an embankment, which is excavated step by step, and the wall nails are installed.

Based on the geotechnical characteristics mentioned above and the characteristics of the wall and nails, the geometry of the wall has been modeled in Plaxis finite element software. The geometry of the built model is shown in Fig. 4.

The results of the finite element analysis of the change in the horizontal shapes of the wall at the end of phase 3 (excavation to a depth of 3 meters) and the end of phase 5 (excavation to a depth of 5 meters) at a distance of 2 meters

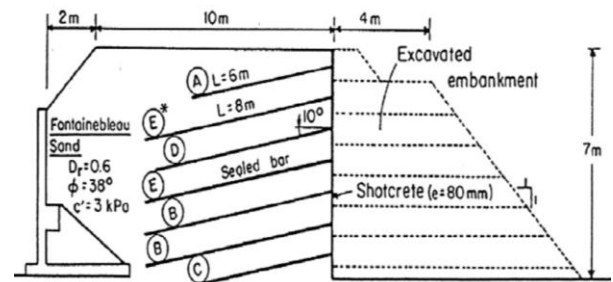


Fig. 3 Specifications of walls and nails used in CLOUTERRE project (Plumelle and Schlosser 1990)

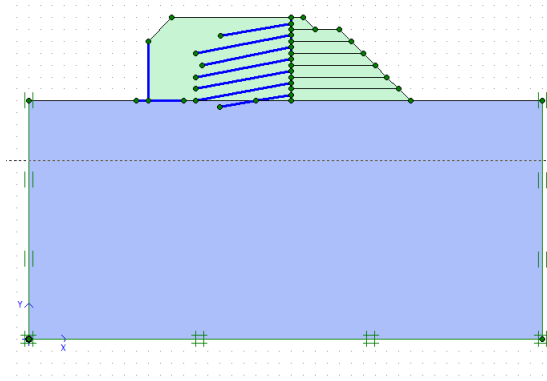


Fig. 4 The geometry of the created model

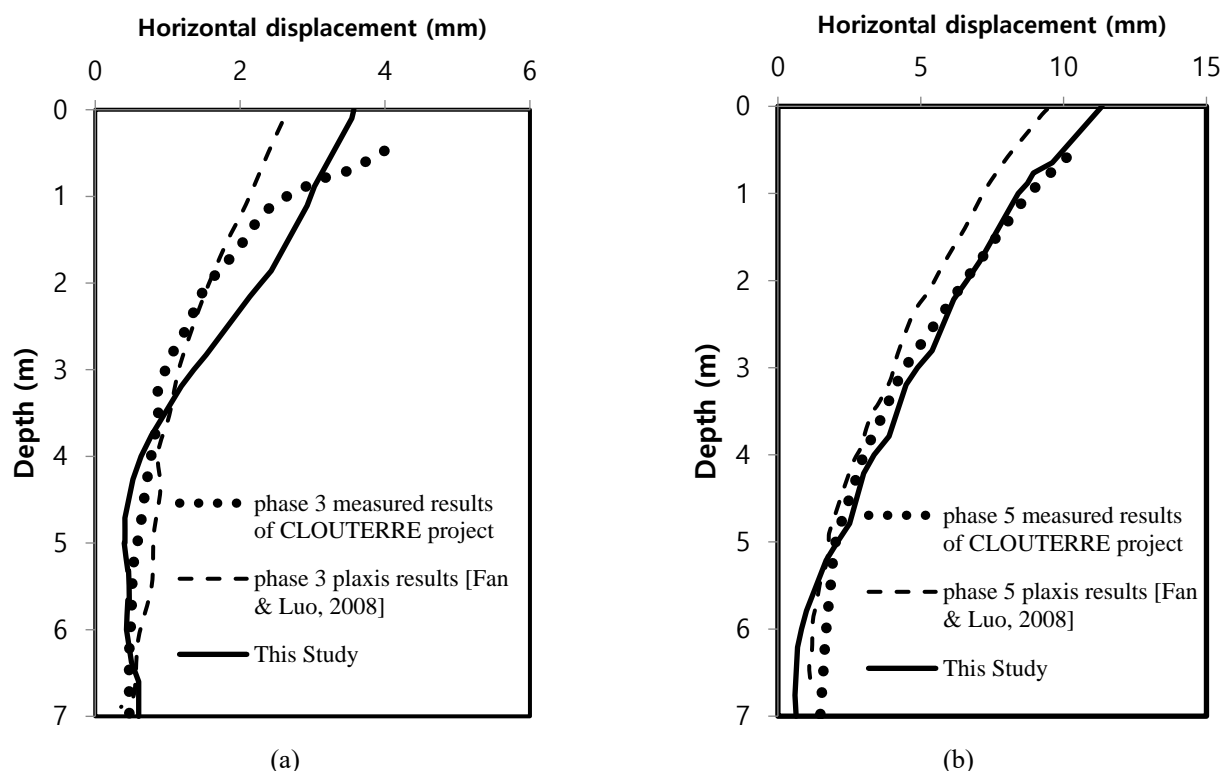


Fig. 5 Comparison of computed lateral displacements in the backfill at 2 m from the wall with field measured results and Plaxis results of Fan and Luo (2008)

from the back of the nailed wall are shown in Figs. 5(a) and 5(b), respectively. The results obtained from the finite element analysis show that the maximum horizontal displacement of the nailed wall occurs at the crest of the wall. It should be noted that finite element analysis was performed using the Mohr-Coulomb model according to the model used by Fan and Luo (2008). As it can be seen from the Figs., the results of the numerical simulations are in acceptable agreement with the results of CLOUTERRE project and Fan and Luo (2008).

### 3. Results and discussion

#### 3.1 Developing numerical modeling

In this section, the effect of horizontal and vertical distances of the nails on the safety factor values of the stability of the nailed slope has been evaluated. In order to achieve and evaluate the results, in a way that is closer to the real conditions of construction, Plaxis 2D and GeoStudio Slope/w have been used. In this regard, models are first created in GeoSlope/w software and the results are evaluated by trial and error procedure. It is tried to determine the optimal nail length for the pit, by changing the length of the nails and taking into account the minimum safety factor of the optimal stability, the length of the optimal nails can be finally determined according to the most critical level of failure formed. It should be noted that the failure surface obtained at the levels close to the ground surface has a larger width, and it has a smaller width at the level close to the bottom of the pit. Therefore, the length of

Table 1 Specifications of the Modeled Soil

Material	Elastic Modulus (MPa)	Unit weight (kPa)	Poisson's Ratio	Cohesion (kPa)	Internal Friction Angle (degree)
Loose soil	200	1800	0.33	20	25

the nails at different levels are variable as well as the real conditions of construction, and the optimal length of each of the nails can be determined in different levels according to the failure surface. Next, the same model has been then re-modeled in Plaxis with the specifications obtained for the geometry of the nails, and the values obtained from the analysis for the pit displacements have been evaluated. The advantage of this process is that the results and modeling are closer to the actual nailing process in executive projects. Although nails with equal length can be used for convenience and less computational costs, but it is rarely considered in the construction process of real projects. Due to this reason -not meeting the optimal conditions of using nails- the construction costs are increases significantly.

To evaluate the effect of nails' distances and to achieve their optimal lengths, three common pits with heights of 4, 8 and 12 meters have been selected in this article. Considering that the length and distance of the nails affect each other, so that by increasing the distance of the nails, their lengths should increase to ensure the stability of the pit. In this regard, for each of the selected pits, by evaluating the factor of safety in slope/w and displacement in plaxis, the effect of changing the distance of the nails has been evaluated as well as determining the optimal length of nails. The distances of the investigated nails are 2.5, 2, 1.5 and 1 meters. It is worth mentioning that the distances of the first nail from the top of the pit and the last nail from the bottom of the pit are 1.5 and 0.5 meters, respectively, which are considered the same for all models according to the operational conditions and the performed analyzes. The characteristics of soil used in modeling, including elastic modulus, unit weight, Poisson's ratio, cohesion and internal friction angle are presented in the Table 1.

