Estimation of the shaft capacity of model piles in a compacted fine-grained unsaturated soil

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ABSTRACT
The conventional shear strength parameters are used in the α, β and λ methods along with other empirical constants to estimate the shaft bearing capacity of single piles in saturated soils. In the present study, a series of single model pile tests were performed in a laboratory environment to study the influence of matric suction on the pile shaft resistance in a compacted fine-grained soil. The model piles were loaded to failure under both saturated and unsaturated conditions under different drainage conditions. The α method by Skempton (1959), β method by Burland (1973) and λ method by Vijayvergiya and Fotch (1972) are modified such that they can be used for estimating the total shaft resistance of piles in unsaturated soils by including the effect of matric suction. There is a good comparison between the measured and estimated values of shaft capacity of the model piles using the modified α, β and λ methods. The test results also show that there is a significant contribution from matric suction towards the shaft resistance of model piles.

RÉSUMÉ

Les paramètres conventionnels de la résistance au cisaillement sont utilisés dans les méthodes α β et λ en conjonction avec d'autres constantes empiriques afin d'estimer la capacité de fût de pieux individuels dans des sols saturés. Dans la présente étude, une série d'essais sur des modèles de pieux à échelle réduite sont effectués dans un cadre de laboratoire afin d'étudier l'influence de la succion matricielle sur la résistance de fût dans un sol compacté à grains fins. Les modèles de pieux ont été chargés jusqu'à la rupture tant dans des conditions saturées que non-saturées sous différentes conditions de drainage. La méthode α de Skempton (1959), β de Burland (1973) et λ de Vijayvergiya et Fotch (1972) sont modifiées de façon à pouvoir être utilisées pour estimer la résistance de fût totale de pieux dans des conditions non-saturées incluant l'effet de la succion matricielle. Les valeurs de capacité de fût mesurées et estimées présentent une bonne concordance pour les méthodes modifiées α, β et λ. Les résultats démontrent aussi que la succion contribue de manière significative à la résistance de fût des modèles de pieux.

1 INTRODUCTION

Several geotechnical structures such as highways, embankments, dams are constructed on or with compacted unsaturated soils in which shallow or deep foundations may be placed. It is also common to use pile foundations in natural fine- and coarse-grained soils where the ground water table is at a greater depth. The stresses associated both with the shallow and deep foundations for such scenarios are distributed within the unsaturated soil zone above the ground water table. Such scenarios are common in semi-arid and arid regions of the world where pile foundations are used for carrying heavy loads and limit the settlements. 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 deep foundations (Douthitt et al. 1998, Costa et al. 2003, Georgiadis et al. 2003, Vanapalli et al. 2010). Typically, pile foundations are designed assuming saturated, dry or submerged conditions. To the best of the knowledge of the authors, there are no laboratory or field studies reported in the literature that discuss the shaft resistance of piles either in coarse- or in fine-grained soils taking account of the contribution of capillary stresses or matric suction.

In this paper, the α method by Skempton (1959), β method by Burland (1973) and λ method by Vijayvergiya and Fotch (1972) are modified such that they can also be used for estimating the total shaft resistance of piles in unsaturated soils including the effect of matric suction. To check the validity of these methods, a series of single model pile tests were performed in a laboratory environment to study the influence of matric suction on pile shaft resistance placed in statically compacted unsaturated glacial till from Indian Head, Saskatchewan, Canada with various saturation degrees. The results of these studies were interpreted using the modified α, β and λ methods. Comparisons are provided between the measured and estimated capacity of the single model pile using the modified α, β and λ methods. There is a reasonably good comparison between the measured and estimated results of the total shaft capacity showing that the proposed methods are promising and can be used in the design of pile foundations placed in fine-grained unsaturated soils.

The modified α, β and λ methods are consistent with the well known principles that are conventionally used in the design of piles in geotechnical engineering practice. These methods are presented in a functional form such that they can be used for predicting the variation of shaft capacity with respect to matric suction using the saturated soil properties and the Soil-Water Characteristic Curve (SWCC). The proposed modified equations take the conventional form of the α, β and λ methods used for saturated soils when the matric suction value is set to zero.

