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A technique for estimating the shaft resistance of test piles in unsaturated soils

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ABSTRACT: A testing program was undertaken in a laboratory environment to evaluate the shaft resistance of jacked mild steel open end pipe test piles embedded in two different sandy soils (i.e., Soil #1: silty sand and Soil #2: clean concrete sand) under saturated and unsaturated conditions. Based on the results of the study, a technique for estimating the shaft resistance of test piles under unsaturated conditions is presented extending an effective stress analysis approach of the conventional β-method. The contribution of matric suction to the total shaft resistance was found to be in the range of 35%-40% of the total shaft capacity in silty sand but almost negligible in clean concrete sand.

1 INTRODUCTION

Limited number of studies are reported in the literature that consider the influence of matric suction or capillary stresses on the load carrying capacity of shallow and deep foundations (Douthitt et al. 1998, Costa et al. 2003, Georgiadis et al. 2003). More recently, some studies have been undertaken to understand the influence of matric suction on the bearing capacity of shallow foundations in both coarse- and fine-grained soils (Vanapalli & Mohamed 2007, Oh & Vanapalli 2009).

The bearing capacity of shallow foundations in unsaturated sands is typically two to four times higher than the saturated bearing capacity. Even low matric suction values in the range of 2 to 6 kPa significantly contribute to the bearing capacity of unsaturated sands (Mohamed & Vanapalli 2006).

The design of pile foundations are conventionally based on the principles of saturated soil mechanics or empirical procedures or based on in-situ test results. Typically, pile foundations are designed assuming saturated, dry or submerged conditions. In many cases, pile foundations may be placed under unsaturated conditions. However, to the best of the knowledge of the authors, no studies are reported in the literature to estimate the shaft resistance of piles in sands due to the contribution of capillary stresses or matric suction.

In the study presented in this paper, a laboratory testing program was undertaken to evaluate the shaft resistance of test piles in two different sands (Soil #1, a silty sand & Soil #2, a clean concrete sand) under unsaturated (moist) and saturated (submerged) condition. The objective of this study is to determine the contribution of matric suction towards the total shaft resistance of piles and propose a technique to estimate the shaft resistance in unsaturated soil conditions extending an effective stress analysis approach of the conventional β-method.

2 BACKGROUND

This section provides background information of the conventional procedure followed in estimating the pile shaft resistance in saturated sands.

The shaft capacity, Q_f for cylindrical piles is given by:

$$Q_f = f_s \times A_s = \sum_{i=1}^{i=n} K_i (\sigma'_z) \tan \delta' (\pi d L) \qquad (1)$$

where f_s = skin friction; A_s = surface area of the pile; σ'_z = vertical effective stress along the pile shaft at depth z; L = length of pile; d = diameter of pile; δ' = angle of friction along the soil/pile interface and K_i=coefficient of earth pressure along pile shaft.

The above equation can be simplified by replacing the coefficients K_i and $\tan\phi'$ by a single factor $\beta = K_i \tan\phi'$ and forming the conventional β method.

$$Q_f = f_s \times A_s = \sum_{i=1}^{i=n} \beta (\sigma'_z)(\pi d L) \qquad (2)$$

A wide range of recommendations are provided in the literature for β values by various investigators (McClelland 1974, Meyerhof 1976, Briaud & Tucker 1997). Significant differences in the recommended β values may be attributed to several factors such as in-situ stress conditions, frictional resistance, and compressibility of the soil, pile type, shape and mode of installation. In this paper, the β values from the pile test results both under saturated and unsaturated conditions were back calculated. In addition, a simple technique is proposed to estimate the shaft resistance in unsaturated soil conditions using the Soil-Water Characteristic Curve (SWCC) and the effective shear strength parameters.