### 3.2 Effect of nail spacing for a pit with a height of 4 meters

In this part, in order to investigate the effect nail spacing, four different distances as 2.5, 2, 1.5 and 1 meters have been considered for the pit with a height of 4 meters. The results obtained from the simulations performed in Plaxis and GeoSlope are presented in Figs. 6-9. As stated earlier, the safety factor of pit stability is first determined by performing limit equilibrium analysis in GeoSlope software -which is determined according to the length of the nails in the height levels of the pit, according to the considered distance and the failure surface- and the displacement of the pit is then obtained after modeling and analysis in Plaxis software. This process is repeated according to the design criteria for different conditions to determine the optimal length and distance of the nails in such a way that the minimum amount of displacement and the highest safety factor are achieved. In the following, the effect of different

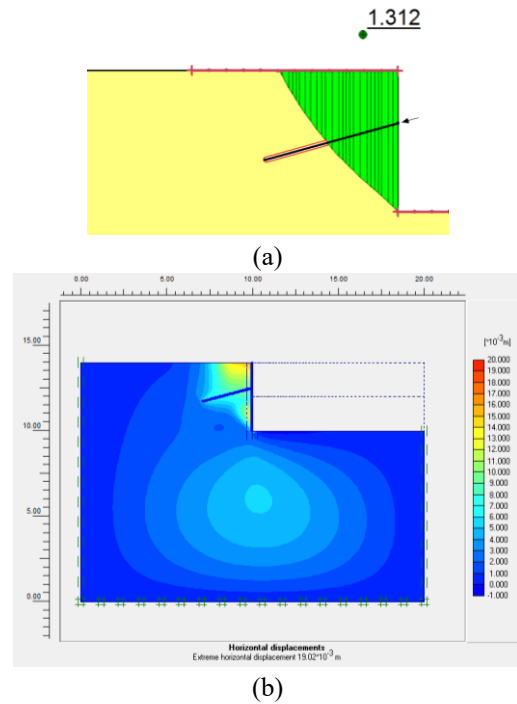


Fig. 6 Results of pit modeling with a height of 4 meters and nail spacing of 2.5 meters: (a) Factor of safety and (b) Displacement

distances of the nails on the values of safety factor and displacement of the pit has been investigated. In the first stage, based on the limit equilibrium analysis performed in the slope/w software and considering the distance of 2.5 meters between the nails, a nail with a length of 4 meters has been determined, which has an optimal safety factor of 1.312 (FS= 1.312) (Fig. 6(a)). In this case, after performing the analysis in Plaxis, the maximum displacement is obtained as 15 mm in the pit crest. (Fig. 6(b)). By examining other cases and taking into account the distance between the nails by 2, 1.5 and 1 meters, 2 nails with a length of 2 meters, 2 nails with a length of 3 and 2 meters and 3 nails with a length of 3 meters have been used, respectively. The values of the optimal safety factor for each case have been obtained as 1.396, 1.450 and 1.516, which are shown in Figs. 7(a), 8(a) and 9(a), respectively. Consequently, for the mentioned cases, the maximum displacement values are equal to 10, 6.5, and 5.2 millimetres, respectively, which are shown in Figs. 7(a), 8(a), and 9(a). It can be said that with the increase of the number of nails or decrease of the distance between nails, the values of the safety factor have increased and the values of maximum displacement of the pit has decreased. Although this behavior is predictable without performing numerical simulations, but it is still necessary to perform modeling and determine the safety factor and maximum

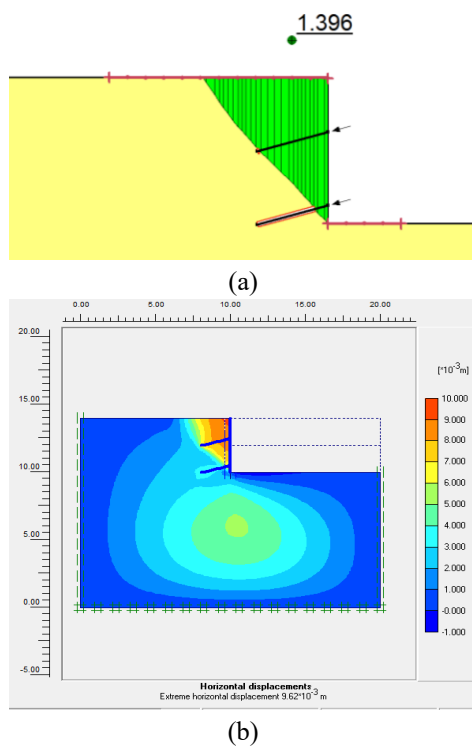


Fig. 7 Results of pit modeling with a height of 4 meters and nail spacing of 2 meters: (a) Factor of safety and (b) Displacement

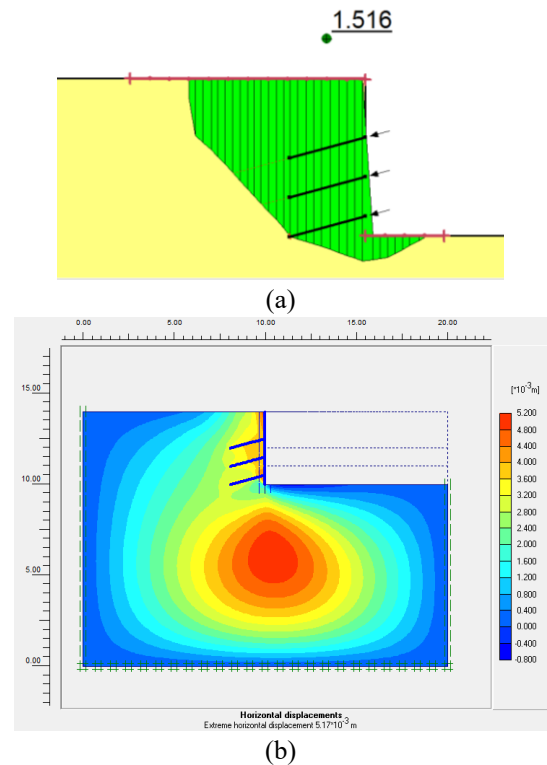


Fig. 9 Results of pit modeling with a height of 4 meters and nail spacing of 1 meter: (a) Factor of safety and (b) Displacement

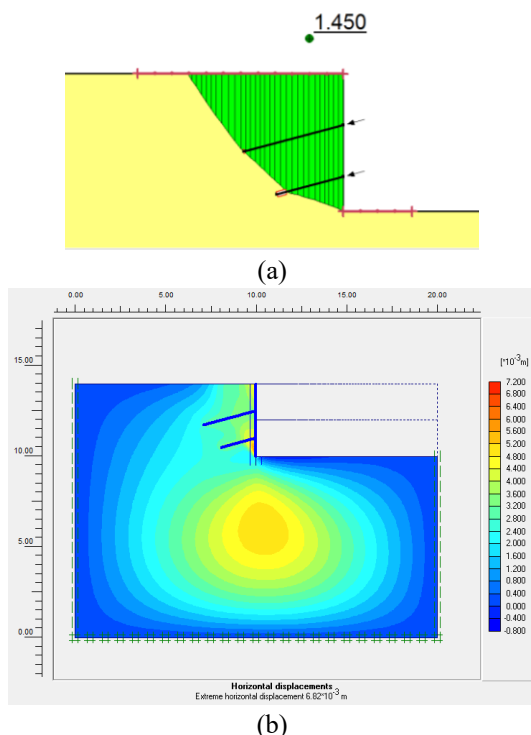


Fig. 8 Results of pit modeling with a height of 4 meters and nail spacing of 1.5 meters: a) Factor of safety; b) Displacement

displacement values for each pit. Identifying the optimal mode by considering the values of safety factor, the

maximum displacement and the length of the nails (economic aspect and material consumption) is of particular importance, and the following results are hence presented.