2 MODIFIED METHODS FOR ESTIMATING THE LOAD CARRYING CAPACITY OF SINGLE PILES IN UNSATURATED FINE-GRAINED SOILS

2.1 Modified α Method

The α method (Skempton 1959) used for estimating the carrying capacity of single piles in saturated fine-grained soils under undrained loading conditions is modified such that it can be used for unsaturated fine-grained soils taking account of the influence of matric suction. The modified α method is proposed in a functional form such that it can be used to predict the variation of load carrying capacity of the model pile with respect to matric suction under undrained loading conditions.

Similar to the approach used for saturated soils, the ultimate shaft capacity of a pile is related to the undrained shear strength, c_u by introducing a dimensionless parameter which is the adhesion factor, α. In other words, the α method is based on the total stress approach (TSA). Oh and Vanapalli and (2009) recently have provided a framework to predict the variation of undrained shear strength, c_u of unsaturated fine-grained soils with respect to matric suction using the saturated undrained shear strength and the Soil-Water Characteristic Curve (SWCC). This equation is used as a tool along with the conventional α method as shown in Eq. [1] to predict the variation of $Q_{f(us)}$ with respect to matric suction. When the matric suction component is set to zero (i.e., saturated condition), the model takes the form of the conventional α method.

$$Q_{f(us)} = \alpha c_{u(sat)}\left[1+\frac{(u_a-u_w)}{(P_a/101.3)}S^{\upsilon}/\mu\right]\pi dL = \alpha c_{u(unsat)}\pi dL \qquad [1]$$

where, $Q_{f(us)}$ = ultimate shaft bearing capacity of a pile for unsaturated condition, α = adhesion factor, $c_{u(sat)}$, $c_{u(unsat)}$ = undrained shear strength under saturated and unsaturated conditions, respectively, P_a = atmospheric pressure (i.e. 101.3 kPa), $(u_a - u_w) = \psi$ =matric suction, S = degree of saturation and ν, μ = fitting parameters.

The undrained strength, c_u of soil specimens under unsaturated conditions can either be measured by conventional unconfined compression tests or can be estimated by using the model presented by Oh and Vanapalli (2009) once the matric suction value of the fine-grained soils is known.

The α.value for both saturated and unsaturated conditions can be determined using the adhesion factor versus undrained shear strength correlation charts proposed by researchers (i.e., Sowers and Sowers (1970), American Petroleum Institute (1974)). More details related to this relationship for unsaturated soils are discussed in Vanapalli and Taylan (2011a).

2.2 Modified β Method

The contribution of matric suction, $Q_{(ua-uw)}$ towards the ultimate shaft capacity of a single pile in unsaturated coarse-grained soils can be expressed as based on the model proposed by Vanapalli et al. (1996) and Fredlund et al. (1996) (Eq. [2]) for predicting the shear strength variation with respect to matric suction for unsaturated soils under drained loading conditions.

$$Q_{(u_a-u_w)} = \tau_{us} A_s = \left[(u_a-u_w)(S^{\kappa})(\tan\delta')\right]\pi dL \qquad [2]$$

where, κ = fitting parameter used for shear strength which is a function of plasticity index, I_p given in Vanapalli et al. (2010) and S = degree of saturation, ϕ' = effective friction angle, $(u_a - u_w)$ or ψ =matric suction, $(\sigma_n - u_a)$ = net normal stress.

A modified expression for estimating the ultimate shaft capacity of piles in unsaturated soils, $Q_{f(us)}$ can be obtained by combining conventional β method (Burland 1973) (i.e., shaft capacity for saturated condition) and Eq. [2] (contribution of matric suction) as given below:

$$Q_{f(us)} = Q_{f(sat)} + Q_{f(u_a-u_w)} = \left[\beta\sigma'_z + (u_a-u_w)(S^{\kappa})(\tan\delta')\right]\pi dL \qquad [3]$$

The modified β method (Eq. [3]) can be used for estimating the ultimate shaft capacity of a single pile taking into account of the contribution of matric suction. This equation will be the same as the conventional β method when matric suction value is set to zero.

