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The effect of pile parameters on the factor of safety of piled-slopes using 3D numerical analysis

Ahmed Abdelaziz, Dahlia Hafez *, **Ashraf Hussein**

Civil Engineering Department, Cairo University, Cairo, Egypt

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KEYWORDS

Slope stability;
Piles;
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Abstract Slope stability can be achieved using different methods. Piles are commonly used to stabilize slopes or to improve slope stability. Stabilized slopes with piles are numerically studied in the current paper. A 3 dimensional (3D) finite element study is carried out to investigate the effect of different parameters on the stability of slopes stabilized with piles. A 3D finite element model was developed using the finite element program PLAXIS. The 3D model was verified using experimental data from the literature for a stabilized silty sand slope in a large-scale physical model. A parametric study was undertaken to study the effect of pile position, pile inclination, pile length and pile diameter on the factor of safety of the piled-slopes. The findings of the research were compared to other findings from the literature. The results show that using the 3D aspect gives more insight into the complicated slope stability problem. The study determines the optimum location of the pile and its optimum inclination to achieve the maximum stability. It shows that after a certain length of the pile, increasing the pile length becomes unnecessary and that the diameter of the pile has a relatively minor effect on the factor of safety of piled-slopes.

Introduction

Slopes can be stabilized using many methods including geotextiles, nails, piles, and pitching [1]. Stabilizing slopes with piles is one of the commonly used methods. The analysis of slopes stabilized with piles can be carried out using either an uncoupled or a coupled approach. Most common methods used to calculate the stability of piled-slopes use an uncoupled approach, where the limit soil pressure is obtained using an analytical, empirical or numerical method and, subsequently, the limit soil pressure obtained is used as an additional resistance in slope stability analysis using limit equilibrium methods. It is found that the loading on piles predicted using the currently available theories may differ significantly or may be similar depending on the investigated problem. The uncoupled approach was studied by many researchers [2–9].

On the other hand, coupled analysis approach is receiving more attention in the recent years where powerful numerical

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* Corresponding author at: 3225 Dougall Ave, Windsor, Ontario N9E1S8, Canada. Tel.: +1 226 2464257.
E-mail addresses: eng.ahmadaziz@hotmail.com (A. Abdelaziz), dahliahafez@gmail.com (D. Hafez), ashrafkh07@gmail.com (A. Hussein).

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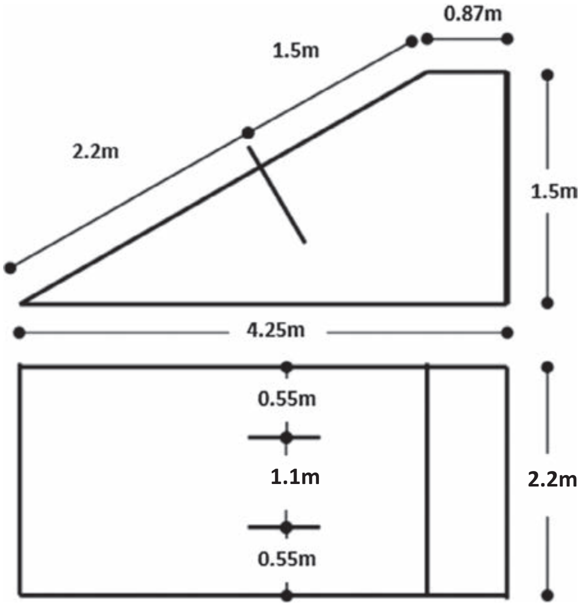

Fig. 1 Geometry of the experimental model by Bozok [14].

Table 1 Properties of soil material for the FE model.

Parameter	Value
E	34 MPa
v	0.25
Maximum dry unit weight	18 kN/m^3
Drained angle of internal friction	33°
Effective stress cohesion intercept	3.4 kPa
Model type	Mohr–Coulomb
Drainage type	Drained
Interface	Rigid

Table 2 Properties of pile material for the FE model.

Parameter	Value
E	$2 * 10^8$ kPa
Maximum dry unit weight	23 kN/m^3
Diameter	0.05 m
Length	0.89 m
Inclination	Perpendicular to surface (I = 40°)
Skin resistance	Linear

tools (2D and 3D finite element analyses) are becoming increasingly available [4,9–12]. In the coupled approach both the pile response and slope stability are considered simultaneously.

In the current study, coupled analysis is performed using a 3D finite element method to investigate the efficiency of stabilizing slopes with piles and to study the effect of different parameters on the slope stability. It is believed that the finite element method will provide good insight into the 3D nature of the complicated problem presented by slopes reinforced using structural members or piles.

In the following sections, the developed 3D finite element model is first presented and verified with an experimental large-scale model. The developed model is then used to perform the parametric study to investigate the effect of pile location, inclination, length and diameter on the factor of safety of slopes stabilized with piles. The results are compared with the literature results. Finally, conclusions giving insight to the optimum choice of parameters which have a direct application to engineers dealing with slope stability are presented.

Finite element modeling

A 3D numerical model is developed using the 3D finite element geotechnical program PLAXIS [13]. The model was verified with an experimental model obtained from the literature. The experimental model is presented followed by the verification of the finite element (FE) model. The 3D FE model to be used in the parametric study is finally presented in this section. More details of the model and its verification are available in the literature [14,15].