In Fig. 10, a comparison diagram related to values of safety factor and maximum displacement of examined pit for different arrangements of nails is presented. As can be seen, with the increase of the distance between the nails, the safety factor decreases, but for a distance greater than 2 meters, a significant decrease in the safety factor is visible.

It should be noted that the amount of displacement obtained from plaxis also shows a significant increase for the distance of nails of more than 2 meters, which is a confirmation of this state. In general, it can be stated that the use of nails at distances of more than 2 meters is not acceptable. On the other hand, for the nail distances less than 2 meters, the displacement values decrease with the decrease of the distance and a higher safety factor is also obtained. Although the result obtained is predictable, in this paper, in addition to examining the stability and control of displacements, the issue of determining the optimal state of the nails - length and economic efficiency - is also considered, which is the main difference of this study and previous published ones. It should be noted that by reducing the distance between the nails, the number of rows used increases and finally the total length of the nails also increases (see Fig. 11). As shown in Fig. 11, considering that the distance of the nails and their length in the analyzes are changed simultaneously, it can be stated that the maximum displacements of the pit are 15 and 10 mm for

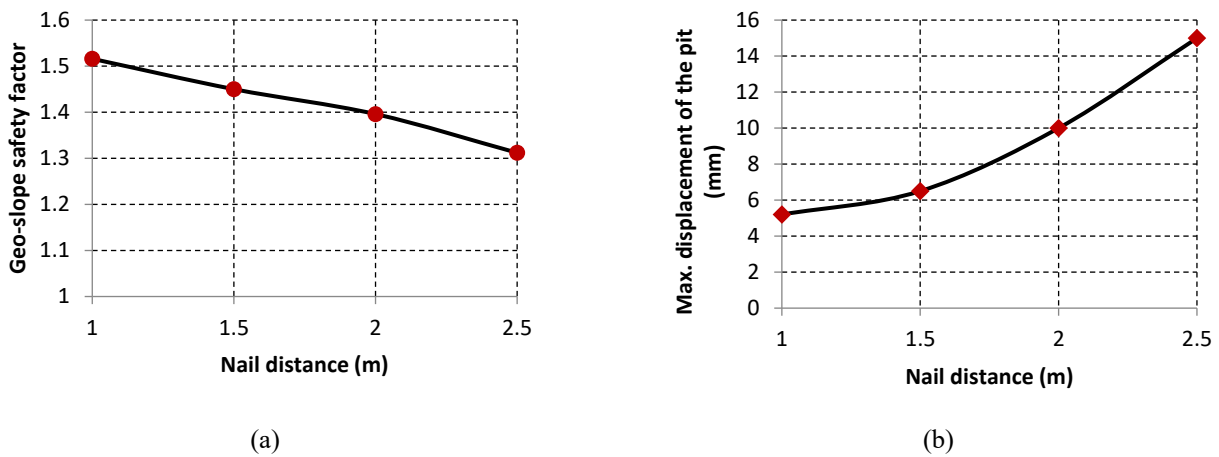


Fig. 10 The effect of pile spacing on (a) the pit safety factor using GeoSlope and (b) the tip displacement of the pit using Plaxis

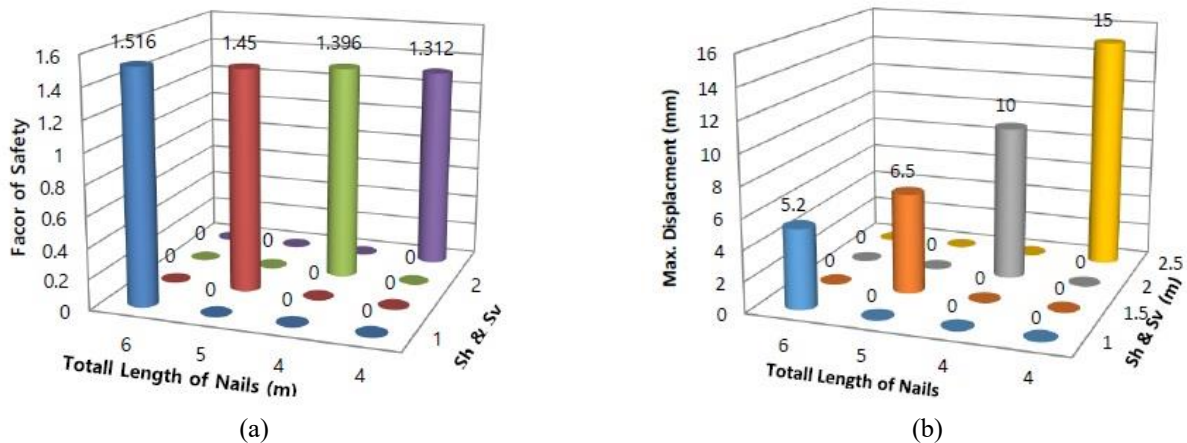


Fig. 11 The effect of nail distances considering the total length of the nails: (a) Safety factor of the pit using GeoSlope and (b) Maximum displacement of the pit using Plaxis

the nails with the distances of 2.5 and 2 meters are relatively high compared to displacements of 6.5 and 5.2 mm for nails with 1.5 and 1.5 distances. Therefore, stabilization of the pit with nails at 1.5 and 1 meter intervals have achieved more suitable displacement values and factor of safety. Finally, considering the total length of nails used, the condition of nails with a distance of 1.5 meters requires a total of 5 meters of nail length, which is more suitable than the condition of nails with a distance of 1 meter, which requires a total of 6 meters of nail length.

### 3.3 Effect of nail spacing for a pit with a height of 8 meters

In this section, the effect of nail spacing as 2.5, 2, 1.5 and 1 meters has been investigated on the factor of safety and displacement of a pit with a height of 8 meters. The results obtained from Plaxis and GeoSlope software for nail spacing of 2.5, 2, 1.5 and 1 meters are shown in Figs. 12 to 15, respectively. Based on the limit equilibrium analysis performed in the slope/w software and considering the

distance of 2.5 meters between the nails, two 8-meter nails and one 6-meter nail have been determined so that the optimal safety factor is obtained as 1.284 (FS= 1.284) in this case (see Fig. 12(a)). In the second case (i.e. nail distance of 4 meters), four nails with lengths of 10, 8, 6 and 4 meters have been determined which are able to provide a safety factor of 1.329 and a maximum displacement of 15 mm (see Fig. 13). In the third and fourth cases (i.e., for the nail distances of 1.5 and 1 meters, respectively), 5 nails with 10, 9, 8, 6, 4 meters lengths and 7 nails with 10, 9, 8, 7, 6, 5, and 4 meters lengths have been used. In these cases, the optimal safety factors are obtained as 1.401 and 1.354 with maximum displacement values of 10 and 7 mm, respectively (see Figs. 14 and 15).