Eq. [3] can also be used for estimating the ultimate shaft capacity of a single pile in unsaturated fine-grained soils for drained loading conditions. However, in unsaturated fine-grained soils, there will be some contribution of adhesion, c_a' towards the shaft bearing capacity. Therefore, a different form of relationship is suggested to estimate the ultimate shaft capacity of piles which is given below:

$$Q_{f(us)} = \left[\varepsilon c'_a + \beta\,\sigma'_z + (u_a-u_w)(S^{\kappa})(\tan\delta')\right]\pi dL \qquad [4]$$

where, c_a' = adhesion component of cohesion, ε = reduction parameter, δ' = internal friction angle between pile and soil, $\beta = K_o \tan\delta'$, where $K_o = (1-\sin\delta')$ which is the mean lateral earth coefficient at rest. A reduction parameter, ε is suggested because the total adhesion, c_a' may not be fully contributing towards the shaft capacity of the pile.

2.3 Modified λ Method

The conventional λ method combines the total (i.e., undrained) and effective (i.e., drained) stress approaches for calculating the shaft capacity of piles driven into clayey type fine-grained soils (Vijayvergiya and Fotch 1972). This technique is useful in reducing the sensitivity of the shear strength parameters measured using the total and effective stress analysis. The total shaft capacity is calculated using the equation below.

$$Q_f = \lambda \left(\sigma'_{v(avg)} + 2c_u \right) \pi dL \qquad [5]$$

where, $\sigma'_{v(avg)}$ = the mean effective stress, c_u = undrained shear strength along the pile length, λ = frictional capacity coefficient which is a function of entire embedded depth of pile.

The λ value varies from 0.12 to 0.5 for pile penetration of 0 to 70 m for the 42 piles load test data gathered and presented by Vijayvergiya and Fotch (1972) (Figure 1). The λ method was modified to propose Eq. [6] to include the influence of matric suction effect in the estimation of shaft resistance of piles in unsaturated soils.

$$Q_{f(us)} = \lambda \left[\sigma'_{v(avg)} + 2c_{u(sat)} \left(1 + \frac{(u_a - u_w)}{(P_a / 101.3)} S^{\upsilon} / \mu \right) \right] \pi dL \qquad [6]$$

The form of this equation will be same as the conventional λ method once the matric suction, $(u_a - u_w)$ component is set to zero. Eq. [6] can also be used to predict the variation of total shaft resistance of pile, $Q_{f(us)}$ with respect to matric suction. The required information using this equation are the undrained shear strength under saturated condition, $c_{u(sat)}$ and the SWCC.

3 TESTING PROGRAM

3.1 Soil properties

The soil chosen for the study is a glacial till obtained from Indian Head, Saskatchewan, Canada. The glacial till collected from the field was air-dried for several days and subjected to gentle pulverization and was passed through a sieve with an opening size of 2 mm (i.e., #10 sieve). The dry soil after reaching the room temperature in the laboratory was mixed with distilled water to achieve the desired initial water contents. The prepared soil-water mixture was placed in sealed double plastic bags stored in a humidity controlled box for at least 3 days to ensure uniform moisture content conditions throughout the sample.