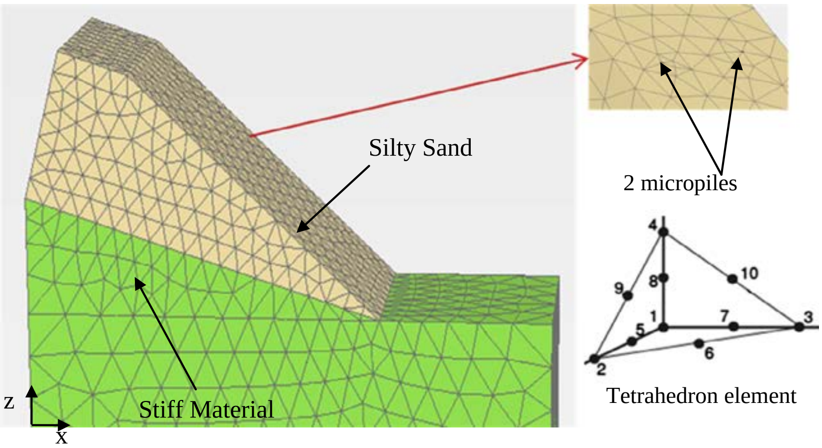

Fig. 2 Finite element mesh.

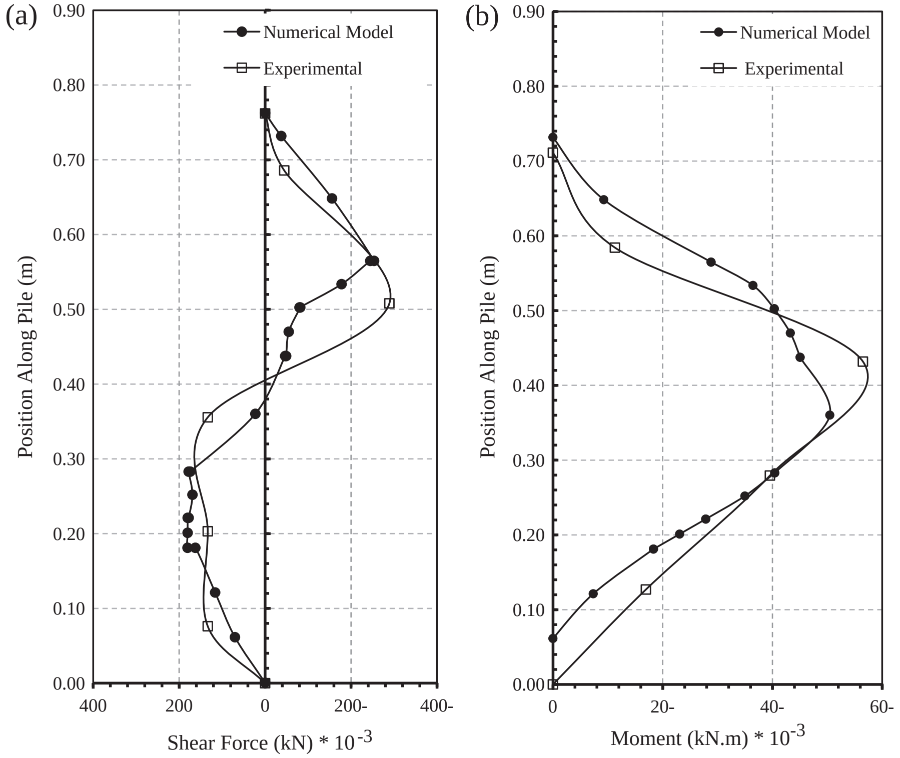

Fig. 3 Verification of FE results using experimental results (a) shear force diagram and (b) bending moment diagram.

Experimental model

The experimental study was carried out by Bozok [14] at the University of Missouri, Columbia. It presents a large-scale physical model of a slope stabilized with micropiles. The model was built in a large-scale landslide simulator. The basic principle behind the device was to induce failure by incrementally increasing the slope angle to the point of failure.

Model geometry

As shown in Fig. 1, the model slope was typically 1.5 m in height and 4.25 m long at the base with an initial inclination of 24°. The micropiles are located near to middle exactly at 2.2 m distance from the toe; two micropiles were used with spacing of 1.1 m. In addition, the model slope was typically 2.2 m in width.

Soil and micropile parameters

The soil used for the model slopes is a silty sand dredged from the Missouri River near Jefferson City, Missouri. To characterize the soil, a series of index tests were performed in the University of Missouri-Columbia geotechnical engineering lab [14]. The soil was classified according to ASTM classification as silty sand SM with fines content of 19%, maximum dry

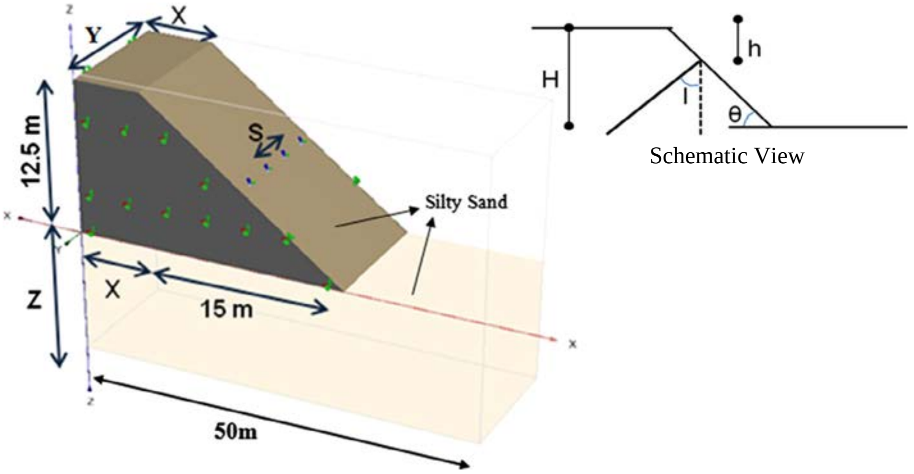

Fig. 4 Model geometry used in the parametric study.

