NUMERICAL MODELING OF THE NEGATIVE SKIN FRICTION ON SINGLE VERTICAL AND BATTER PILE

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Keywords

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Abstract

In this paper the negative skin friction on single vertical and batter pile is investigated. First, a finite-element model (using ABAQUS software) based on the studies Lee et al. and Comodromos and Bareka was developed. After that, the results of the model were compared and validated. Then a single vertical end bearing and a single skin friction pile under different earth-surface loadings were analyzed and the down-drag force as well as the neutral plane location were studied. Subsequently, the performances of the single end bearing and the friction pile, with different inclination angles between 0 and 30º, were analyzed.
Moreover, the sensitivity analysis was implemented using 2-D models. This showed a satisfactory compatibility with the results of the study of Lee et al. and Comodromos and Bareka. Finally, it was concluded that the drag load of the pile and the neutral plane position depend on the condition of the soil surrounding the pile, the 2D or 3D model type , the earth-surface loading intensity, the type of end-bearing pile or friction pile and the pile's inclination angle. The simulation results agree well with the experimental findings.

1 INTRODUCTION

Evaluation of Negative Skin Friction (NSF) is a common problem in the design and construction of a pile in soft ground that is subjected to an earth-surface loading or the drawdown of an underground water table, etc. [1, 2, 3]. The development of an additional compressive force (dragload) in the form of excessive pile settlement (downdrag) could cause construction and maintenance difficulties for the supported structure [4]. However, the NSF is a function of the normal effective stress on the pile skin and for the development of friction forces, two surfaces are needed to prevent a contact between the two surfaces, but the drag load cannot cause settlement by itself [5]. The NSF is usually mobilized at its ultimate limit, except for the proximity to the neutral plane, and a limiting relative displacement of the soil and the pile is assumed to achieve full mobilization of the skin friction [6, 7]. So, disregarding the design recommendations of the pile drag load could lead to a collapse of the structure, e.g., a quay or bridge, built on pile foundations. Several reports can be found relating to the NSF, the dragload and the down drag on single piles. Poulos and Davis (1980) [8], Chow et al. (1990) [9], Lee (1993) [10], Teh and Wong (1995) [11], Fellenius (1972 and 1989) [12, 13] indicated that neutral planes that are developed in piles depend on the surrounding soil's settlement and the rigidity of the pile material; they also mentioned that the larger the bearing of the pile tip, the deeper the neutral plane, and accordingly, the higher the drag force. Jinyuan et al. (2012) [14] studied the NSF in a single pile under various influencing factors, including the consolidation time, the pile/soil interface, the lateral earth-pressure coefficient, the soil–pile limiting displacement, the intensity of the surcharge , the soil compressibility, and the stiffness of the bearing layer. It was found that the neutral plane changes significantly with the consolidation time and the stiffness change in the bearing layer.

Van Der Veen (1986) [15] stated for a given pile, the more allowable the settlement, the deeper the neutral plane, and accordingly, the lower the drag force. The majority of these reports have introduced semi-empirical formulae to predict the location of the neutral plane, and accordingly to estimate the drag force for a given pile and soil condition. However, these formulae do not incorporate the settlement of the pile as a governing parameter. However, the drag load of batter piles has not been studied so widely. The batter pile is applied in combination or exclusively with a vertical pile as the transmission of force to the foundation to be used. The batter pile's performance is a suitable action against the horizontal loads. Very limited information and experimental data can be found about the batter piles' NSF in the literature. Hanna and Nguyen (2003) [17] showed that the shaft resistance decreases with an increase in the inclination angle of the pile for both compression and tension loadings. The full-scale test results reported by Meyerhof and Yalsin (1992) [16] showed that the shaft resistance capacity of a pile increases due to an increase in the pile's inclination angle, while Hanna and Afram (1986) [26] concluded that there is no significant change in the shaft's resistance with an increase in the pile's inclination angle. The results showed that the effect of the type of pile and the load distribution were an important parameter that could affect the bearing capacity and the pile's resistance. Lee et al. (2002) [18] studied the drag-load, the down-drag and discussed the efficiency of pile groups under NSF conditions using a FEM, and the effects of parameters like the ground surface load, the friction coefficient of the pile-soil interface, the arrangement of the pile groups, and the spacing of the piles. Emilios et al. (2005) [19] studied the drag-load and the neutral plane of a single pile in a layered soil influenced by the sequence of the pile-head and the earth-surface loading using FLAC3D software. Poulos (2008) [20] presented a design method for pile foundation under NSF, and discussed the NSF's effective characteristics on the residual stress of the pile, the pile-head loading and the efficiency of the pile group. Prakash and Subramanyam (1965) [21] developed an experimental batter pile model and indicated that the resistance of the negative batter pile is more than that of the positive batter pile in the lateral loading condition. Rajashree and Sitharam (2001) [22] described the nonlinear modeling of vertical and batter piles according to the finite-element method. In this model, the resistance and the lateral displacement of the batter pile induced by static and cyclic loads were investigated. In this research the soil was not modeled as continuous media, but was considered as springs with equivalent stiffness. Poulos and Madhav (1971) [23] considered the manner of a batter pile in a lateral static load and showed that laterally the displacement of a batter pile depends on the pile's inclination angle. In this research some experimental results of Emilios et al. (2005) [19] were compared with the finite-element model obtained using ABAQUS software. First, a 3D numerical model was used to determine the negative skin friction and the drag load in a vertical friction and end-bearing pile under different earth-surface loadings. Then some effective parameters, like the loading and the inclination angle of the pile, were studied and compared in 2D and 3D conditions. The soft clay was undrained in the numerical model.

