Numerical Simulation of Predicting the Shaft Capacity of Single Pile in Unsaturated Soil

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Abstract. Pile foundations that placed above the groundwater table zone where the soil is typically in a state of the partially saturated case have been considered in this study. To appreciate the effect of the matric suction on the skin resistance of single pile foundations that placed in unsaturated clayey soil. A series of small scale and full-scale single model pile are simulated using the software Plaxis 3 D. Mohr-Coulomb model (Elastic-perfectly plastic model) that takes into account the effect of the matric suction has adopted in the analysis. Also, in this study comparison among numerical models and laboratory, small scale single and full-scale pile models have done. In general, the value of shaft capacity obtained by the numerical investigations are in good agreement with laboratory model pile test results.

Keywords: Unsaturated soil; matric suction; single pile; shaft capacity; Plaxis 3D.

1. Introduction
Generally, soil mechanics principles have two approaches dry or saturated soils and other approaches between them called unsaturated soils or partially saturated. However, most piles are placed in unsaturated soils. Unsaturated soils have three phases (solid, water, and gas) and contractile skin phase that made matric suction among particles of soil that could increase shear strength and other parameters such as stiffness of soil, so increase adhesion between soil and pile [1]. Variation of properties to many soils when it giving out or absorbing water. A variation of air pressure and pore water pressure effect on the stress state of the soil model [2,3]. Nearly all of the classical soil mechanics basic are appropriate for fully saturated soils, in a deal with unsaturated soils should be concerning by main point (changes of volume concerning changes degree of saturation [4]).

The difference between the pore air pressure ($u_a$) and pore water pressure ($u_w$) that refers to matric suction. Many investigations have connected among shaft capacity of pile foundation, matric suction, and behavior of partially saturated soils. A considerable deal of interest has been toward to pile foundation design for engineering basics wherein the mechanics of partially saturated soils have been applied extensively [5-7]. Carrying load capacity and settlement are required information for pile foundation design in saturated and unsaturated soils. Shear strength and stiffness of the vicinity soil also called soil-pile interface supply considerable assistance into the load-settlement behavior of a pile foundation [8].

The theory of plasticity was used for simulating partially saturated soil behavior by using the proposed elastoplastic new model, which was an oval-shaped model similar to the modified Cam-Clay Model (MCC) [2]. The arrangement of this model differs based on the value of suction. This model is appropriate for a little to say the swelling partially saturated soils such as soils including silt, sand, and
clay with low-plasticity. Many loaded piles are founded above the groundwater table zone and these piles are affected with matric suction. Vanapalli and Taylan [1] founded a new small model pile test in unsaturated soil and proposed using three a modified $\alpha$, $\beta$ and $\lambda$ methods to look forward to the influence of matric suction on maximum skin resistance. Also, a single pile skin resistance influenced by the contribution of matric suction on along of pile. In this study numerical examinations of the small-scale single pile embedded in partially saturated fine-grain soil were carried out by Mohr-Coulomb model. The Mohr-Coulomb model significant adhesion strengths between the partially saturated soil and steel pile was employed to analyze skin resistance from small scale single pile load tests in the laboratory.

2. Testing Approach of laboratory Model
A group of small single pile model load tests under different conditions (fully saturated and partially saturated compacted clayey soil in short-term state) as shown in Fig. 1. A glacial till soil that tested by Vanapalli and Taylan, 2012 [1] was depended on this study. The main goal of the test approach is to calculate the effect of matric suction on the skin resistance of small model pile and comparing between laboratories and numerical results.

3. Physical and Mechanical Properties of Soil
The used soil properties (physical and mechanical) are tabulated in Table 1. The skin resistance of the small-scale model pile was suggested to be obtained at two moisture contents; 13% and 16% in the dry side of the optimum. These moisture contents were selected from the density-water content curve data. The dry unit weight of the tested soil at these moisture contents was equal to 14.5 kN/m$^3$ and 16.1 kN/m$^3$ respectively. The values of matric suction of the laboratory model were evaluated by the axis-translation method [9]. The value of moisture content was (13% and 16%) for matric suction of (205 and 110) kPa respectively. The tests were taken for the moisture contents on the dry side of optimum at less than 90% of the degree of saturation values which generated in significantly high matric suction.