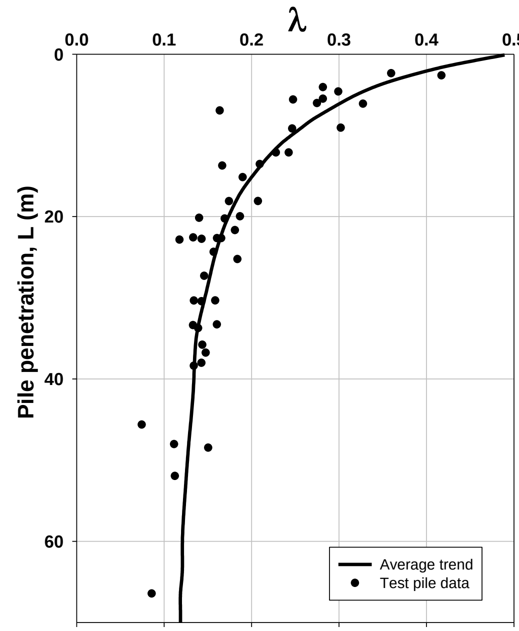

Figure 1. Frictional capacity coefficient, λ vs. pile penetration (modified after Vijayvergiya and Fotch, 1972).

Table 1. Properties of the soil used in the test program

Soil Properties	Value
Optimum water content (%)	18.6
Maximum dry unit weight, (kN/m^3)	16.7
Saturated unit weight, (kN/m^3)	18.5
Specific gravity, G_s	2.70
Sand (%)	28.0
Silt (%)	42.0
Clay (%)	30.0
Liquid limit, w_L	36.2
Plastic limit, w_L	15.0
Plasticity index, I_p	21.2

The compaction characteristics of the tested soil were determined using static compaction energy of 350 kPa. The compaction curve was obtained by preparing statically compacted individual soil specimens at different water contents and densities. A total of ten different specimens (i.e., 50 mm diameter and 20 mm height) were prepared and compacted in the specimen rings with different water contents. Figure 2 shows the compaction curve and Table 1 summarizes the soil properties.

3.2 Equipment and methodology

The shaft bearing capacity of model piles were proposed to be determined at three different water contents of 13% (dry of optimum), 16% (dry of optimum) and 18% (close of optimum) (see Figure 2). The key objective of the present research program was to determine the influence of matric suction on the total shaft capacity of model piles under drained and undrained loading conditions for saturated and unsaturated compacted soils in a specially designed test tank using the modified α, β and λ methods. The dimensions of the tank used in the study are 300 mm in diameter and 300 mm in height. The soil was compacted statically with 350 kPa stress into the test tank using a specially designed compaction base plate. This was achieved using conventional triaxial equipment loading frame.

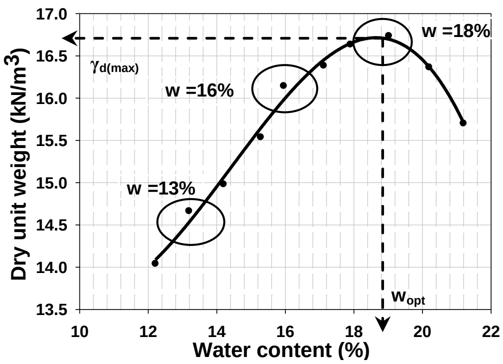

Figure 2. Compaction curve for the Indian Head till.

Solid stainless steel model piles with outer diameters equal to 20, 30 and 45 mm and inner diameters respectively of 18.8, 28, and 44.5 mm with a total length of 450 mm were used in the present study. The model piles were loaded to failure within the test tank filled with statically compacted test soil to determine the shaft capacity. The equipments used in the study are shown in Figure 3a and 3b.

The prepared soil for the chosen initial water content was then statically compacted in five layers. The loading was controlled by a calibrated loading ring. Before a next soil layer was placed, the compacted layer was scarified to achieve uniform to density conditions over the entire depth of the soil in the test tank.

The cylindrical hole was useful to avoid the generation of excessive stresses adjacent to soil while driving the pile (Figure 4). After the borehole drilling was completed, model pile was jacked down to a depth of 200 mm leaving a 20 mm of gap. In other words, the void facilitates in the measurement of shaft resistance over a length of 20 mm without any contribution from the end bearing resistance. The experimental studies have shown that the peak load occurs much before the 20 mm penetration of the pile. More details are discussed later in the paper.