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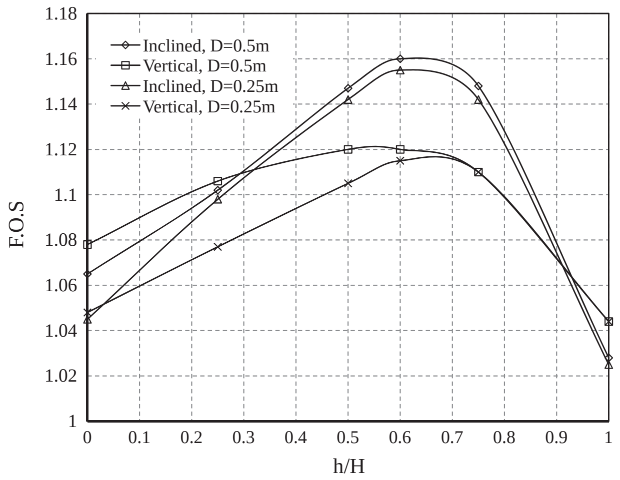

Fig. 5 Effect of pile position on factor of safety, $L = 5$ m, $D = 0.5$ m, and $D = 0.25$ m.

unit weight of 18 kN/m^3, drained angle of internal friction of 33° and effective stress cohesion intercept of 3.4 kPa. The micropiles used had a 0.05 m nominal diameter. They were drilled and gravity-grouted reinforced micropiles. The modulus of elasticity, E, of the micropile was $2 * 10^8$ kN/m^2.

Test procedure

The experimental cycle involved constructing the model slope, installing the reinforcing members, wetting the model to bring the soil as near saturation as possible, testing the model by tilting the simulator (container) incrementally until failure. The initial inclination of the model slope was 24° and it was tilted until failure occurred at an inclination of the model slope of 40°.

Verification of the FE model

The 3D finite element model was developed using PLAXIS 3D [13]. PLAXIS is a special purpose three dimensional finite element analysis program that has been developed specifically for the analysis of deformations and stability in geotechnical engineering projects.

Geometry and material modeling

The dimensions of the FE model were taken similar to the experimental model geometry presented in Fig. 1. The soil