Fig. 16 shows in the case that the distance between the nails is more than 2 meters, the displacement value has increased a lot, which shows that the use of nails in this case is not acceptable. For nail distances of less than 2 meters, it can be seen that by reducing the distance, the displacement values are reduced and the graph has a gentler slope, and correspondingly a higher safety factor has been

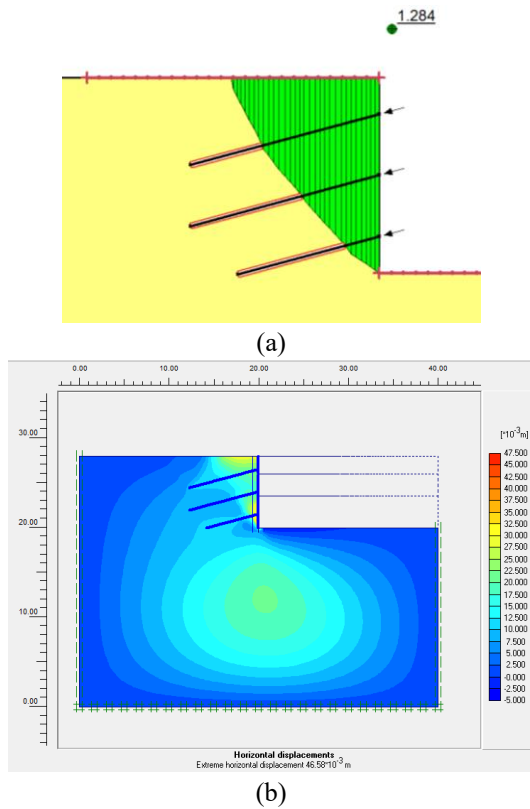


Fig. 12 Results of pit modeling with a height of 8 meters and nail spacing of 2.5 meters: (a) Factor of safety and (b) Displacement

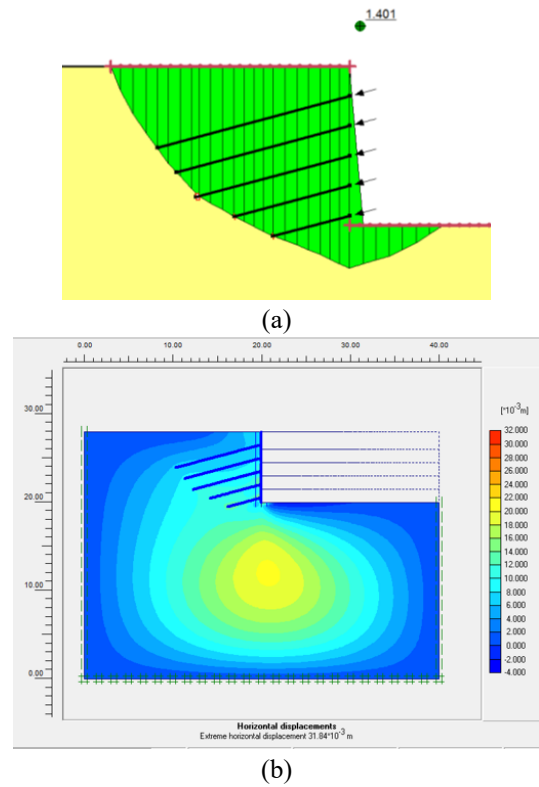


Fig. 14 Results of pit modeling with a height of 8 meters and nail spacing of 1.5 meters: (a) Factor of safety and (b) Displacement

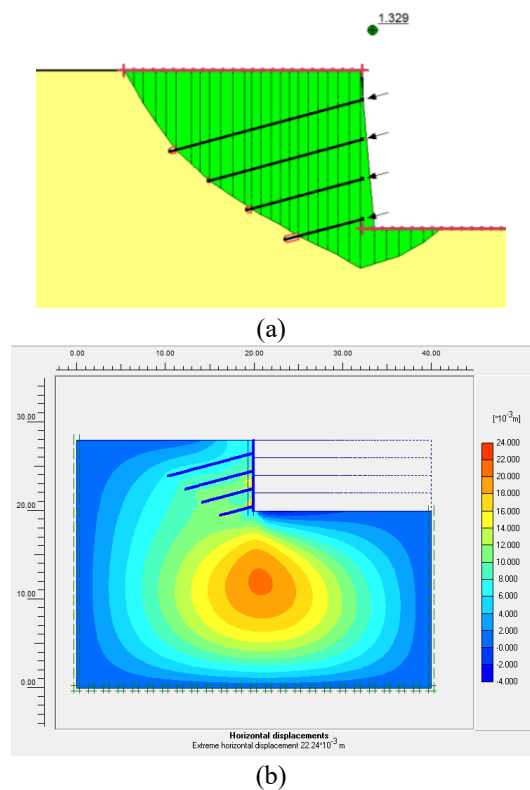


Fig. 13 Results of pit modeling with a height of 8 meters and nail spacing of 2 meters: (a) Factor of safety and (b) Displacement

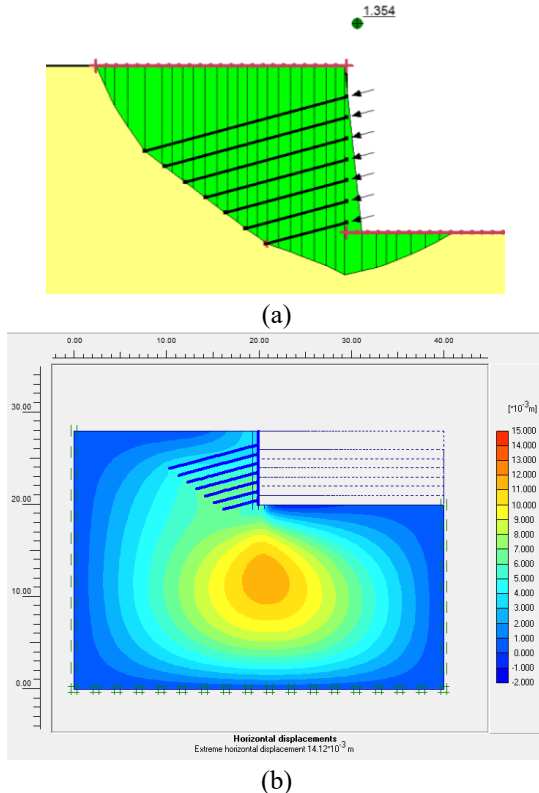


Fig. 15 Results of pit modeling with a height of 8 meters and nail spacing of 1 meter: (a) Factor of safety and (b) Displacement

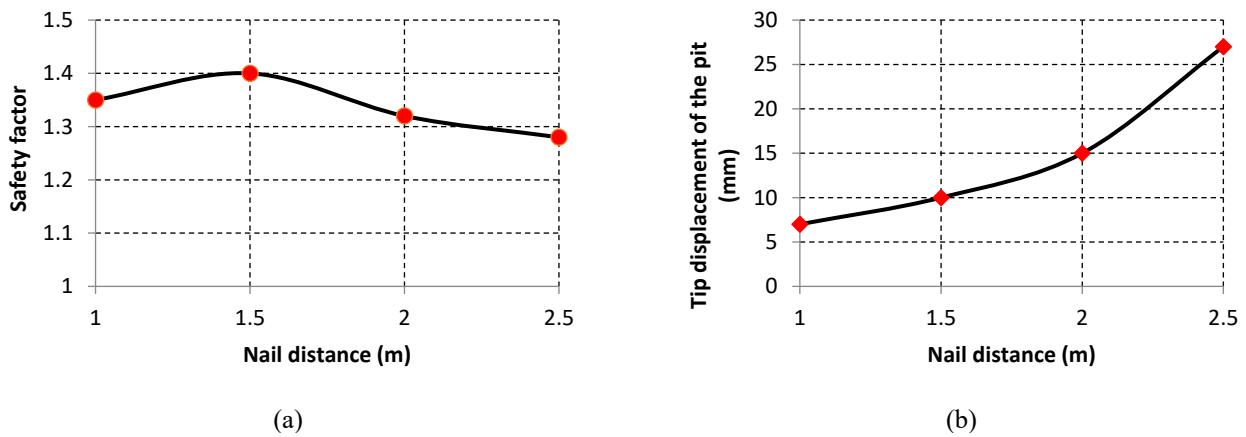


Fig. 16 The effect of nail spacing on (a) the safety factor of pit using the GeoSlope software, and (b) the displacement at the top of the pit using the Plaxis software