3 A TECHNIQUE FOR ESTIMATING THE SHAFT RESISTANCE OF PILES IN UNSATURATED SANDS

A general expression for estimating the shaft resistance of piles in unsaturated sands $Q_{f(us)}$, can be expressed as shown in Eq. (3);

$$Q_{f(us)} = Q_f + Q_{(u_a - u_w)} \tag{3}$$

The contribution of ultimate shaft resistance due to matric suction $Q_{(u_a - u_w)}$, can be estimated extending the approach proposed by Vanapalli et al. (1996) and Fredlund et al. (1996) for predicting shear strength of unsaturated soils using the SWCC and the effective shear strength parameters (Eq. 4).

$$\tau = \left[c' + (\sigma_n - u_a)\tan\phi'\right] + \left[(u_a - u_w)(S^{\kappa})(\tan\phi')\right] \tag{4}$$

where c' = effective cohesion, ϕ' angle of internal friction, κ = fitting parameter used for obtaining a best-fit between the measured and predicted values; and S = degree of saturation.

The second part of Eq. (4), represents the shear strength contribution due to matric suction:

$$\tau_{us} = \left[(u_a - u_w)(S^{\kappa})(\tan\phi')\right] \tag{5}$$

Extending the same philosophy, the contribution of ultimate shaft resistance due to matric suction along the interface of soil and pile material (Hamid and Miller, 2009) can be estimated using Eq. (6)

$$Q_{(u_a - u_w)} = \tau_{us} \times A_s \tag{6}$$

A general expression for estimating shaft resistance of piles can be obtained by substituting Eq. (5) and Eq. (6) in Eq. (3) as given below:

$$Q_{f(us)} = Q_f + \left[(u_a - u_w)(S)^{\kappa}(\tan\delta')\right]\pi dL \tag{7}$$

In Eq.7, the fitting parameter κ value equal to 1 can be used for non-plastic soils such as sands (Vanapalli & Fredlund, 2000). Eq. (7) can be used for estimating the variation of shaft resistance of the pile with respect to matric suction, $(u_a - u_w)$ using the SWCC (i.e. relationship between the degree of saturation, S and matric suction).

In the present study, SWCCs were measured using pressure plate apparatus. The measured SWCC results were also compared with the estimated SWCC using i) computer software SoilVision 2000 (Fredlund et al. 2002) which uses the grain size analysis data and the volume-mass properties, ii) “one point” measurement technique proposed by Vanapalli and Catana in 2005.

4 DETAILS OF THE TESTING PROGRAM

The geotechnical test pit at Lakehead University with the dimensions of 2.2, 4.4 and 2.5 meters (width, length and height respectively) was used in the research program. The test pit was divided into two smaller units (A and B) using timber lagging at the centre of the pit length (Fig. 1). The sample soil was placed in pit A, while pit B was left empty and used only for controlling the suction values in pit A by changing the height of the water table during the tests.

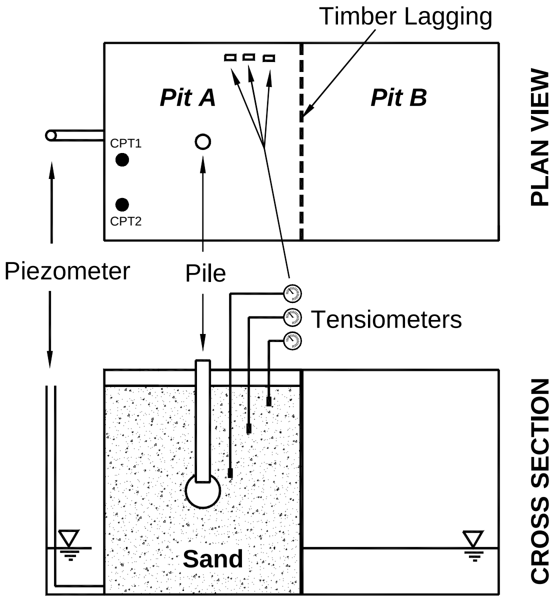

Figure 1. Schematic of the test pit used in the present study

4.1 *Soil and Pile Properties*

Soil #1 is a well graded silty sand (42% silt + 58% sand) and Soil #2 is poorly graded commercially available washed concrete sand (100% sand). Soils were subsequently placed into the test pit A in layers of 150 mm of thickness and compacted with a vibratory plate compactor.

