Influence of lowering groundwater level on the behavior of pile in soft soil

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Abstract. The article presents the results of numerical analysis of the development of negative skin friction forces of a single pile by lowering the level of the groundwater table in soft clay soils. The analysis is conducted with a three-dimensional model (3D) using the ABAQUS software package. Results from the present work are found to be in congruent with the available published results. Moreover, the influence of lowering of the groundwater table in distribution of negative skin friction and axial forces on the pile as well as the maximum relative displacement between the soil and pile at various stages has been observed. The compression of the pile material is also taken into consideration in the study. Based on the results of the current numerical analysis, an equation has been proposed for estimating the additional load on the pile, which is caused by negative frictional forces.

1. Introduction

One of the reasons for the failure of pile foundations in soft soils is a negative friction that may develop on the outer surfaces of the pile as demonstrated by Terzaghi [1-3]. Negative friction occurs on the side surfaces of the pile due to the displacement of the surrounding soil deposits relative to the pile. The phenomenon of negative friction on a pile can occur for various reasons: as a result of urban planning sites by raising the level of the surrounding area, additional loading created on the ground surface with long-term effect, dynamic impact on the ground of heavy transport and industrial installations, lowering the level of groundwater, self-compaction of new embankments, influences caused by nearby driven piles, or a combination of two or more of the aforementioned factors [4-20]. However, these literatures reported that occurrence of negative friction on the side surfaces of piles mainly happens to be groundwater reduction.

In recent decades, urban construction has been intensively developed in various coastal areas of the world, such as Alexandria (Egypt) and Hanoi (Vietnam). These sites are characterized by the construction of a large number of high-rising buildings with deep foundations of overlying soft clay soils having a considerable thickness. At the same time, the development of urban and commercial activities has been causing significant decrease in the level of groundwater. As such, piles located in these regions have been exposed to negative frictional forces, causing additional axial load on them. In some cases, these situations lead to catastrophic failures of the overlying buildings and other structures. In General, the problem of accounting for the effects of soft soil on piles covers three main issues: deter-
mination of the load-bearing capacity of a single pile in soft soil, determination of final pile settlement, and the time of consolidation of the soil.

This article, therefore, aims at studying the development of negative friction forces and the determination of axial forces in the pile and their maximum values caused by groundwater lowering as a result of human developmental activities.

2. Numerical model
The centrifuge model [11] was used to verify the numerical model of a single pile in a soft clay soil adopted in this paper using the ABAQUS [20]. The geometric dimensions and physical parameters of the finite element 3D model are shown in Figure 1. Soft clay is modeled as a Cam Clay model characterized by three parameters namely, \( M, \lambda, \) and \( k; \) where \( M \) is the slope of the critical state line in \( q-p' \), \( \lambda \) is the slope of the isotropic compression line in \( e-ln(p') \) and \( k \) is the slope of the line unloading/loading in the \( e-ln(p') \). The sand layer is modeled as the Mohr-Coulomb model whereas the pile is modeled as a 3D linear elastic material; the interface element is installed between the pile and the surrounding soil to simulate the interaction behaviour in accordance with the Coulomb model as shown in Figure 2. The characterized properties of piles and soil elements are shown in Table 1. The model has symmetry along the x and y axes. Therefore, only one-quarter of the whole finite element has been meshed. The 8-node pore pressure element (C3D8P) is used for soil modeling. An 8-node element (C3D8R) with reduced integration elements is used for modeling the pile. The bottom boundary condition of whole model is assumed to have a fixed support in all directions. The side boundary condition of soil domain is limited from laterally displacement, whereas along the symmetry plane, the boundary conditions are restrained from deformations along the perpendicular direction. A surcharge load of 45 kPa is applied on upper surface of the soil, in addition to the boundary pore pressure of drainage (\( U= 0 \) kPa) is set at the top soil surface.

| Table 1. Summary of material properties used in numerical analysis [11]. |
| --- | --- | --- |
| Properties | Pile | Bottom sand | Clay |
| Constative model | Liner-elastic | Elastoplastic | Cam-Clay |
| Saturated unit weight, \( \gamma_{sat} \text{ (kN/m}^3 \) | 27 | 19.4 | 16.3 |
| Poisson’s ratio of soil, \( \nu \) | 0.35 | 0.30 | 0.35 |
| Modulus of elasticity \( E, \text{ (kPa)} \) | \( 7 \times 10^7 \) | \( 1.2 \times 10^5 \) | N/A |
| \( M \) | N/A | N/A | 0.98 |
| \( \lambda \) | N/A | N/A | 0.14 |
| \( K \) | N/A | N/A | 0.012 |
| Pre-consolidation pressure, \( p_o \text{ (kPa)} \) | N/A | N/A | 64 |
| The initial void ratio, \( e_o \) | N/A | 0.73 | 1.6 |
| Friction angle at the critical state, \( \phi' \) | N/A | 29.7° | 25° |
| Angle of dilation, \( \psi' \) | N/A | 8.3° | 0° |
| Coefficient lateral earth pressure at rest, \( k_o = (1-sin \phi') \) | N/A | 0.50 | 0.58 |
| Coefficient of the vertical permeability, \( k \text{ (m/s)} \) | N/A | \( 1 \times 10^{-4} \) | \( 1 \times 10^{-8} \) |
| N/A- not available |
Figure 1. Representative 3D finite element mesh and boundary conditions

Figure 2. Behavior of interaction at pile-soil interface in ABAQUS [18]
3. Results and discussion

3.1 Model verification

The results of ABAQUS 3D modeling and centrifuge model [8] were compared and results are presented in Figure 3. Good agreements could be observed among the simulated and measured values of shear stresses and axial forces in the pile. These results confirm the possibility of using properties of this model to study the effect of groundwater level lowering on the behaviors of single pile embedded in soft clay soil using program ABAQUS.