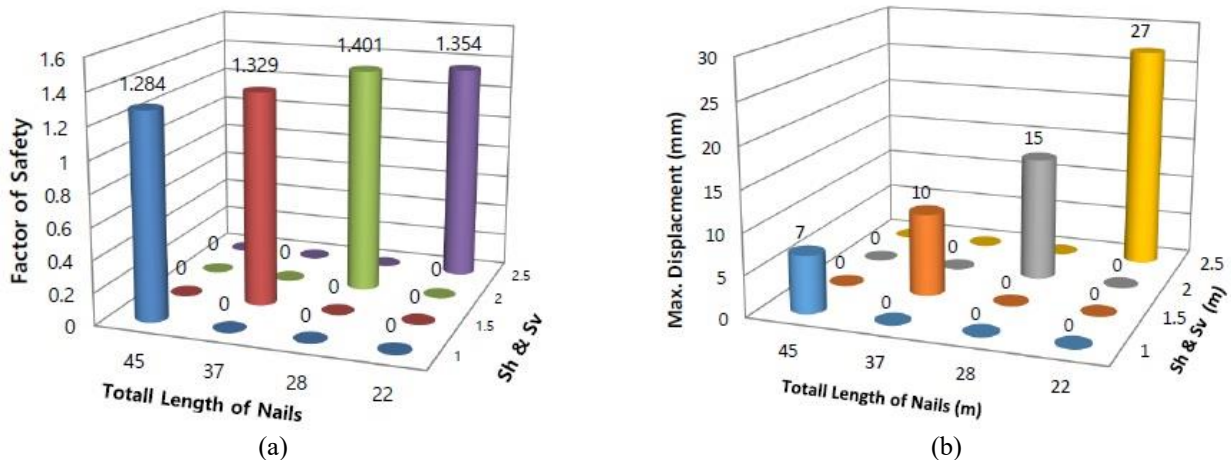


Fig. 17 The effect of nail spacing considering the total length of nails on (a) the safety factor of pit using the GeoSlope software, and (b) the displacement at the top of the pit using the Plaxis software

obtained. The results of the GeoSlope software based on Fig. 16(b) show that the values of safety factor for the distances of 2, 1.5 and 1 meters are better compared to that obtained for the distance of 2.5 meters. Also, considering the nail with a distance of 1.5 meters has provided a higher safety factor. By simultaneously examining the safety factor and pit displacement along with the total length of the nails used (Fig. 17), it can be stated that the most appropriate safety factor is for the nail with a distance of 1.5. In this case, the maximum displacement is 10 mm (Fig. 17(b)) and the total length of the nails is 37 meters (Fig. 17(a)), which is a suitable option for an 8-meter pit. Although it seems that the nail with a distance of 1 meter caused the least displacement, but the total length of the nails used is about 45 meters. Therefore, due to the fact that the safety factors of the pit for the distance of 1 and 2 meters are almost the same, the nails distance of 2 meters can be considered as the optimal distance, as compared to the nails with the distance of 1 meter, uses less of the total length of the nail (i.e., 28 meters). As a result, the distance of 1.5 meters of nails is placed in the first priority and the distance of 2 meters is placed in the second priority.

### 3.4 Effect of nail spacing for a pit with a height of 12 meters

In this part, the effect of nail spacing with 2.5, 2, 1.5 and 1 meters has been evaluated on the factor of safety and displacement of the pit with a height of 12 meters. Based on the limit equilibrium analysis performed in the slope/w software and setting the distance of 2.5 meters between the nails, five nails with lengths of 10, 9, 7, 7 and 6 meters have been determined, and the optimal safety factor is calculated as 0.922 (FS=0.922) (see Fig. 18). After performing the analysis in Plaxis, the pit is collapsed because the distance of 2.5 meters of nails could not withstand the stability of such a pit against displacement and failure. Therefore, in the Plaxis software, the 12-meter pit with a distance of 2.5 meters is collapsed and does not reach the final stage to be able to read the displacements. In the second case (i.e. considering 2 meters distance between the nails), six nails with lengths of 13, 11, 9, 8, 7 and 6 meters have been able to provide a safety factor of 1.335 and a maximum displacement of 15 mm (Fig. 19). In the following, by checking the third and fourth cases, and setting the distance

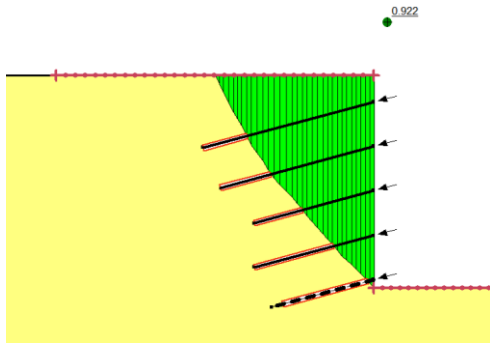
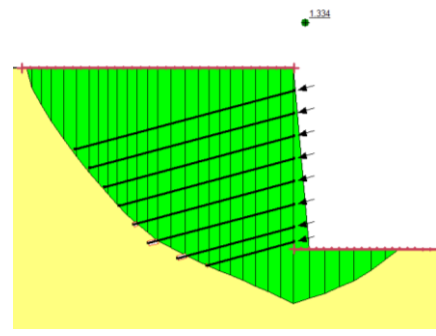
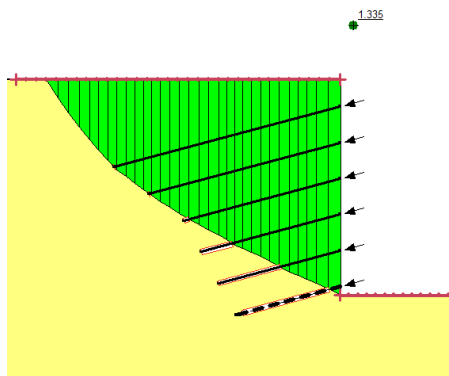


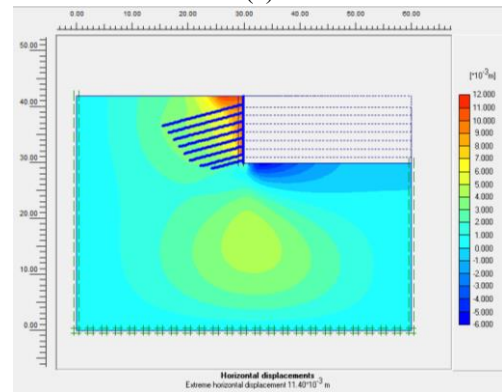
Fig. 18 Safety factor of the pit with 8 meters height and nail spacing of 2.5 meters



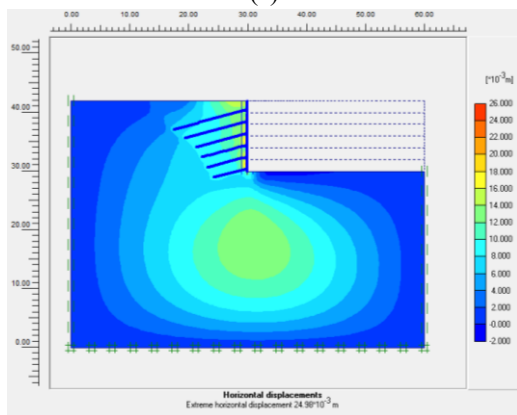
(a)



(a)



(b)

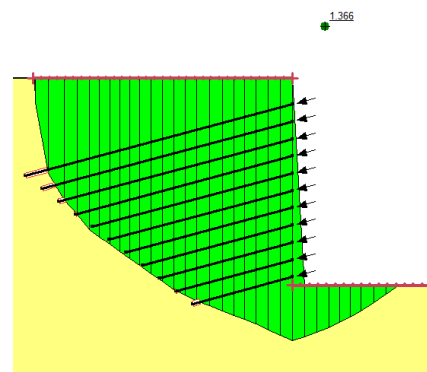


(b)

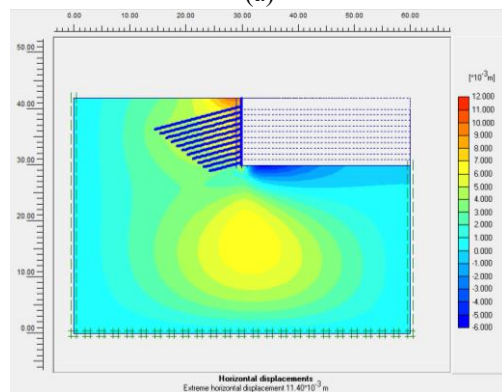
Fig. 19 Results of pit modeling with a height of 12 meters and nail spacing of 2 meters: (a) Factor of safety and (b) Displacement

of the nails by 1.5 and 1 meter, 8 nails (with 15, 14, 13, 12, 11, 10, 8 and 6 meters length) and 10 nails (with 16, 15, 14, 13, 12, 11, 10, 9, 8, 7 and 6 meters length) have been used, respectively so that for each of them, the optimal values of safety factors are obtained as 1.334 and 1.366, and the maximum displacement values have been obtained as 12 and 11 mm (Figs. 20 and 21).