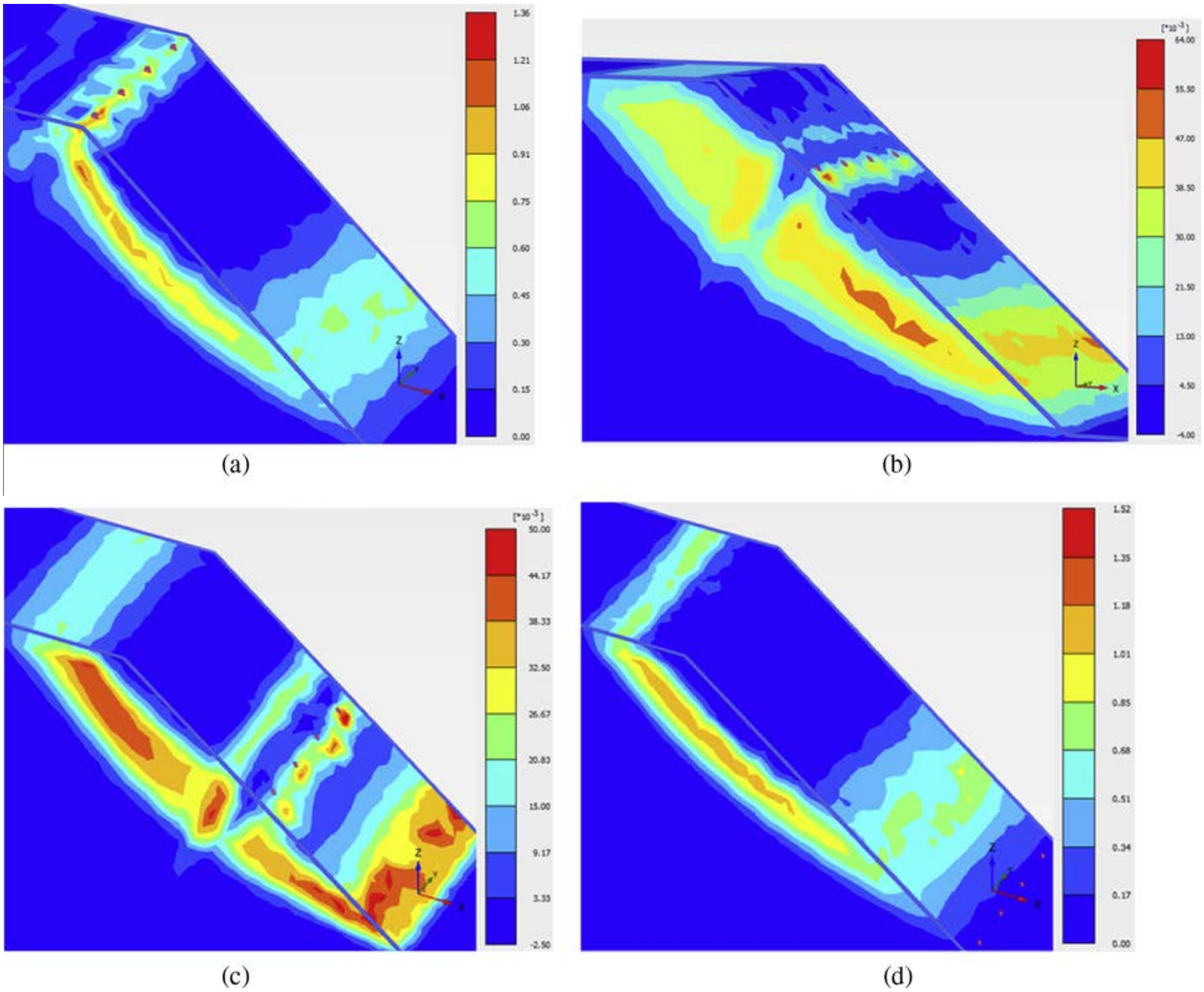

Fig. 6 Failure wedge of slope for different locations of pile, (a) $h/H = 0$, (b) $h/H = 0.25$, (c) $h/H = 0.5$ and (d) $h/H = 1.0$.

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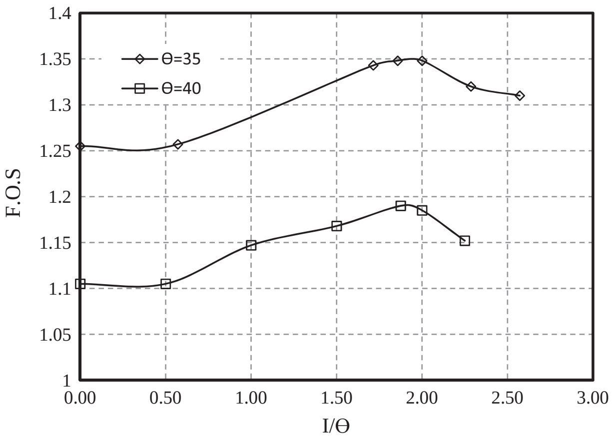

Fig. 7 Effect of pile inclination on factor of safety, $L = 5$ m, $D = 0.5$ m.

material of the sloping ground was modeled as silty sand (SM) similar to the experimental material. The rest of the material is modeled as a very stiff material to simulate the container configuration as shown in Fig. 2. The micropiles are defined as two embedded piles perpendicular to the surface. In addition, the head condition of micropiles is assumed to be free.

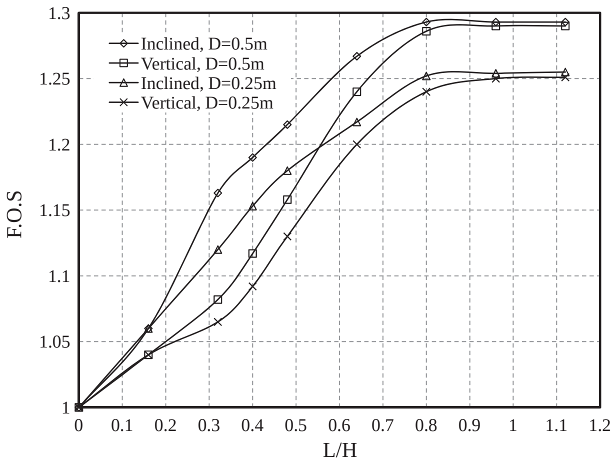

Fig. 9 Effect of pile length on factor of safety, $D = 0.5$ m and $D = 0.25$ m.

Initial states of stress were considered: hydrostatic states of stress with $Ko = 1.0$, and lateral stresses equal to one half of the vertical stress with $Ko = 0.5$, where Ko represents the coefficient of lateral earth pressure at rest. The pile-soil interface