2 MODELING AND CALIBRATION

The effects of negative skin friction on the drag load and the down drag were studied and the batter and vertical piles were compered in the modeled soil according to Lee et al. (2002) [18]. The pile was considered to be elastic with a diameter of 0.5 m and a height of 20 m. The profile of the soil was layered as a top soft clay layer that was underlined by a bottom dense sand layer. The pile shaft was placed in the soft soil and the end of it was settled on the dense sand. The elements that were used in the three-dimensional model of the soil and the pile are continuous eight-node brick elements, the reduced integration method (C3D8R) and continuous 20-node cubic elements (C3D20). In addition, continuous 4-node plain stress elements (CPS4) were considered in the two-dimensional model. The constitutive models that were used for the soil and the pile are the elastic-perfectly plastic Mohr-Coulomb non-associated flow rule model and the linear elastic model, respectively. A fine mesh was employed for the central part of the soil, where the maximum stresses and strains are expected. Following a short parametric study, a total of 8 brick elements around the cylinder circumference in this central part were found to be sufficient to achieve a convergence of solution, whereas the size of the brick elements in the longitudinal direction was chosen to be equal to 0. 5 m. The soil and pile materials' properties are summarized in Table 1.

Geometry, stratification and meshes of the model made using the 3D finite-element software ABAQUS is shown in Fig 1.

Table 1. Material properties used in the analysis by Lee et al. (2002).

Material	Model	E (kPa)	C (kPa)	υ	φ (°)	Ψ (°)	K_0	γ (kN/m^3)
Concrete pile	Isotropic elastic	2,000,000		0.15				25
Soft clay	Mohr–Coulomb	5000	30	0.4	20	0	0.65	18
Dense sand	Mohr–Coulomb	50,000	0.1	0.3	45	10	0.5	20

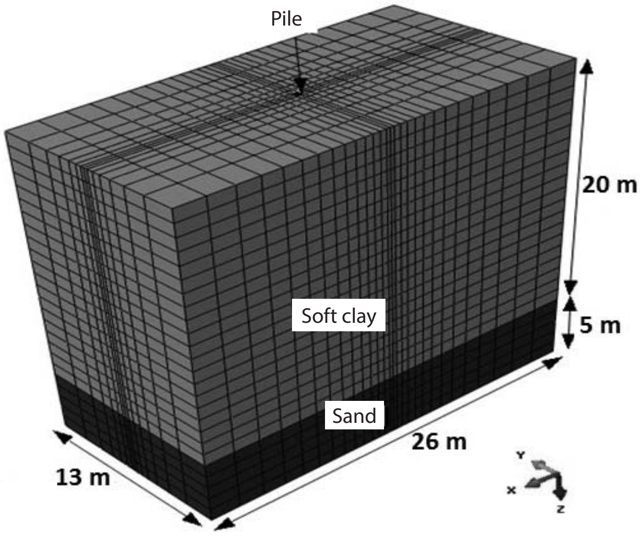


Figure 1. Finite-element model of a vertical single pile in soil.