Mild steel open end pipe piles of 65 mm outer diameters were used in the present study. The shear strength parameters of the soil-steel interface were determined in cyclic-direct shear tests at constant normal load. The friction angles determined for soil and soil-steel interfaces (i.e., for both Soils #1, Soil

#2) are summarized in Table 1 along with the other properties of the soils.

Table1. Properties of two soils tested

Soil		#1	#2
Optimum water content, w	%	12.5	12.5
Maximum dry unit weight, γ_d	kN/m^3	18.7	18.9
Angle of friction. ϕ'	deg.	40	40
Soil/Steel angle of friction, δ	deg.	36/28	24/22
Placed water content, w_p	%	8.5	6.5
Placed dry unit weight, γ_{dp}	kN/m^3	19.4	18.9
Placed total unit weight of unsaturated soil, γ_{unsat}	kN/m^3	21.0	19.7
Degree of compaction	%	104	100
Total unit weight of sat. soil γ_{sat}	kN/m^3	22.0	21.5

**The effective cohesion is equal to zero for both of the soils*

4.2 *Instrumentation and Pile Installation*

A load frame with 10 tonne capacity was used for pile installation and testing. After the installation of the piles, the soil inside the pile was removed with a hand auger and a void was created below the toe of the pile. The main purpose in creating the void below the pile toe was to eliminate the toe resistance during compressive loading, thus permitting direct measurement of shaft resistance in compression and in tension. Different views of the test setup of the model piles are shown in Figure 2. The test piles were not instrumented.


(a) (b)

Figure 2. Test setup of model pile (a) loading of pile in compression, (b) shaft resistance of pile in tension

Commercially available jet fill-type tensiometers, pressure cells and a vibrating wire piezometer were used to collect data during testing. Tensiometers were installed at 0.3, 0.6 and 1.2 meters below the soil surface to measure the matric suction (Fig.1). A vibrating wire piezometer was placed in Soil # 1 with the tip located approximately 1.0 m below the ground surface to measure pore water pressures in the soil during the fluctuations of water levels.

Total pressure cells were also installed at four different elevations along the pit wall. The measured horizontal stresses increased almost linearly with depth resulting in earth pressure coefficients, K_i of approximately 0.7 for both soils in terms of total stresses.

4.3 *Pile Testing*

The piles were tested in axial compression and tension by loading in increments of approximately 20 N up to the point at which no further load increment could be sustained. Usually a testing set consisted of a test conducted in compression and followed by a tension test.

Tests were carried out by varying (raising/lowering) water levels representing the saturated and unsaturated conditions. Four different tests were conducted for Soil #1 as follows: Test 1: unsaturated, Test 2: saturated, Test 3: unsaturated again and tested after one week, and finally Test 4: the new pile installation.

For Soil #2, the pile was repeatedly tested, alternating between tension and compression. This resulted in continuously decreasing pile shaft capacities. Three key tests were conducted using Soil #2. Test 1 was conducted under unsaturated condition. The pile was tested again after a period of 4 days, under unsaturated condition (which is Test 2), and finally the soil was saturated (submerged) and tested (which is Test 3).

4.4 *Test Results*

The results of the pile tests that were accompanied by tensiometer readings are summarized for Soil #1 and Soil #2 in Figures 3 to 6. For each test, the maximum initial loads and the maximum loads that were experienced after the last load application are shown for compression and tension.

For both soils, the shaft capacities in tension and compression decreased during the repeated loading. In each case, it was apparent that the cavity below the pile toe had collapsed after the water table had been raised to the soil surface. This was confirmed from the observations of soil movement into the hollow pile shaft which contributed to the development of some end bearing. In addition, the soil portions adjacent to the lower pile shaft had loosened up, resulting in a decrease of the shaft capacity.

4.4.1 *Soil # 1 (Silty sand)*

After raising and lowering the water table, very low shaft capacities were observed in Test 3 when compared to the Test 1 due to the collapse of the cavity (Fig. 3). For this reason, the pile results Test 2 and Test 3 are considered not fully comparable to Test 1.

The pile was removed and subsequently reinstalled about 0.6 m away from the original location (i.e. Test 4). The subsequent load tests after the new pile installation showed slightly higher capacities than Test 1 reflecting the slightly densified conditions due to the effective stress changes experienced due to water table fluctuations.