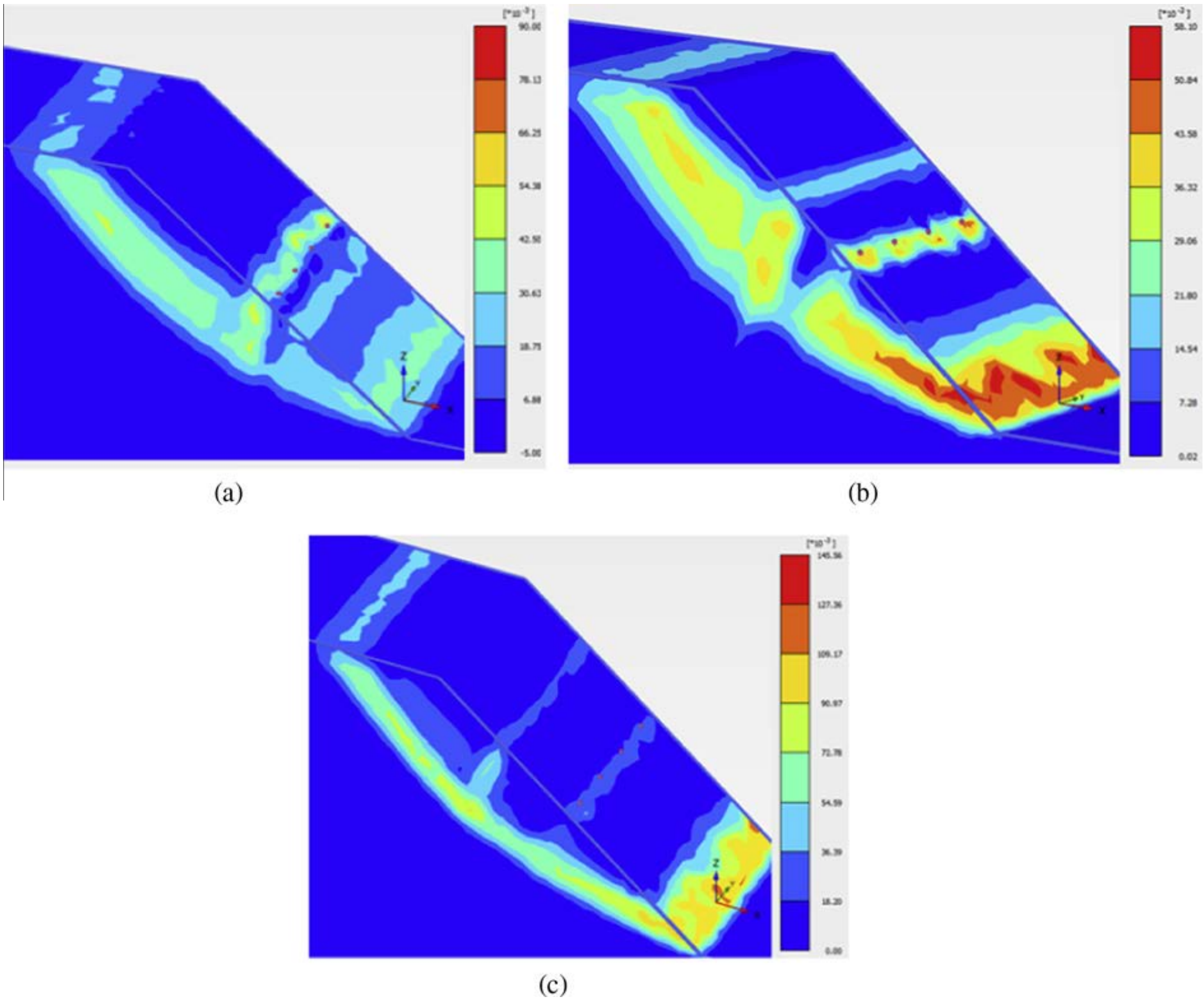

Fig. 8 Failure wedge of slope for different pile inclinations (a) $I = 0°$, (b) $I = 60°$ and (c) $I = 75°$.

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was modeled as an elasto-plastic model to describe the behavior of the interface. These interface conditions represent extreme case for the shear strength on the pile-soil interface, $\mu = 0.65$ (or $\tan 33°$). The interface is taken as a rigid interface where $\mu = \tan(R \bullet \Phi)$, R is the coefficient of friction between soil and materials, and for the rigid interface R is equal to 1.

The soil constitutive model used for the FE analyses was the elasto-plastic model with a Mohr–Coulomb failure criterion. A dilation angle, ψ, equal to zero was assumed for the Mohr–Coulomb model. The soil shear strength parameters used in the FE analyses were typical shear strength parameters of soils under drained loading condition. The micropile constitutive model used for the FE analyses was the linear-elastic model. The soil and micropile properties used are summarized in Tables 1 and 2, respectively.

Mesh and boundary conditions

Fig. 2 shows the used finite element mesh. Tetrahedron elements with 10 nodes were used to create the mesh. The size of mesh was medium that is refined near the pile location. It was found that the medium mesh resulted in a slightly higher lateral force on pile than the trial of a fine mesh (about 3% difference). However, the fine mesh required triple the time required by the medium mesh. Therefore, the medium mesh refined around piles was chosen for all further analysis (Fig. 2). The boundaries of the mesh were constrained in the y-direction while they were free in the x-direction and z-direction.

Method of analysis

In this study, three phases were used to construct the PLAXIS model: (1) initial phase by activating the stiff materials to proceed with Ko procedures, (2) phase_1 by activating slope, micro-piles and phreatic surface using consolidation type as calculation type with groundwater flow and time interval 1000 s, and (3) phase_2 which is the (c–φ Reduction). In the c–φ Reduction, the shear strength parameters are reduced by factors until the model reaches the failure state [13].

Verification with experimental results

This model was verified by comparing the obtained straining actions (bending moment and shear force) from the developed F.E. Model with experimental results of Bozok [14]. By performing the c–φ reduction analysis in Plaxis, it was found that the F.S. obtained for the slope with 40° was 1.01 which shows that the slope was very close to failure at the angle of 40°. Therefore, it can be reasonably assumed that the F.S. in both the experimental study and the finite element study is equal to 1 at slope angle of 40° and that the factors of safety for both studies are in very good agreement.

The straining actions acting on the micropiles after activating the slope, micropiles, phreatic surface (after phase 1 and before phase 2 (c–phi reduction)) for the slope of 40° were compared to the straining actions acting on the micropiles at the slope angle of 40° obtained in the experimental study by Bozok [14]. The experimental investigation by Bozok [14] predicts the bending moment and shear force diagrams from deformation measurements. The comparison between the experimental results [14] and the finite element results that were obtained from this research shows good agreement as shown in Fig. 3.