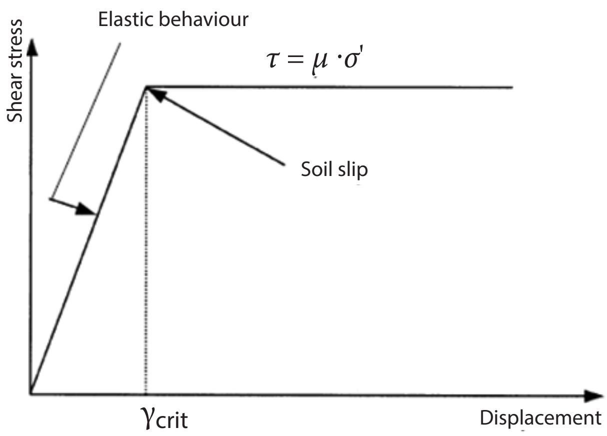
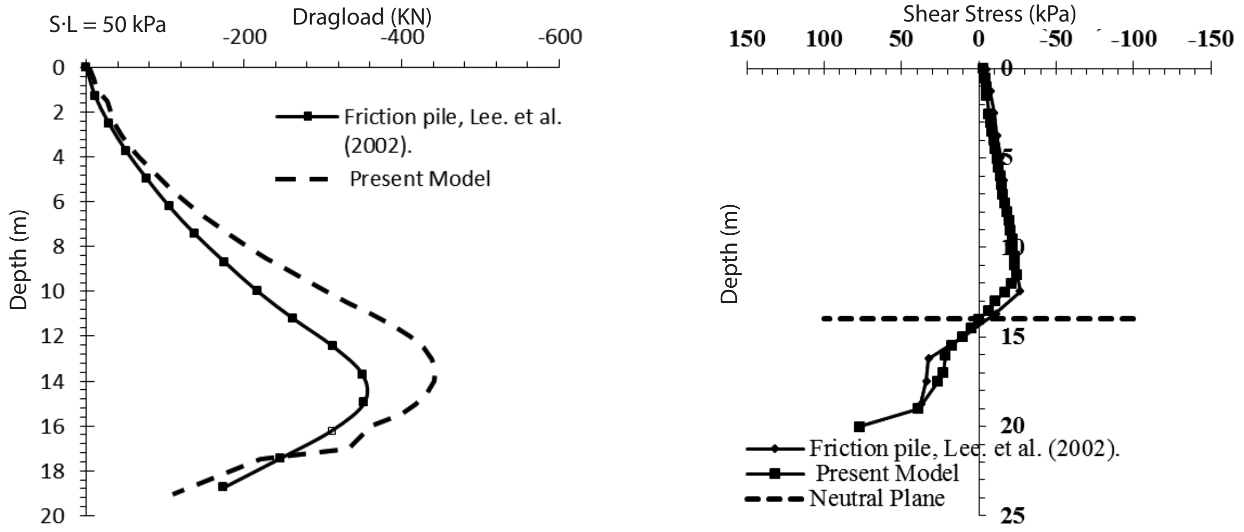


Figure 2. Behavior of the interface element by Lee et al. (2002).

The size of the soil elements in the vicinity of the pile is finer to increase the accuracy of the analysis, and then larger further from the pile to avoid a long computational time. The boundary of the model is far enough from the pile to resist the stress conflict. The model was first solved to achieve the in-situ stresses and then the initial displacements were set to zero and before the main analysis, the pile and soil interaction was used with the penalty method and the interface friction coefficient was supposed to be 0.3–0.4. Also, the soil's residual stresses change due to pile's installation was overlooked. Because of the type of pile, according to the method of installation, it was assumed to be bored. The stiffness of the lower soil was assumed to be the same as the upper soft-soil layer to model the frictional pile in the NSF analysis. However, it is assumed to be 10 times larger than the upper soft layer for the end-bearing pile. The constitutive model of the interface elements between the pile and soil is defined by the Mohr-Coulomb shear failure criterion. The interface elements can be separated if tension is developed across the interface and gapping is formed between the pile and the soil interface and the shear and normal forces are set to zero. The normal effective stress, σ', between two contact surfaces was multiplied by the interface friction coefficient, μ, to give the limiting frictional shear stresses $\tau = \mu \cdot \sigma'$. If the shear stress applied along the interface is less than $\tau = \mu \cdot \sigma'$, the surfaces will be stuck .Otherwise, the nodes of the elements in the contact will slide (Fig.2). It was found that the pile's behavior is governed mainly by the interface behavior.