In Fig. 22, a comparison is presented related to the safety factor and the maximum displacement of the pit for different distances of the nails for a pit with height of 12-meter. The results of the comparison of safety factors show that the distance of 2 and 1.5 meters of nails have been able

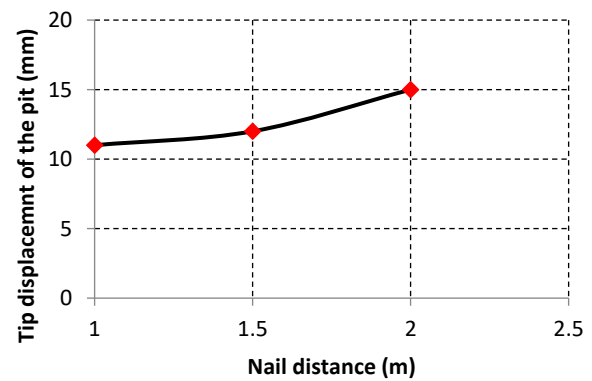
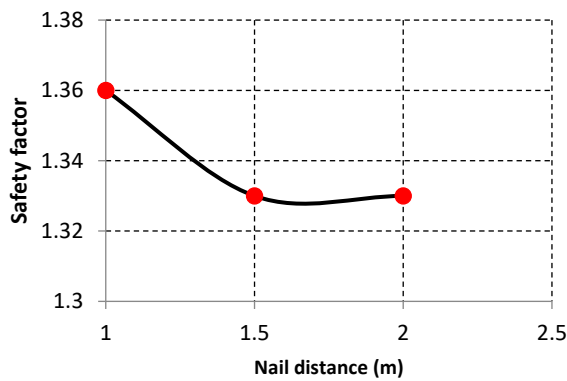


(a)



(b)

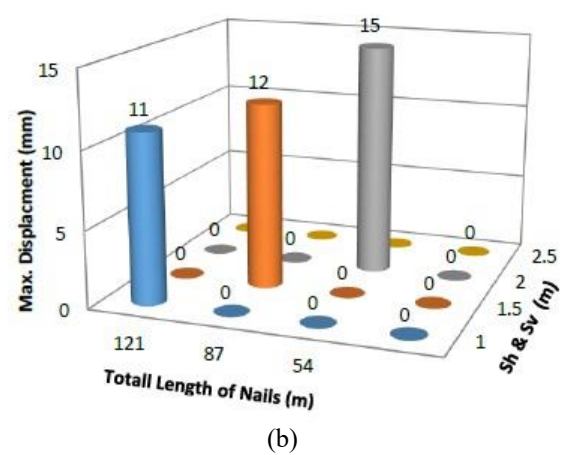
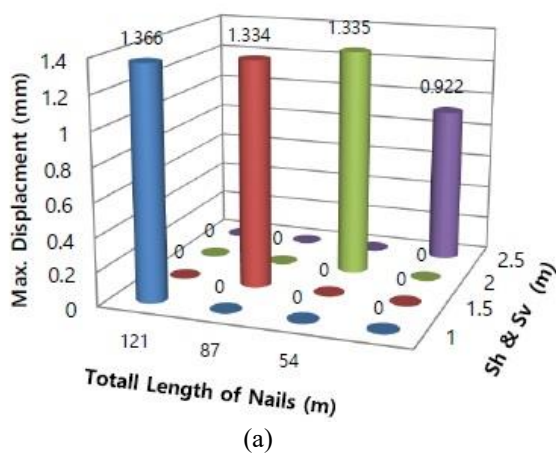
Fig. 21 Results of pit modeling with a height of 12 meters and nail spacing of 1 meter: (a) Factor of safety and (b) Displacement



(a)

(b)

Fig. 22 The effect of nail spacing on (a) safety factor of the pit using the GeoSlope software, and (b) displacement at the top of the pit using the Plaxis software



(a)

(b)

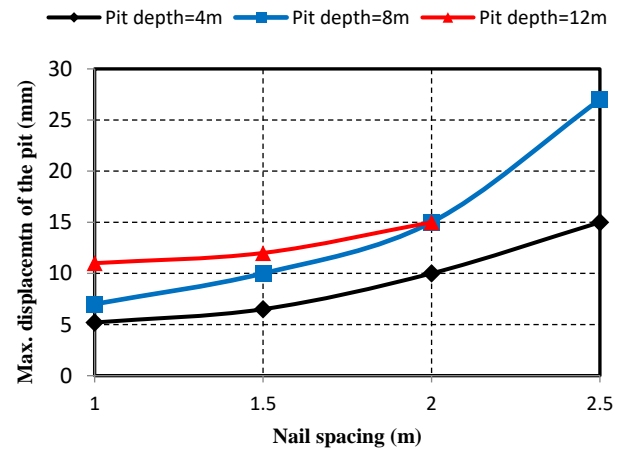
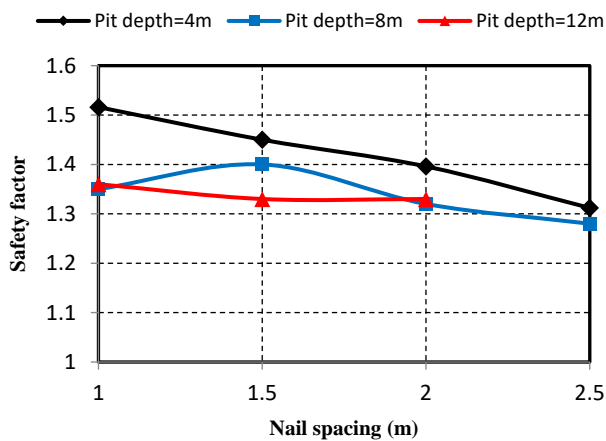
Fig. 23 The effect of nail spacing considering the total length of nails on (a) safety factor of the pit using the GeoSlope software, and (b) displacement at the top of the pit using the Plaxis software

to create almost similar values of safety factor of stability and the highest safety factor has been obtained by the distance of 1 meter of nails. On the other hand, with the increase of the nail distance from 1 to 2 meters, the values of displacement above the pit increase with a gentle slope, which the lowest displacement is corresponding to the condition of the nail with a distance of 1 meter. In the following, considering that the total length of the nails is also important, the results of the safety factor and maximum displacement of the pit have been compared in the 3D diagrams (Fig. 23). In the three-dimensional results, by simultaneously examining the safety factor and the pit displacement values along with the total length of the nails used, it can be stated that the most appropriate safety factor for the nail with a distance of 1.5 is 1.334 (Fig. 23-b), and it has created a maximum displacement of 12 mm. If it is considered that a second priority is proposed, although it seems that the nail with a distance of 1 meter caused the minimum displacement, but the total length of the nails used in this case is 121 meters. Therefore, taking into account that the safety factor of stability of the pit for nails with a distances of 2 is almost the same as that with a

distance of 1.5 meters, a distance of 2 meters can be considered. In this case, the total nail length is less (54 meters) compared to the nail spacing of 1.5 meters (87 meters). As a result, nails with a distance of 1.5 meters are placed in the first priority and nails with a distance of 2 meters are placed in the second priority