The matric suction values measured during the test at 0.3 m, 0.6 m and 1.2 m are given in Fig. 4. Even under submerged conditions, the matric suction values never reached zero, but stayed for all three instruments in the range of 0.9 to 1.5 kPa.

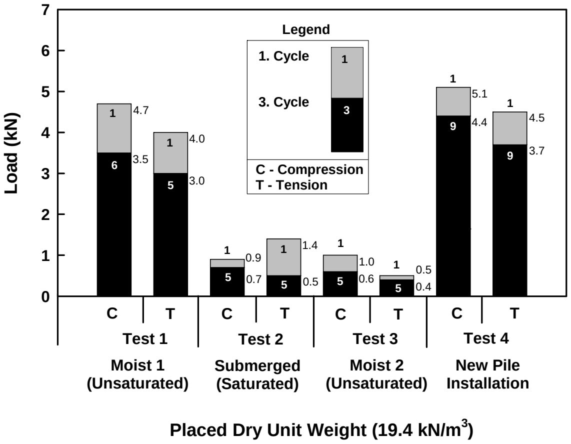

Figure 3. Summary of pile test results for Soil#1

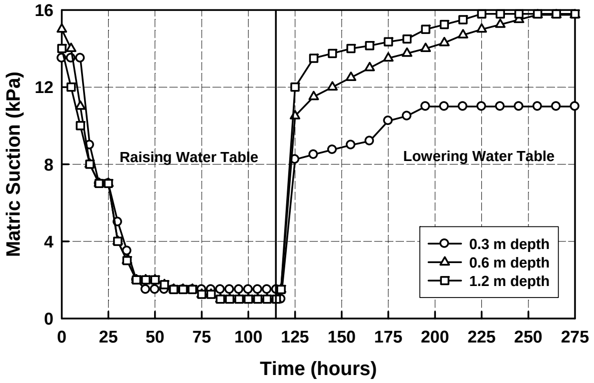

Figure 4. Matric suction changes during raising and lowering the water table level for Soil #1

4.4.2 *Soil #2 (Concrete sand)*

In Test 1, load dropped to 2.2 kN at the end of first cycle and to 1.7 kN after the sixth load application in compression. In tension this values are 3.1 kN and 1.9 kN for respective loading cycles (Fig.5). The continuously decreasing shaft capacities can be associated with repeated alteration in loading conditions. After four days, the pile was retested (i.e. Test 2). It was observed that the capacities of the pile in compression and in tension had decreased further. Finally, under submerged condition only the tensile capacities could be recorded due to the same reason as in Soil #1 (the cavity below the pile toe had collapsed when the water table was raised).

The matric suction values were measured in Soil # 2 before raising and lowering the groundwater level. The matric suction values were decreased at all three levels by adding water to the soil surface using a garden-sprinkler. The largest decrease was observed near the surface, changing from 10 kPa to 3 kPa almost immediately. The smallest change occurred at the lowest tensiometers with 6 hours delay from 18 kPa to 16.2 kPa (Fig. 6). The tensiometers readings increased again after ending the water application to the soil surface.