Finite element model used in the parametric study

The verified finite element model was used to perform the parametric study; however, the dimensions of the model were changed to simulate real slopes and piles. The size of the slope in the FE model was taken 12.5 m in height and 15 m long at the base with an inclination of 40°. The piles are located at the middle exactly; four piles were used with a spacing of 2.5 m (Fig. 4). The soil was modeled as silty sand.

A boundary analysis was carried out to study the effect of the location of the boundaries on the factor of safety (values of X, Y, and Z (Fig. 4)). The value of X was changed from 5 m to 25 m, Y was changed from 10 m to 50 m and Z was changed from 10 m to 30 m. The effect of the change of boundaries on the percent change in the factor of safety (F.S.) reached a maximum of 4%. To reduce the time of the numerical process the values of X, Y and Z were taken as 15 m, 10 m and 10 m, respectively.

Parametric study

In this section, the effect of changing pile parameters (position, inclination, length and diameter) on the factor of safety (F.S.) of slopes is presented. A reference case of a pile with length $L = 5$ m, diameter $D = 0.5$ m is first used. Each parameter is investigated and the optimum value of this parameter is then used to continue the parametric study. Fig. 4 shows the position of the piles (h), Inclination of pile (I) from the vertical, Height of slope (H) and slope angle (θ) in the piled-slope configuration.

Effect of pile position

The position of piles (h) is varied between 0, 0.25, 0.5, 0.6, 0.75 and 1.0 of the total height of slope (H). The total height of the slopes is equal to 12.5 m. The inclination of piles (I) is measured from the vertical axis. Two configurations of piles were used: vertical and inclined piles. The inclined piles were taken perpendicular to the surface with $I = 40°$. The vertical piles have an inclination angle (I) of 0°.

Fig. 5 shows the factor of safety of the slope as a function of the position of pile for a pile with length 5 m. The behavior of inclined and vertical piles with diameters 0.25 m and 0.5 m is shown in the figure. The factor of safety increases with increasing h/H ratios up to $h/H = 0.5$ to 0.6. The factor of safety then decreased with increasing h/H ratio for both the inclined and vertical piles. From the figure, it is shown that, for the studied cases, the best location of piles is when h/H is generally between 0.5 and 0.7.

To give more insight to the slope behavior, the failure wedges (showing total strain) for different pile locations are presented in Fig. 6 for inclined piles with $L = 5$ m and $D = 0.5$ m. When piles are located at the top ($h/H = 0$), it appears that the piles interfere with the slip surface at the top of the slope (Fig. 6a). By increasing the value of h, better improvement in the stability of the slope is achieved. When piles are located at the toe of the slope ($h/H = 1$), there is almost an ignorable effect (Fig. 6d). This is reflected in Fig. 5, where the values of the F.S. when the piles are located at the top of the slope ($h/H = 0$) are higher than the values of the F.S. when the piles are located at the slope toe ($h/H = 1$).

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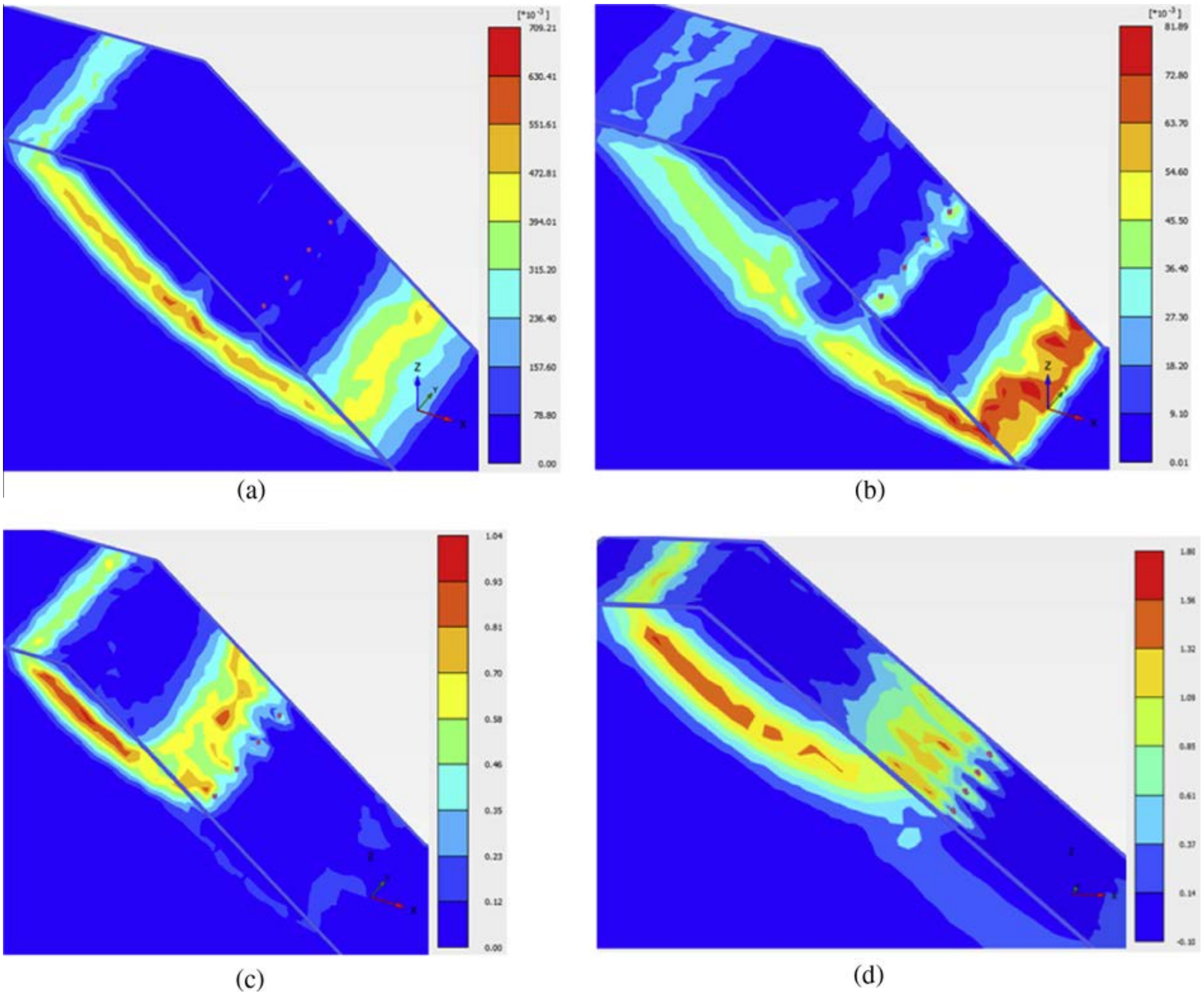