Table 1. Physical Properties of the tested soil [1].

| Soil property                  | Value | Soil property                  | Value |
|-------------------------------|-------|-------------------------------|-------|
| Moisture content at optimum, $M_{opt}$ (%) | 18.6   | Clay percentage               | 30    |
| Maximum dry unit weight, $\gamma_{dmax}$ (kN/m$^3$) | 16.7   | Liquid limit, LL (%)         | 33    |
| Total unit weight, $\gamma_{sat}$ (kN/m$^3$)  | 18.5   | Plastic limit, PL (%)         | 17    |
| Sand percentage               | 28     | Plasticity index, PI (%)      | 16    |
| Silt percentage               | 42     | Undrained shear strength, cu (kPa) | 11.5  |
The Soil Water Characteristic Curve SWCC of the samples designed with different moisture contents of 13% and 16% are shown in Fig. 1. By using the pressure plate apparatus to prepare these SWCC following the drying path. More information on the matric suction tests employing both the pressure plate apparatus the modified null pressure plate and are explained in [10,3]. The laboratory samples were prepared by mixing with the quantity of water-limited and placed it in a tank with dimensions (300 mm in diameter and 300 mm in height). Compaction of samples statically by a specially designed compaction base plate with 350 kPa. The compaction and model pile load tests were carried out employing a standard triaxial test loading frame [1].

4. Estimation of the Ultimate Skin Resistance of Piles in Partially saturated Soils

4.1. Using Modified \( \alpha \) Method

Many studies related to the skin resistance of a single pile to the undrained shear strength, \( c_u \) of the clayey soils [11,12]. In this study, for analyzing the results of the steel model pile tested and placed in partially saturated and saturated soil the modified \( \alpha \) method was adapted. Also, back estimating the variation of adhesion factor between model steel piles and unsaturated soil concerning matric suction. Eq.1, it connected between undrained shear strength in saturated and partially saturated soils according to matric suction employing soil-water characteristic curve for partially saturated condition, \( c_u(\text{unsat}) \).

\[
Q_f(\text{unsat}) = \alpha c_u(\text{sat}) \left[1 + \frac{u_a - u_w}{P_a/101.3} \nu \right] \mu \pi \text{d}l \tag{1}
\]

where, \( c_u(\text{sat}) \), = saturated undrained shear strength, \( P_a \) = air pressure (i.e. 101.3 kPa), and \( \nu \), and \( \mu \) = fitting parameters. The fitting parameter \( \nu \) is based on the types of soils and it is 2 for the clayey soils. The fitting parameter \( \mu \) is 9, however, it is a function for the plasticity index (PI).

![Figure 2. Soil water characteristic curve (SWCC) [1].](image)

4.2. Numerical Modeling

In this section the numerical model will be defined. The Mohr-Coulomb model (MCM) is adopted in this study. Table 2 showed the essential parameters used in this model. The linear elastic-perfectly plastic constitutive model finite element extending MCM yield criterion was used in the numerical analysis include the conventional shear strength parameters (\( c_u \)) estimated from unconfined compression, the elastic modulus under saturated (\( E_{\text{sat}} \)) and unsaturated conditions (\( E_{\text{unsat}} \)) are required. Oh et al. [13] proposed Eq. 2 to evaluate the influence of respect to elastic modulus (E) at partially saturated condition (\( E_{\text{unsat}} \)) with soil suction employing modulus of elasticity at fully saturated condition.
(E_{sat}) and two fitting parameters \( \alpha \) and \( \beta \) values 1.5 and 2 respectively. The Plaxis 3D software is used in this research for modeling soil mechanical behavior. The non-soil material such as stainless steel should be taken into account during modeling processes. Concerning the model dimensions as cited by [1] width and height equal 300 mm and the height of pile equal 200 mm. The full-scale model with height and width are 6 and 10 m respectively and the pile height is 4m and its diameter 0.4 m which present in this study. However, the carrying capacity of pile foundations can be obtained accurately by field tests. The field test of pile carrying capacity is time-consuming, needs trained professional and heavy equipment of expensive cost. All these reasons contribute to estimating the pile carrying capacity and settlement behavior using numerical methods.

\[
E_{\text{Unsat}} = E_{\text{Sat}} \left[ 1 + \alpha \frac{\mu_a - \mu_w}{\rho_a/1013} \beta \right]
\]

**Table 2.** Essential properties of the input parameter for Mohr-Coulomb (MCM).

| Materials | Matric suction \((u_a-u_w)\) kPa | Degree of saturation | Young modulus \((E)\), kPa | Poisson’s ratio \((\mu)\) | Undrained Strength, kPa |
|-----------|-------------------------------|----------------------|---------------------------|--------------------------|--------------------------|
| S1        | 0                             | 90                   | 2500                      | 0.49                     | 11.5                     |
| US2       | 205                           | 43                   | 15000                     | 0.49                     | 68                       |
| US3       | 110                           | 65                   | 8000                      | 0.49                     | 80                       |
| Steel pile* | -                             | -                    | 2000000                   | 0.2                      | -                        |

* The model adopted for pile behavior is the linear elastic model.