#### 4. Comparing the results

Fig. 24 shows the safety factor of stability and maximum displacement at the top of the pit obtained from GeoSlope and Plaxis software for pits with heights of 4, 8 and 12 meters. It is clearly seen that considering the nails with a distance of more than 2 meters causes a high displacement and the safety factor has also decreased significantly, as in the pit with a height of 12 meters, the distance of 2.5 meters between the nails has caused collapse in the soil as well as pit. The safety factor values related to the nail spacing of 1, 1.5 and 2 meters do not have much difference, and it can be seen only in the pit with a height of 4 meters, changing the nails spacing causes significant



(a)

(b)

Fig. 24 Comparing the results of the effect of nail spacing on the safety factor of pits with depths of 4, 8, and 12 meters, using (a) the GeoSlope software to calculate the safety factor and (b) the Plaxis software to calculate the maximum displacement at the top of the pit

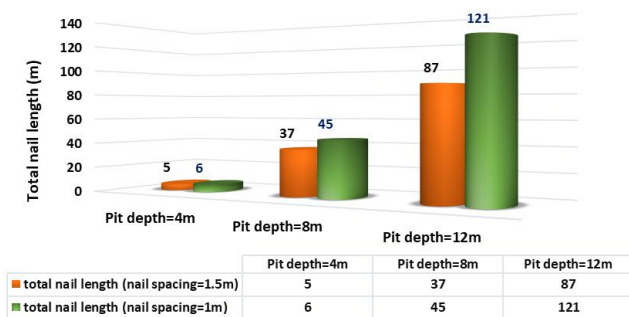


Fig. 25 Comparison of the total nail length in the optimal state with another state

Table 2 Total nail length and percentage reduction of optimal state

	Pit depth = 4 m	Pit depth = 8 m	Pit depth = 12 m
Total nail length (optimal nail spacing = 1.5 m)	5	37	87
Total nail length (nail spacing = 1 m)	6	45	121
Total nail length reduction (m)	1	8	34
Percentage reduction (%)	0.17	0.18	0.28

changes in the safety factor values (Fig. 24(a)). This issue can be seen almost in the maximum displacement values of the pits, that the distances of 1.5 to 2 meters can be considered for pits of 4, 8 and 12 meters. This choice is due to the fact that using nail distance of 1 meter significantly increases the total length of nails. Finally, according to the values of safety factor and the maximum displacement of the pits, as well as taking into account the optimal length of the nails, the optimal distance of 1.5 meters can be determined for the pits with heights of 4 and 8 meters and the optimal distance of 2 (or 1.5) meters for a pit with a height of 12 meters.

Considering that one of the valuable outcomes of this paper is the determination of the optimal state for defining the distance and the corresponding optimal length of the nailing system in various common pits, the identification of this optimal state with regard to the displacement parameters and the safety factor has led to a reduction in the total length of the nails. This section compares the total length of nails in the optimal state (nail distance of 1.5 m) with that in another state (nail distance of 1 m). Ultimately, the reduced length values and the percentage reduction of the total length of nails for the optimal state have been

calculated and presented for pit depths of 4, 8, and 12 meters. As shown in Fig. 25 and Table 2, for a 12-meter pit, the optimal total nail length with a spacing of 1.5 meters is 87 meters. Compared to the state with a nail spacing of 1 meter (which has a total nail length of 121 meters), this represents a reduction of 34 meters, or 28 percent, in nail consumption and consequently in nailing costs. The reductions in nail length and nailing costs for the 8-meter and 4-meter pits are approximately 18 percent and 17 percent, respectively. In other words, by considering the optimal state, the consumption and costs of executing nailing and stabilizing pits can be reduced by about 20 percent for shallow pits and by more than 20 percent for relatively deep pits.

### 5. Proposing empirical relationship

In this section, the results of Plaxis and GeoSlope that already presented in previous sections have been implemented to find some practical relationships for calculating response of pits in terms of displacement (maximum displacement of pit), factor of safety (GeoSlope

Table 3 Constant coefficients of Eq. (1) and corresponding R2 values for each selected response parameter

$\beta$	$\alpha_0$	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\alpha_4$	$\alpha_5$	$\alpha_6$	$\alpha_7$	$\alpha_8$	$R^2$
$d_{\max}$	-3.894	-3.636	30.22	0.3849	2.082	-24.8	-0.2942	0.8722	4.879	0.994
$f_{\text{sg}}$	1.909	-0.1319	-0.047	0.0060	0.0540	-0.108	-0.00232	-0.00211	0.0148	0.9437
$l_o$	-8.993	-5.232	16.11	1.829	3.728	-16	-0.8833	0.7778	2.765	0.9999

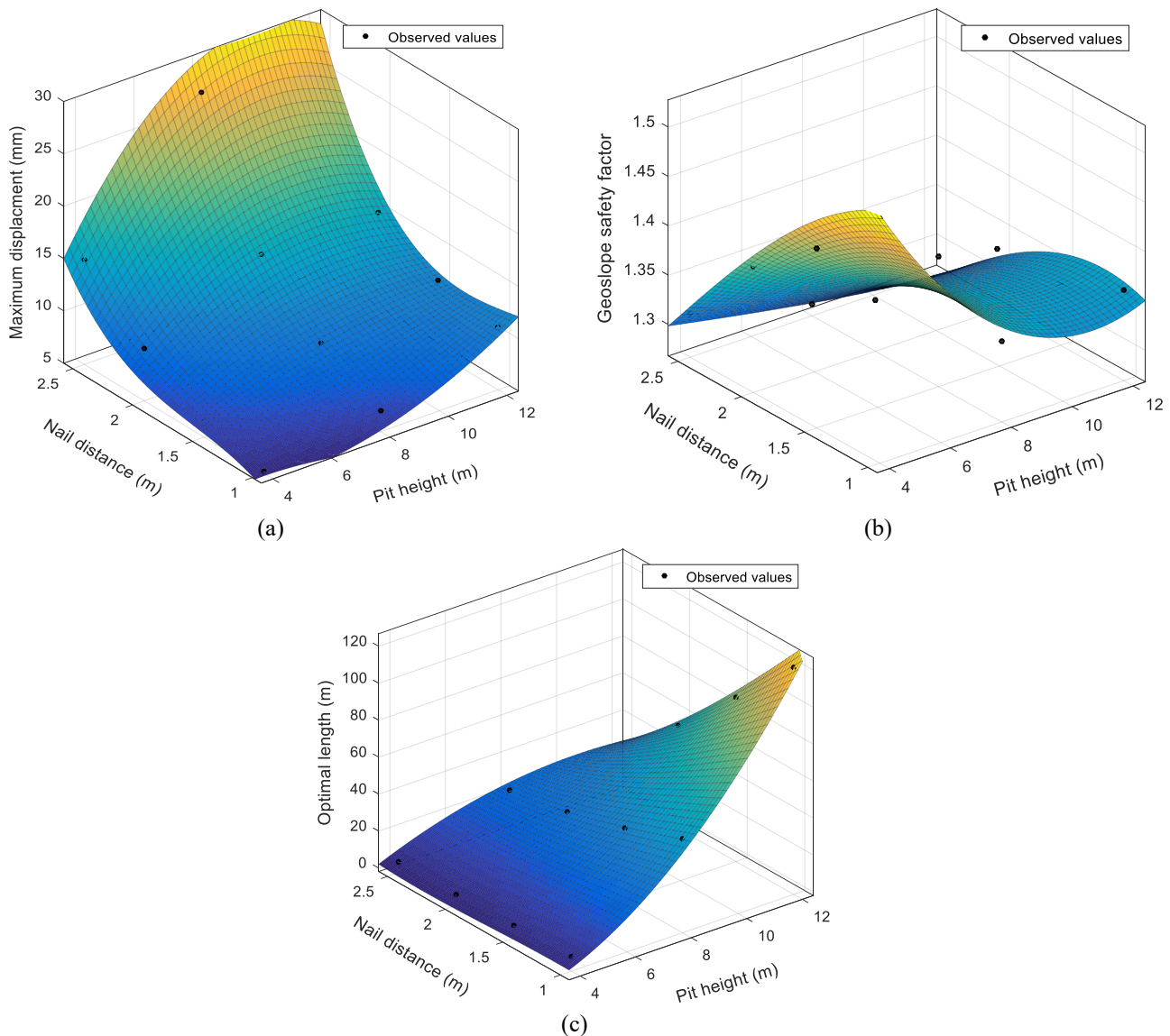


Fig. 26 Response parameter of pit: (a) maximum displacement of pit (mm) and (b) GeoSlope safety factor; c) Optimal length of nail (m)