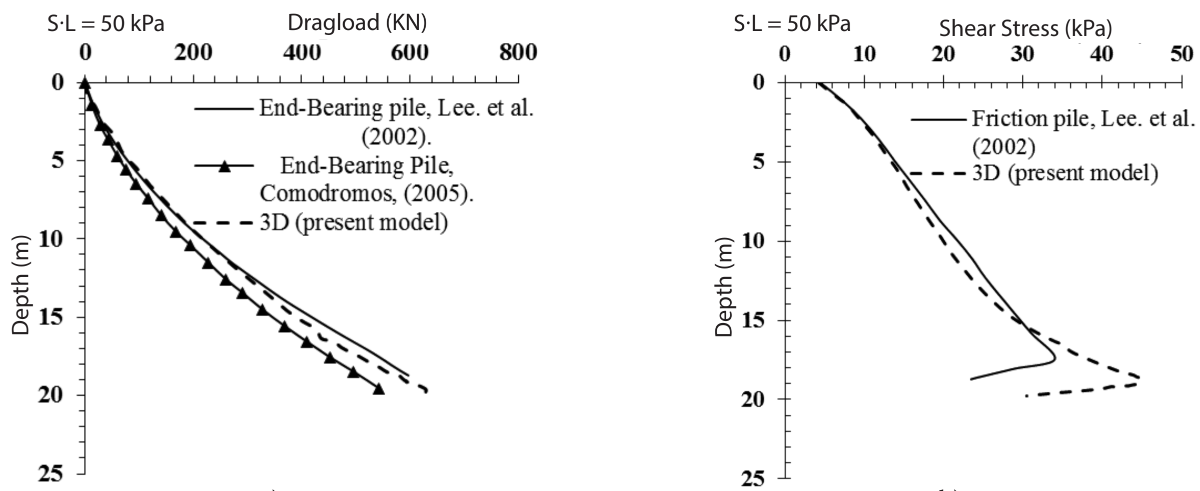
The coefficient of the Earth Pressure at Rest (K_0) was considered using the method of Jaky (1948) [25] for normal soils for clay and dense sand as 0.65 and 0.5, respectively. The interface friction coefficient, μ, ($\mu = \tan \delta$) was supposed to be 0.3–0.4, because it was accepted in the Mohr-Coulomb way.

As shown in Figs. 3 and 4, the shear stress on the pile skin and the axial drag load of the pile resulting from the present numerical model are very close to Comodromos (2005) [19] and Lee. (2001) [24]. Simplified methods assumed that whole mobilization of the shear strength above and below the pile neutral line; however, an analysis using ABAQUS software let us consider the partial mobilization of the shear strength according to the applied shear strain.



a) b)

Figure 3. a) Shear-stress distributions along the pile surface and b) axial drag load for a single friction pile.



a) b)

Figure 4. a) Shear-stress distributions along the pile surface and b) axial drag load for a single end-bearing pile.

3 COMPARISON OF 2D AND 3D MODELS

In general, the combination of the axial load and the moment would cause the pile to behave differently than the vertically loaded pile; therefore, the critical case for this combination was dependent on the type of piles. In forming the plastic inside batter pile we tend to bend the plastic to be created within the pile behavior batter pile proportionally different. 2D and 3D modeling of the vertical and the end-bearing batter piles were first compared under an earth-surface loading of Δp = 50kpa.