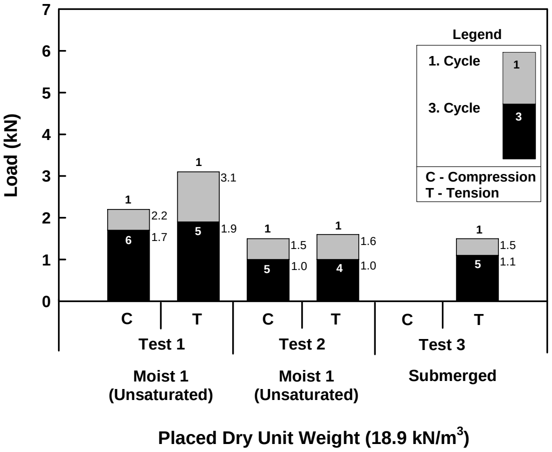

Figure 5. Summary of pile test results for Soil #2

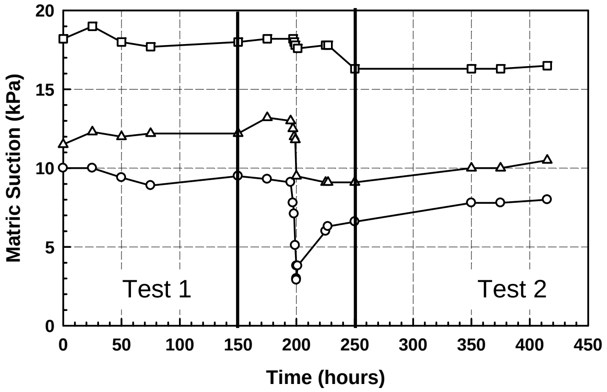

Figure 6. Variation of tensiometer readings in Soil #2 with time prior to, during and after water sprinkling

5 ESTIMATING THE SHAFT RESISTANCE

The shaft resistances of the tested piles were also calculated using Eq. 7. A value of $\beta = 0.35$ was chosen, which is an average value of various methods summarized in the literature (McClelland 1974, Meyerhof 1976, Briaud and Tucker 1997).

Matric suction values used in the calculations are obtained from the tensiometer readings for the related depths. The corresponding degree of saturation values were estimated from the SWCCs for the two soils (Fig. 7 and 8). The computed results (calculated and measured) are summarized in Table 2 and Table 3 for Soil #1 and Soil #2 respectively to provide comparisons.

Two key observations can be made from the summarized results. The first observation is related to the contribution of matric suction to the total shaft resistance and the second is related to the difference between the measured and calculated total shaft resistances.

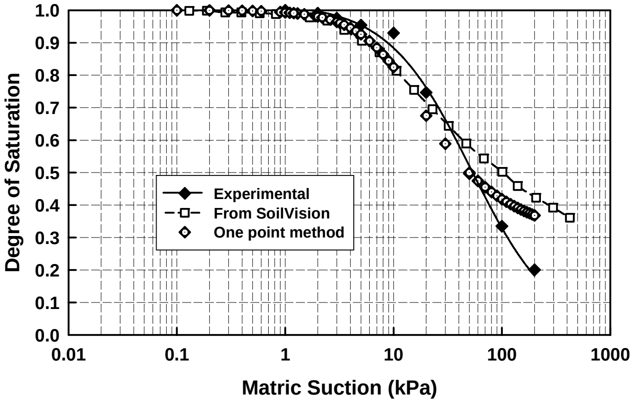

Figure 7. Measured and predicted soil-water characteristic curve for Soil # 1

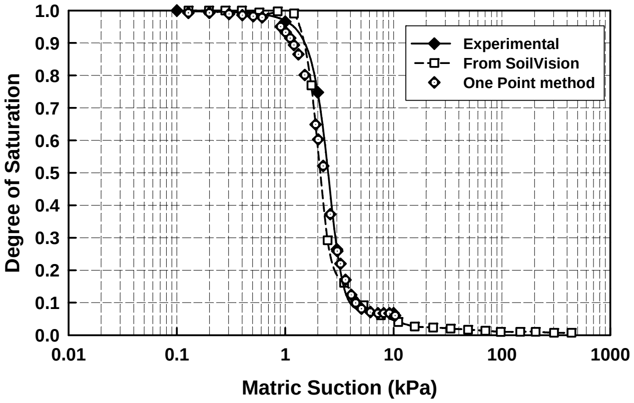

Figure 8. Measured and predicted soil-water characteristic curve for Soil #2

Table 2. Comparison between the measured and calculated shaft resistances for Soil #1 (β = 0.35)

Test #	Shaft Length Intervals	Matric Suction	Degree of Saturation (S)	Cal.		Meas.
				$Q_{(u_a-u_w)}$	$Q_{f(us)}$	$Q_{f(us)}$
	(m)	kPa	-	kN	kN	kN
T1	0.45 0.45 0.60	13.5 15.0 14.0	0.780 0.765 0.775	1.84	3.1	4.7
T2	0.45 0.45 0.60	1.50 1.00 0.90	0.985 0.999 0.999	0	0.74	0.9
T4	0.45 0.45 0.60	11.0 16.0 16.0	0.810 0.755 0.755	1.82	3.11	5.1

The total shaft resistance was found to be 35%-40% of the total shaft capacity in the Soil #1 which was silty in nature. However, contribution of matric suction to the total shaft resistance was almost negligible in Soil # 2 which was clean concrete sand.