software) and optimal length. By examining the results after a lot of trial-and-error process, it was finally found that the response parameter ( $\beta$ ) can be expressed as

$$\beta(h, d) = \alpha_0 + \alpha_1 h + \alpha_2 d + \alpha_3 h^2 + \alpha_4 h d + \alpha_5 d^2 + \alpha_6 h^2 d + \alpha_7 h d^2 + \alpha_8 d^3 \quad (1)$$

where  $h$  is the pit height (m);  $d$  is the nail displacement (m);  $\beta$  is the response parameter of pit that can be considered as maximum displacement of pit, safety factor according to GeoSlope software ( $f_{\text{sg}}$ ) and optimal length ( $l_o$ ) (see Table 3). The parameters  $\alpha_0$  to  $\alpha_8$  are constant coefficients which

are obtained from the curve fitting. The final values of these  $\alpha_i$  coefficients as well as the coefficient of determination ( $R^2$ ) values are shown in Table 3 for different response parameters. It is clear that the  $R^2$  values are higher than 94% in all cases, hence indicating a very satisfactory accuracy of the proposed formula for prediction of response parameters (usually,  $R^2$  values higher than 80% are considered satisfactory in the field of civil engineering (Momeni *et al.* 2019, Momeni and Bedon 2020, Momeni *et al.* 2021)).

Fig. 26, show the predicted response parameter as

Table 4 Comparison between the results of the proposed formula and FE model for a pit with height 6.0 meters

	S=1.0 m			S=1.5 m			S=2.0 m			S=2.5 m		
	$d_{max}$	$f_{sg}$	$l_o$	$d_{max}$	$f_{sg}$	$l_o$	$d_{max}$	$f_{sg}$	$l_o$	$d_{max}$	$f_{sg}$	$l_o$
Eq. (11)	5.58	1.42	23.57	8.77	1.40	19.31	13.15	1.35	15.16	22.40	1.29	14.52
FE	6.05	1.45	24.60	8.31	1.43	19.32	12.93	1.37	14.16	21.32	1.30	10.38
$\Delta$ (%)	7.76	2.07	4.18	5.24	2.09	0.05	1.67	1.46	6.59	4.82	0.77	28.51

function of pit height and nail distance, and the corresponding fitted planes according to Eq. (1). It should be noted that in these Figs., for each response parameter, the numerical data collected from numerical analyses are represented by points, that are used for curve fitting (Eq. (1)).

According to Fig. 26(a), it can be seen that the  $d_{max}$  parameter typically increases with increasing the pit height and nails distance. Fig. 26(b) reveals that the safety factor increases by decreasing the pit height and nails distance. It should be noted that this trend cannot be extended to the safety factor of Plaxis and it is more complicated. Fig. 26(c) shows that the optimal length of nails has a good relationship with input parameters. As can be seen, by increasing in the pit height the optimal length increases, and by increasing in the nail distance, the optimal length decreases, which reveals that the nail distance is an important parameter to find the optimum length of nails, which is the objective of the current study.

### 5.1 Calculation examples

In conclusion, to emphasize the applicability and usefulness of the proposed relationship in section 5.2, several calculation examples are presented. The objective of these examples is to demonstrate the applicability of the proposed formula in calculating the controlling parameters. Furthermore, the results are compared with those obtained through finite element and the limit equilibrium analysis to demonstrate the efficiency and accuracy of the proposed formula. To this end, a 6-meter pit is considered, and the parameters  $d_{max}$ ,  $f_{sg}$ , and  $l_o$  are calculated for different distances between the nails. It is worth mentioning that the height of the considered pit differs from that of the pre-analyzed pits used in the development of the proposed formula. This example allows for an assessment of the formula's application in finding controlling parameters outside of the data bank. The results are presented in Table 4, and it should be noted that the percentage scatter  $\Delta$ , as obtained by the proposed equation, is also provided for each case with respect to the corresponding FE solution.

The results presented in Table 4 demonstrate that the proposed equation is highly accurate for estimating the expected parameters for various pit heights. The calculated percentage scatter between the values obtained by the proposed equation and the FE method confirms this claim. In almost all cases, the scatter is within an acceptable range of less than 8%, indicating that the proposed relationship is reliable and practical. However, it is important to note that the proposed equation is based on interpolation within the

range of the intended pits. In the other words, although it can provide an initial estimation of the controlling parameters for other pits with different conditions, the accuracy of the results must be carefully examined through engineering judgment and rigorous FE simulation. Nonetheless, the high computational cost of the rigorous approach makes the proposed approximate relationships an attractive alternative for obtaining practical and reliable estimates. These findings highlight the potential value of the proposed equation in providing accurate estimates of expected parameters for different pit heights, while also underscoring the need for additional research to further evaluate the accuracy of this relationship.

## 6. Conclusions

In this study, the behaviour of nailed walls has been investigated by numerical and limit equilibrium methods. For this purpose, several pits with different heights were evaluated by changing the distance of the nails, and the effect of changing in the nail's distance on the total length of the used nails was investigated by determining the safety factor via slope/w and displacement by Plaxis. The most important results of this study are as follow:

- Although the safety factor in the GeoSlope software decreases with the increase of the distance between the nails, but it was found that at distances of more than 2 meters, this reduction trend is very significant and severe. The results obtained from GeoSlope are consistent with the results obtained from Plaxis software, that a large value of displacement has been created for the nail distance more than 2 meters which was shown that the use of nails in this case is not appropriate.
- By simultaneously considering the three parameters of the total optimal length of the nails, the safety factor and the maximum displacement of the pit, the optimal distance of 1.5 meters was determined for the pit with a height of 4 and 8 meters and the optimal distance of 2 (or 1.5) meters was obtained with a height of 12 meters.
- The total length of the nails for an 8-meter pit with a distance of 1.5 meters is 37 meters. In the second priority, the nail with a distance of 1 meter was placed as the minimum, the total length of the nails is 45 meters and the consumption of materials has increased by 22%.
- In the three-dimensional results, the total length of the nails for a pit with a height of 12 meters and a nail

spacing of 1.5 meters was 87 meters. In the second priority, considering the nails with a distance of 1 meter, the total length of the nails used was obtained 121 meters. In the latter case, the consumption of nail materials has increased by about 40%, which shows how much the simultaneous evaluation of stability parameters and displacement along with the amount of materials used can be important and economical.

- The results of various models for different urban pits (with a height of 4, 8 and 12 meters) with variable distances of nails in range of 1, 1.5, 2 and 2.5 showed that by repeating the analyzes in the finite element and limit equilibrium methods, the best and most optimal arrangement of nailing can be determined economically as well as the stability and resistance of the pit.
- The results showed that the proposed formula, which employs various coefficient factors to calculate maximum displacement, safety factor, and optimal nail length, exhibits high accuracy and efficiency when compared to the results obtained from finite element analysis.
- By considering the optimal state, the consumption and costs associated with nailing and stabilizing pits can be reduced by approximately 20 percent for shallow pits and by more than 20 percent for relatively deep pits.

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