5. Results and Discussion

In this part a comparison among the estimated, calculated and Plaxis 3D software results of carrying capacity of the pile models are shown in Figs. 3-8 and Tables 3-5. The figures show the ultimate skin resistance of single steel pile, the soil suctions value (measured and predicted) were comparable results at low of degree of saturation values (S1) with matric suction = 0 kPa, and US2 with matric suction = 205 kPa; US3.-16% with matric suction = 110 kPa). However, the predicted skin resistance values were low at the saturated sample with matric suction values equal 0 kPa at low shear strength 11.5 kPa with fully saturation that effect on factor of adhesion between pile surface and soil materials (shear strength decreased with the degree of saturation increased), also the ratio \((u_a-u_w)/\alpha\) and \((u_a-u_w)/c_u\) were opposites. The results of the MCM were lower than the experimental results may be because MCM neglected dilation value, and neglected variation of modulus of elasticity with depth, on the other hand, MCM results approximately in good agreement with laboratory model results which based on linearity theory the variation among these results in Tables 3-4 and Fig.7 based on different conditions.

**Table 3.** Ultimate shaft capacities \((Q_s)\) using different methods.

| Degree of saturation, S% | Matric suction \((u_a-u_w)\) kPa | \(c_u\) (Meas.), kPa | \(\alpha\) | \(Q_s\) Eq. (1), kN | \(Q_s\) Lab. Model, kN | \(Q_s\) Plaxis, kN |
|--------------------------|-------------------------------|----------------------|---|----------------|----------------|----------------|
| 90                       | 0                             | 11.5                  | 0.9 | 0.13              | 0.11           | 0.141          |
| 43                       | 205                           | 68                    | 0.75 | 0.564             | 0.68           | 0.575          |
| 65                       | 110                           | 80                    | 0.76 | 0.676             | 0.55           | 0.491          |

**Table 4.** Ultimate shaft capacities \((Q_s)\) using estimated and predicted methods

| Degree of saturation, S% | Matric suction \((u_a-u_w)\) kPa | \(c_u\) (Meas.), kPa | \(\alpha\) | \(Q_s\) Eq. (1), kN | \(Q_s\) Plaxis 3D, kN |
|--------------------------|-------------------------------|----------------------|---|----------------|-----------------|
| 90                       | 0                             | 11.5                  | 0.9 | 51.99            | 67              |
| 43                       | 205                           | 68                    | 0.75 | 225.83           | 276             |
| 65                       | 110                           | 80                    | 0.76 | 270.65           | 254             |
Figure 3. The relationship between skin resistance and vertical displacement at different matric suction (0, 205, and 110) kPa respectively by (MCM) small scale pile.

Figure 4. The relationship between skin resistance and vertical displacement at different matric suction (0, 205 and 110) kPa respectively by (MCM) full-scale pile.

Figure 5. Comparison among the modeling results and matric suction.
Figure 6. Comparison between the skin resistance of full-scale models and matric suction.

Table 5. Results of the back-calculated of adhesion factor by different methods.

| Degree of saturation, % | Matric suction $(u_a-u_w)$, kPa | Back calculated (α) Small-scale Model | Back calculated (α) Full-scale Model |
|------------------------|----------------------------------|--------------------------------------|--------------------------------------|
| 90                     | 0                                | 0.97                                 | 1.1                                  |
| 43                     | 205                              | 0.49                                 | 0.63                                 |
| 65                     | 110                              | 0.67                                 | 0.8                                  |

Figure 7. Relationship between the adhesion factors and matric suction.
Figure 8. Relationship between the \((u_a - u_w)/c_u\) and \((u_a - u_w)/\alpha\) of full scale and small-scale models.

6. Conclusions
In this study, laboratory, theoretical and numerical modeling studies were used for examining the behavior of skin resistance pile under undrained conditions in a saturated and unsaturated homogeneous layer that is prepared in the laboratory using two moisture contents. Numerical modeling (small and full scales) are made by different parameters founded or evaluated from the laboratory modeling process to simulate the behavior of the skin resistance pile. The main points may be expressed in the following:

- The laboratory modeling results explain the significant effect of matric suction on shear strength and stiffness of soil and interface between steel pile-soil.
- The carrying capacity of the friction pile model increase with increased matric suction under undrained loading conditions.
- Experimental and numerical models are compatible according to output results, then the unsaturated soil stiffness and soil suction changes with depth based on degree of saturation.
- The values of \(\alpha\) were back-calculated to determine the difference between the calculated values from Eq. 1. These values obtained from the back calculations were very close to the first estimated values.
- The numerical studies based on the input parameters taking into account the effect of matric suction in the modeling of the analysis steel pile behavior.

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