As is clear from Fig. 5, there is compatibility between the results of the 2D and 3D modeling and the overall trend of skin friction along the pile is similar. The skin shear stress at the pile head is equal to zero in the 2D modeling, which differs from the 3D modeling. The 2D modeling shows less skin shear stress up to a pile depth of about 5 m; however, it shows more skin shear stress from a depth of 5 m up to nearly the pile end, in comparison with the 3D modeling. Both types of modeling show approximately the same results at the pile end. The influence of strain in the third dimension has mainly the effect in the case of soil failure. This factor

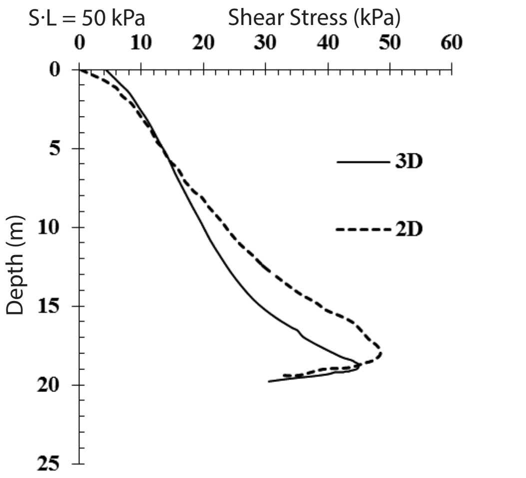


Figure 5. Skin shear-stress development along the end-bearing vertical pile.

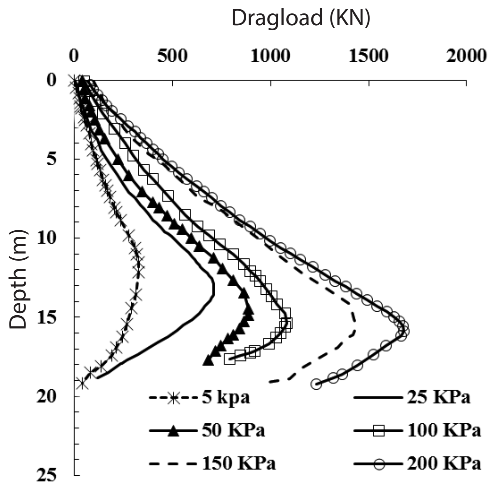


Figure 6. Drag load along the single friction pile under various earth-surface loads.

could affect the actual bearing pile capacity. In the 3D modeling, at the end of the pile shear, the failure zone spreads out in three directions; neverthless, the shear zone is two dimensional in the 2D modeling. This means a larger end bearing capacity and less skin friction development for the pile in the 3D modeling, compared to the 2D modeling.

4 DRAG LOAD AND NEUTRAL PLANE IN THE VERTICAL SINGLE PILE

In this part, the magnitude of the drag load and the location of the neutral plain are estimated for the friction and the end bearing pile under different earth-surface loads.

As shown in Fig. 6, increasing the earth-surface load leads to an increase in the cumulative drag load. The application of a surface load of 5 KPa leads to a maximum drag load of 300KN, and increasing the surface load up to 200 KPa shows an increasing trend in the drag load up to a maximum value of 1600KN, indicating a non-linear relation between the surface load and resulting drag load. The decreasing trend after the maximum value of the drag load is due to the change of the shear-stress direction (the neutral line) in the pile skin. Since in this case the neural point in the end-bearing pile is formed lower and subsequently the cumulative force in the shell of pile against the down drag is less, it leads to more bearing capacity.

Fig.7 presents the displacement of the neutral plane along a friction pile for an earth-surface loading of 5 kPa