Fig. 10 Failure wedge of slope for different pile lengths (a) $L = 2$ m, (b) $L = 6$ m (c) $L = 10$ m and (d) $L = 12$ m.

Effect of pile inclination

Based on the results from the previous section, piles are placed at midheight $h/H = 0.5$. The reference case of length equal to 5 m and diameter equal to 0.5 m is used. The inclination of piles (I) from the vertical is varied (0°, 20°, 40°, 60°, 75° and 90°). Two slope angles (θ) are considered; 35° and 40°.

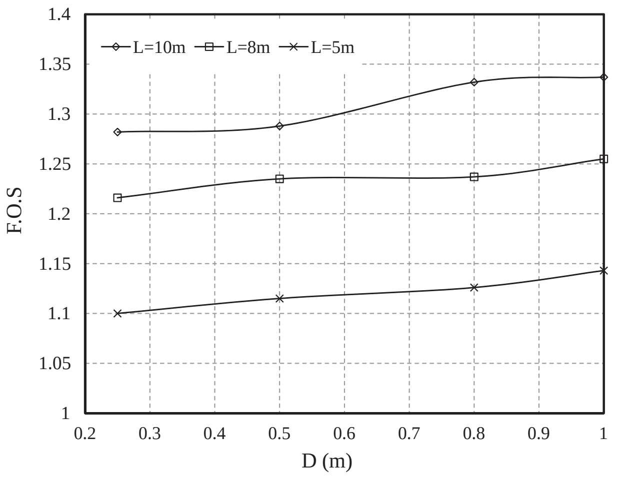

Fig. 11 Effect of pile diameter on factor of safety (vertical piles, $S = 2.5$ m).

Fig. 7 shows the F.S. of the slope as a function of inclination. The F.S. increases with increasing I/θ ratios up to $I/\theta = 1.8$; the factor of safety then decreases with increasing I/θ ratio for both the slope angle 35° and 40°. It can be deduced that the best inclination of piles (I) for the slope angle of 40° is 75°. Fig. 8 shows the failure wedges (showing total strain) for different pile inclinations for the slope angle of 40°, $L = 5$ m, $D = 0.5$ m and $h/H = 0.5$.

Effect of pile length

Based on the previous sections the pile parameters are taken as $h/H = 0.5$, $I = 75°$, $\theta = 40°$, and $D = 0.5$ m and L is varied. In addition a case of vertical pile $I = 0°$ and a diameter of 0.25 m are considered. This section focuses on the effect of pile length (L) on F.S. The length of piles is varied between 0, 2, 4, 6, 8, 10, 12 and 14 m. The total height of the slope equals to 12.5 m.

As shown in Fig. 9, the F.S. increases with increasing L/H ratios up to $L/H = 0.8$; the factor of safety then remains unchanged with increasing L/H ratio for both the inclined

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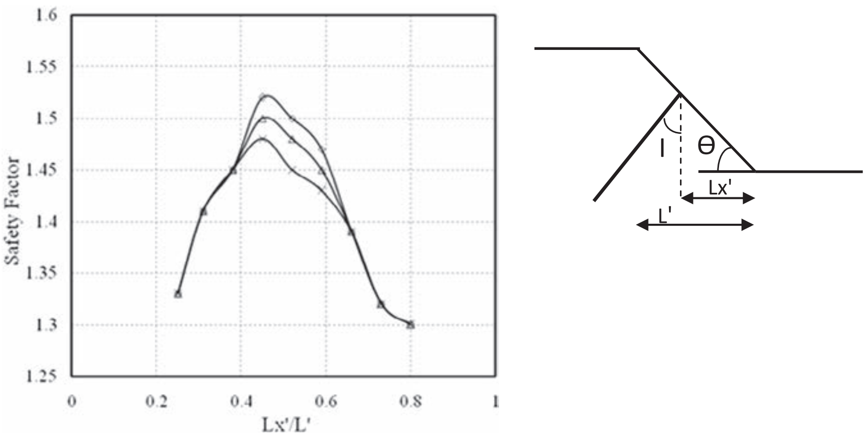

Fig. 12 Effect of pile position on factor of safety by Jeong et al. [16].