![Comparison of simulated and measured values](image)

**Figure 3.** Comparison of simulated and measured values

3.2 Influence of lowering groundwater table

The effect of lowering groundwater table (G.W.T) on the distribution of negative skin friction forces against the normalized depth (ZL) of a single pile was carried out for five levels (G.W.T = 0, -2, -4, -6, and -8 m), respectively. Figure 4(a) shows that the distribution of shear stress along the side surface of the pile and the normalized depth of the neutral plane \( L_{NP}/L \) (the point of zero shear stress) increase with decreasing depth of the G.W.T. The normalized depth of the neutral plane changes from 0.71 to 0.85 when the G.W.T value changes from 0 to -8 m. This is possibly associated with the settlement of the soil deposits around the pile due to water reduction, which increases the vertical effective stresses \( \sigma' = \gamma' z \) along the normalized depth of the pile. Figure 4(b) shows the distribution of axial force developed along the normalized depth of the pile also increase with decreasing depth of the G.W.T.

Figure 5(b) shows that the maximum axial forces in the pile \( (Q_{s,\text{max}}) \) increase with a decrease in the level of G.W.T, which is associated with an increase in the maximum relative displacement between the pile and surrounding soil \( (\text{S}_{\text{soil}} - \text{S}_{\text{pile}}) \) as shown in Figure 5(a). From Figure 5 it is clear that the maximum relative displacement increases 5 times, while the maximum axial load increases 2.5 times as a result of the lowering in the groundwater level from 0 to -8 meters.
Figure 4. Distribution of shear stresses and axial forces in the pile for five different groundwater depths

Figure 5. Distribution of maximum relative displacements and maximum axial forces in the pile for five different groundwater levels
3.3 Estimation of maximum axial forces

Based on the numerical analysis conducted in the present study, an equation (1) is proposed for estimating $Q_{s,\text{max}}$ that could be developed on a single pile embedded in soft clay soil as a result of negative skin friction and is given by:

$$Q_{s,\text{max}} = \Omega \int_0^{L_p} \left( S_{\text{soil}} - S_{\text{pile}} \right) K_o \sigma' \zeta d\zeta$$  

where $\Omega$ - perimeter of the pile (m); $L_p$ = depth of the neutral plane (m); $S_{\text{soil}}$ = maximum settlement of soil (mm); $S_{\text{pile}}$ = the maximum settlement of pile (mm); $K_o$ = the coefficient of lateral earth pressure at rest; $A$ - constant value, ranging from 10 to 12; $\gamma_{\text{crit}}$ - limit displacement for full mobilization of shear stress which is equal to 5 mm; $\sigma'$ - the vertical effective stress at depth $L_p$.

Table 2 shows data comparing the values of $Q_{s,\text{max}}$ determined by the proposed equation (1) with the values from previous studies. The results show that the differences between the values of the maximum axial forces in the pile do not exceed 8%. Therefore, this equation can be used with sufficient confidence for estimation of axial maximum force developed along the pile shaft due to negative skin friction.

Table 2. Estimating the maximum axial force following the proposed equation.

| Cases         | Qs, (max), previous Study (kN) | Qs, (max), present equation (1), (kN) | $\Delta$ Difference (%) |
|--------------|-------------------------------|-------------------------------------|------------------------|
| Yaru et al. [11] | 850                           | 880.51                              | +3.58                  |
| Lam et al. [17]  | 950                           | 1029.91                             | +7.75                  |
| Ng et al. [13]   | 1100                          | 1123.54                             | +2.14                  |
| Liu et al. [16]  | 842                           | 900.29                              | +6.88                  |

4. Conclusion

From the present study, the following conclusions may be inferred.

1. In this study the authors demonstrated the efficacy of ABAQUS computer program for investigating the implications of groundwater level reduction on the behavior of a single pile in soft clay soils.

2. The study showed a significant effect of the lowering ground water level in the development of negative friction and axial forces in the pile, which should be taken into consideration while designing pile foundations in soft soils in areas with the problem of groundwater level lowering.

3. Analysis of published numerical results on the subject under consideration allows determination of the maximum forces in the cross section of the pile caused by groundwater reduction with satisfactory accuracy and precision for practical purposes.

4. The lowering of ground water level has significant effect on the relative displacement, maximum axil force and the normalized depth of the neutral plane.

5. Finally, a simplified equation is proposed to estimate the maximum axial force developed in a single pile, considering influences from surcharge load and groundwater level lowering.

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