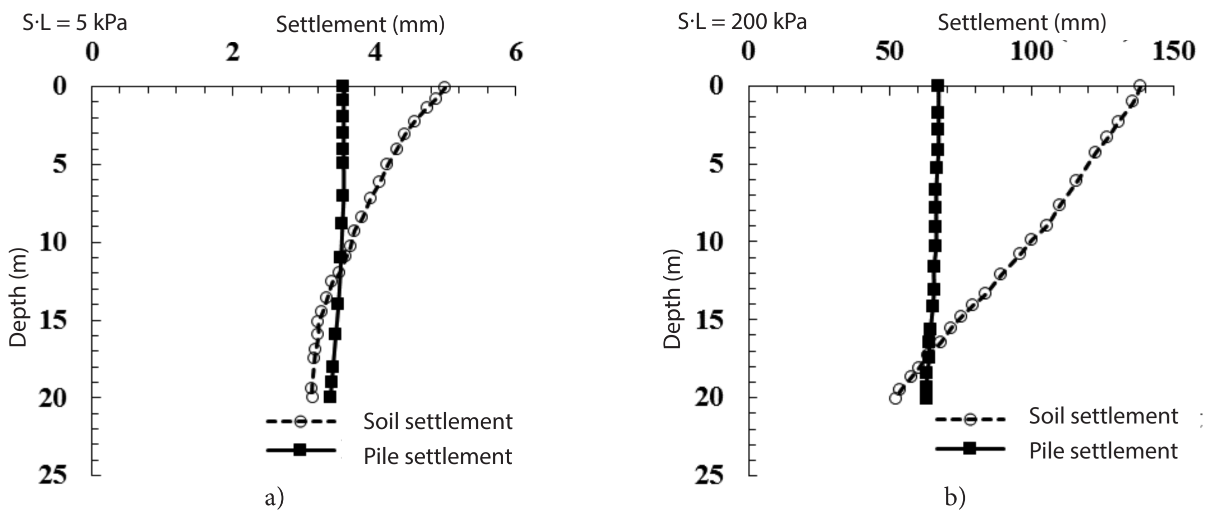


Figure 7. Pile and surrounding soil settlements for a surface load of: a) 5 and b) 200 KPa.

and 200 kPa. It is clear that the location of the neutral plane changes from a depth of 14m to 17.4m, as the surcharge increases from 5 KPa to 200 KPa.

Fig. 8 shows the drag load imposed on the end-bearing vertical pile for various earth-surface loadings.

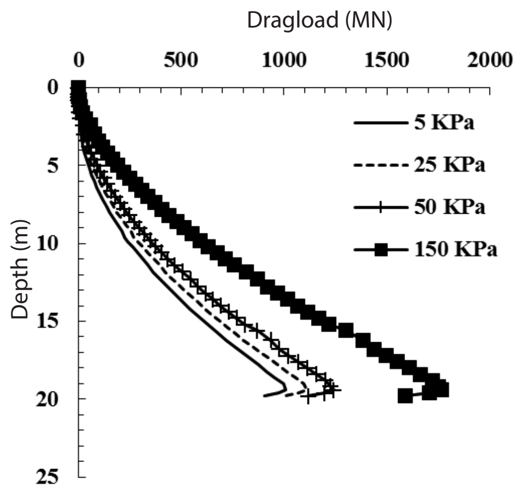


Figure 8. Drag load along the single end bearing pile for different surface loads.

As expected, larger drag loads are developed as earth-surface surcharge increases. As the pile is rested on a stiff layer with a surrounding soft soil, the neutral plane forms near the stiff layer so that an increased surcharge can push the neural plane down to the end of the pile. Comparing Figures 6 and 8 indicated that under a constant earth surcharge, the drag load is more for an end-bearing pile than for a friction pile.

5 DRAG LOAD IN THE BATTER PILE

In order to investigate the effect of the pile's inclination drag load a numerical model was produced in 3D conditions. The inclination angle of modeled batter pile was 15 degrees with respect to the vertical axis. The 3D model is shown in Fig 9.

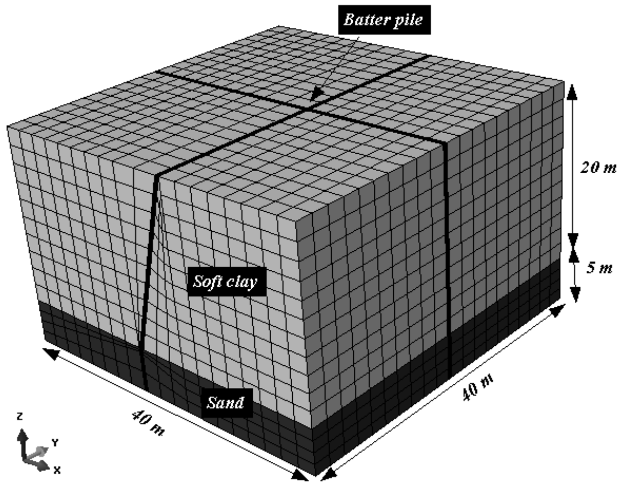


Figure 9. Finite-element mesh of a single batter pile and a soil profile.

The material properties, including the soil and the pile, completely correspond to those mentioned in Fig.1 and Table 1. It is clear that the boundaries were defined far enough from the pile in order to eliminate the interaction between the boundaries and the pile.