Since the matric suction contribution is the same from both the measured and calculated values, it can be concluded that the difference between them can be attributed to the β values which are dependent on the stress condition of the soil. For this reason, β values were back calculated to understand the influence of unsaturated soil conditions.

Table 3. Comparison between the measured and calculated shaft resistances for Soil #2 (β = 0.35)

Test #	Shaft Length Intervals	Matric Suction	Degree of saturation (S)	Cal.		Meas.
				$Q_{(u_a-u_w)}$	$Q_{f(us)}$	$Q_{f(us)}$
	(m)	kPa		kN	kN	kN
T1	0.45 0.45 0.60	18.0 12.0 10.0	0.025 0.048 0.050	0.057	1.25	2.2
T2	0.45 0.45 0.60	16.5 10.0 8.00	0.030 0.050 0.060	0.055	1.24	1.5

5.1 *Back calculated β values*

The β values were back calculated from the measured shaft capacities for three different conditions (i) saturated condition Eq. (8); (ii) unsaturated condition (with matric suction) Eq. (9) and (iii) unsaturated condition without matric suction Eq. (10).

$$\beta = \frac{Q_f}{\left(\frac{\gamma' L}{2}\right)(\pi d L)} \tag{8}$$

$$\beta = \frac{Q_{f(us)} - Q_{(u_a-u_w)}}{\left(\frac{\gamma L}{2}\right)(\pi d L)} \tag{9}$$

$$\beta = \frac{Q_{f(us)}}{\left(\frac{\gamma L}{2}\right)(\pi d L)} \tag{10}$$

The back calculated values of β using Eq's. (8), (9) and (10) are summarized in Table 4 using first cycle loads for Soil #1 and Soil #2 for compression only. Appropriate effective unit weights values from Table 1 were used in the calculations. The back calculated β values (Table 4) for Soil #1 are approximately 35-40% lower if the influence of matric suction is ignored. For saturated condition in Soil #1, β value is much lower as it reflects the effect of looser soil conditions near the pile shaft after the collapse of soil in to the cavity below the pile tip.

Table 4 The back calculated β values from measured shaft capacities for Soil #1 and Soil #2 for compression

Soil Type	Test#	Meas. $Q_{f(us)}$	$Q_{(u_a - u_w)}$	Back calculated β values		
		kN	kN	Eq#8	Eq#9	Eq#10
#1	T1	4.7	1.84	-	0.8	1.30
	T4	5.1	1.82	-	0.9	1.41
	T2	0.9	0	0.43	-	-
#2	T1	2.2	0.057	-	0.66	0.64
	T2	1.5	0.055	-	0.44	0.43

In Soil # 2, which is clean sand with zero fine content, the back calculated β values were approximately the same for both saturated and unsaturated conditions.

6 SUMMARY

The shaft resistance of steel pipe test pile that was jacked hydraulically into two different sands was determined under saturated and unsaturated conditions in an instrumented geotechnical test pit. The objective of this study was to determine the contribution of matric suction towards the total shaft resistance of piles and propose a technique to estimate the shaft resistance in unsaturated soil conditions.

The contribution of matric suction was found to be between 35%-40% of the total shaft capacity of the test piles for silty sand but almost negligible for clean sands. Thus, it can be concluded that in unsaturated soils, with the exception of clean sands and granular soils, the contribution of matric suction to the total shaft capacity of piles cannot be neglected. In addition, a simple technique was proposed to estimate the shaft resistance in unsaturated soil conditions using the Soil-Water Characteristic Curve (SWCC) and the effective shear strength parameters conventional β-method.

The results of this study are promising to predict the contribution of matric suction towards shaft resistance using well established β-method for sandy soils in the literature. However, more pile load tests need to be performed and evaluated to better understand the contribution of matric suction towards the shaft capacity of piles in different types of sandy soils.

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