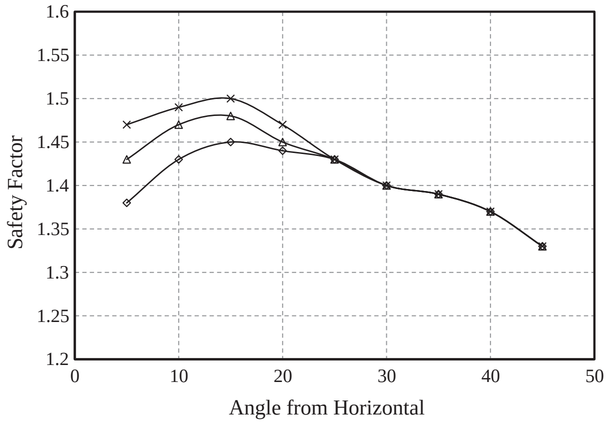

Fig. 13 Effect of pile inclination on factor of safety by Jeong et al. [16].

and vertical piles and both diameters ($D = 0.5$ and $D = 0.25$). It is also shown that the inclined piles with angle 75° have more pronounced effect on F.S. than vertical piles up to $L/H = 0.8$. After that length, the difference between inclined and vertical piles becomes negligible.

The failure wedges for the different pile lengths are shown in Fig. 10 for inclined piles ($I = 75°$ and $D = 0.5$ m). As the length of piles increases, the penetration depth into the slip surface increases. After increasing the length of piles up to 10 m which is equivalent to $L/H = 0.8$, the soil stability does not improve with increasing the length of piles.

Effect of pile diameter

The spacing between piles is taken as 2.5 m. The diameter of piles (D) is varied from 0.25, 0.5, 0.8 to 1.0. The configuration of piles used in this study is only vertical piles located at the midheight ($h/H = 0.5$) with lengths 5 m, 8 m and 10 m. Inclined piles can face difficulty in construction if large diameters are used. Fig. 11 shows the F.S. of the slope as a function of the diameter of piles. The F.S. increases with increasing D; however, the improvement is not significant. The percentage of change in F.S. is equal to about 4% to 5% for the studied pile lengths.

Comparison with the literature

The results obtained in previous sections were compared with results obtained from a study by Jeong et al. [16]. The study presented the effect of soil nails on the factor of safety of slopes. However, the trends of both studies can be compared. Flac 2D, a commercial FE software, was used to perform the analyses by Jeong et al. [16] for a slope with a height of 10 m and a slope angle of 33.7°. The soil constitutive model used for the soil was the elasto-plastic model with a Mohr–Coulomb failure criterion. The soil was assumed to have a unit weight of 20 kN/m^3 with an angle of internal friction, φ', and cohesion intercept, c', of 20° and 10 kPa, respectively. Young's modulus and Poisson's ratio of the soil were chosen to be 200 MPa and 0.25, respectively. The nails constitutive model used for the FE analyses was the linear-elastic model with Young's modulus of $2 * 10^8$ kPa. The nails have a diameter of 25.4 mm with inclination 5–45° from the horizontal, and length between 11 and 14 m.

Figs. 12 and 13 show the F.S. as a function of the pile position and pile inclination, respectively by Jeong et al. [16]. The F.S. increases with increasing Lx'/L' ratios up to $Lx'/L' = 0.5$ then starts to decrease (where Lx' is the horizontal distance from the toe of the slope to the pile and L' is the horizontal distance from the toe of the slope to the top of the slope as shown in Fig. 12). The behavior of soil nails shown in Fig. 12 is similar to that of piled-slope shown in Fig. 5 where the optimum location is around the midheight of the slope. This is also consistent with the results obtained by Won et al. [11], Wei and Cheng [17] and Li et al. [18].

Fig. 13 shows the F.S. as a function of inclination of pile; however, the inclination is from the horizontal. The results are consistent with the obtained results in the current study (Fig. 7) where the optimum inclination was 75° from the vertical.

Summary and conclusions

The paper presents a 3D finite element study of slopes stabilized with piles. A finite element model was developed and verified using experimental results. The 3D model was used to study the effect of different parameters on the factor

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of safety (F.S.) of slopes. These parameters included the pile location from the top of the slope (*h*), the pile inclination from the vertical (*I*), the pile length (*L*) and the pile diameter (*D*). The results were compared with results from the literature. A slope with height (*H*) equal to 12.5 m and slope angle 40° was investigated. The following conclusions can be withdrawn for the studied cases of the silty sand slope:

1. The optimum pile location is at the middle portion of the slope to achieve the max F.S. ($h/H = 0.5$–0.7).
2. Vertical piles give lower F.S. than inclined piles. As angle of inclination (*I*) increases, F.S. increases up to (*I*) of about twice slope angle ($1.8\ \theta$). As (*I*) increases beyond ($1.8\ \theta$), F.S. starts to decrease again. For the slope angle of 40°, the best inclination was 75° from the vertical.
3. As the length of pile increases, the F.S. increases up to a length of $L = 10$ m ($L = 0.8\ H$). However, after that length ($L = 0.8H$), the F.S. remained constant as the pile length increases. In addition, at lengths equal to or greater than 0.8 *H*, the difference between the F.S. for inclined piles and that for vertical piles become negligible.
4. As the diameter increases, the F.S. of slopes increases, however the increase in F.S. is relatively minor.
5. Some findings of this study agree with trends of behaviors of stabilized slopes found in the literature.

Conflict of interest

The authors declare that there are no conflict of interests.

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