The pile was assumed to be loaded at the rest condition (k_0), before inducing the surcharge. As the surcharge is

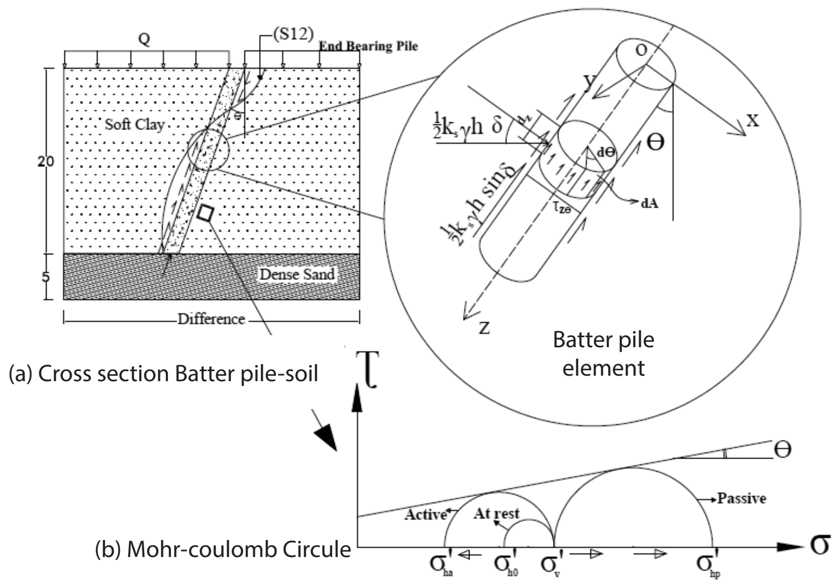


Figure 10. a) A cross-section of a soil profile batter pile and the applied stress on the pile, b) limits of the normal pressure acting on he pile skin.

loaded, the batter pile is subjected between the active (k_a) and the passive (k_p) loading, which produces a complex condition to predict the behavior of the pile. It is possibly related to the flexural deflections and the longitudinal distortions of the pile. Fig. 10 illustrates the explained process for a batter pile. Based on this figure, between k_a and k_p along the pile for a batter pile.

6 EFFECT OF THE INCLINATION ANGLE IN THE DRAG LOAD FORCE

For a closer look at the batter pile behavior under different inclination angles, some sensitivity analyses for both the friction and the end-bearing batter piles under a constant earth-surface load of Δp = 50kPa were performed. The loading of the batter pile is similar on the vertical pile loading for comparing the results under the same conditions.

Figure 11 shows the drag force of the end-bearing piles for different inclination angles. The sign and direction of the drag force change along the pile and this condition intensifies with an increase of the pile inclination angle. In this condition the pile is subjected between the active and the passive force surrounding from the soil, the skin shear stress and then the drag force's direction change along the pile. In other words, the pile is subjected to a longitudinal distortion and flexural bending that may lead to a change in the sign of the shear stress and the drag force in it.

The deformed shape of the batter pile is shown in Fig.12, illustrating the above process. This is the reason why the batter pile is subjected to a different circumferential force at the different depths. However, it is certain that a greater inclination angle leads to a greater dragload of the batter pile.

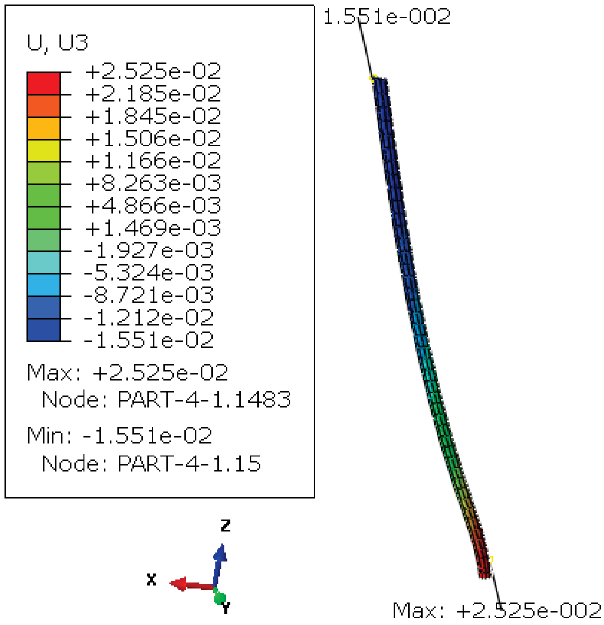


Figure 12. Deformation of an end-bearing batter pile under earth-surface loading.

Figure 13 shows the drag force of the batter frictional pile with different inclination angles. As shown, the pile drag force increases with an increase of the inclination angle. It is considered that the maximum drag load force occurs nearly at the end of the frictional batter pile and then rapidly decreases. The friction batter pile's behavior is simpler with respect to the sign of the drag force and the pile's longitudinal distortion. Comparing Figures 11 and 13 we can conclude that the drag force of the frictional batter pile is about four times larger than that of the end-bearing batter pile.

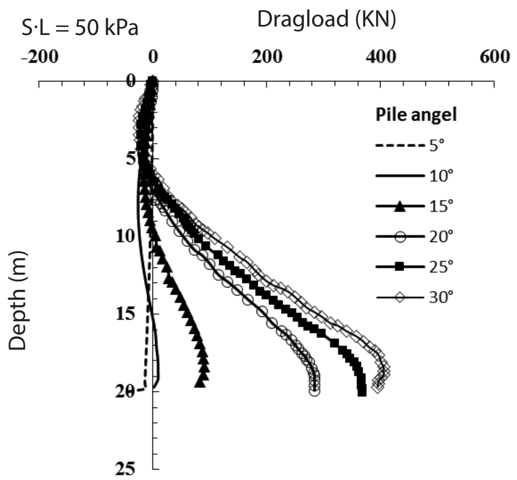


Figure 11. Drag load along the end-bearing batter pile.

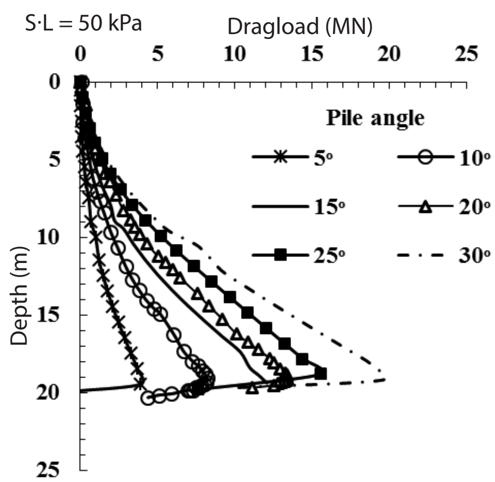


Figure 13. Drag load along the friction batter pile.

7 CONCLUSIONS

This paper deals with the negative skin friction in a single vertical and a batter pile in two-layer soil. A model based on the study of Lee et al. (2002) [18] was developed and the results were compared and evaluated. The results of the model showed good compatibility with this study's conclusions. Then some other factors, such as the third-dimension of the model, the intensity of the surface load, the batter pile's inclination angle, and the type of pile were investigated. In this study the soil conditions were in accordance with the paper of Lee et al. (2002), so the soil characteristics can vary as a factor in future discussions.

The analysis of the results shows that:

1. The drag load of the pile is completely dependent on the surrounding soil's condition, the intensity of the surface load and the batter pile's inclination angle. Also, the neutral plane's position on the pile depends on these conditions and its location tilts into the resistant subsoil layer.
2. In the vertical or near-vertical positions, the pile acts as a column in the soil and is only subjected to an axial force However, for large inclination angles, close to 25 degrees, the pile works like a beam column that is subjected to an axial force, the flexural momentum sand shear forces. In this situation the normal forces between the pile and the soil vary between the active and passive cases and make the interaction between the pile and the soil more complex.
3. The drag load of the pile under an earth-surface loading for an end-bearing vertical pile is more than a pile. This trend is also dominant in the batter pile; the difference is that the maximum drag load in the pile does not necessarily occur in the neutral plane.
4. Increasing the earth-surface loading, the neutral plane in the frictional and the end-bearing pile moves to a greater depth of the soil. The neutral plane is almost at the bottom of the pile for the end--bearing piles; however, it is formed in the end one--third height of the piles for the frictional pile.
5. Despite the vertical pile, no specific neutral plane forms in the batter piles. In the batter piles, the shear-stress direction on the pile periphery changes in a region. Also, the pile drag load increases with an increase of the inclination of pile.

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