Figure 5 presents the testing program as a flow chart. The model piles were loaded in saturated compacted soils in the present study both under drained and undrained loading conditions. The compacted soil was saturated by gradually allowing downward flow of water from top of the soil through the 9.8 mm thick compaction base plate which had apertures (see Fig. 3a).

The compactor plate was placed on top of the compacted soil sample and fixed to the loading frame in order to avoid possible volume change due to swelling.

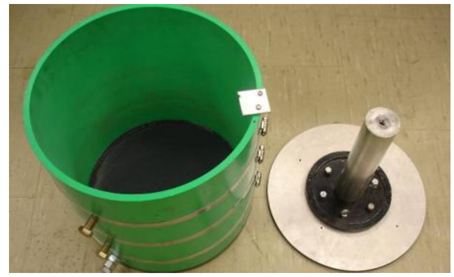

Figure 3a. Testing tank and the compaction base plate.

Figure 3b. Model piles and thin-wall tubes.

Figure 4. Driving a hole in the compacted soil using thin-wall steel tube for installing the model pile.

A piezometer was used attached to the side of the tank to check the saturation conditions of the soil. The compacted soil can be assumed to be saturated when the level of water in the piezometer reached the same water level within the test tank. The degree of saturation was also verified by measuring matric suction with a tensiometer that was placed in the compacted soil. The tensiometer reading of $(u_a - u_w) = 0$ kPa provided another indication that the compacted soil is saturated. The degree of saturation values were also close to 100% from mass-volume relationships assuring that the soil sample tested was in a state of saturated condition. The unsaturated soil samples compacted with different water contents were directly tested.

The load and displacement were measured by a load cell and a LVDT were recorded simultaneously using a Data Acquisition System. The conventional shear strength tests (i.e. interface direct shear test and unconfined compression tests) were also conducted on specimens collected from the compacted soil outside the loading zone of the pile.

The model piles were tested under drained and undrained loading conditions using a strain rate equal to 0.0120 mm/min and 1 mm/min respectively for both saturated and unsaturated conditions. The strain rates were so chosen to ensure that the drainage conditions that was proposed to be tested.

The tank was wrapped with plastic covers while conducting the tests, to avoid evaporation such that the proposed initial matric suction condition for testing does not change. This precaution is necessary particularly for drained load tests (i.e., slow test) as it takes 10 hours for conducting these tests.

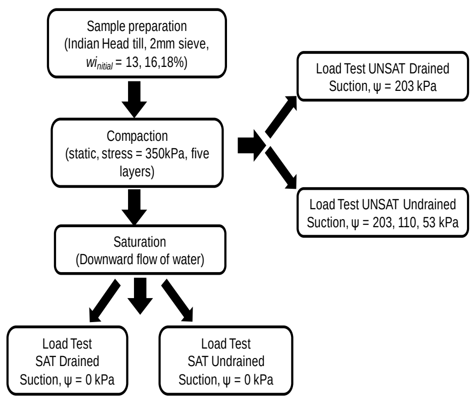

Figure 5. Flow chart of the testing program.

4 SUCTION MEASUREMENTS

The physical properties of the compacted soil for different water contents and the matric suction values measured using the axis translation technique (Hilf, 1956) with a modified null pressure plate are summarized in Table 2.

The pressure plate apparatus was used for measuring the SWCCs following the drying path. The measured SWCCs of the specimens prepared with an initial water content of 13%, 16% and 18% are presented in Figure 6. More details of the matric suction measurements using both the modified null pressure plate and the SWCC using pressure plate are discussed in Vanapalli and Taylan (2011b).

5 MODEL PILE TESTS

The model pile test results conducted on both saturated and unsaturated soil samples are presented in Figure 7 through Figure 10. The different initial compaction water content (i.e., 13%, 16%, 18%) under both saturated and unsaturated conditions have significant influence on the model pile capacity.

The typical mode of failure for unsaturated-drained and undrained tests is shown in Figure 7. The mobilized soil pile adhesion shows both the peak (t_{max}) and residual values (t_{res}) is consistent with the results on other fine-grained clays in the literature.

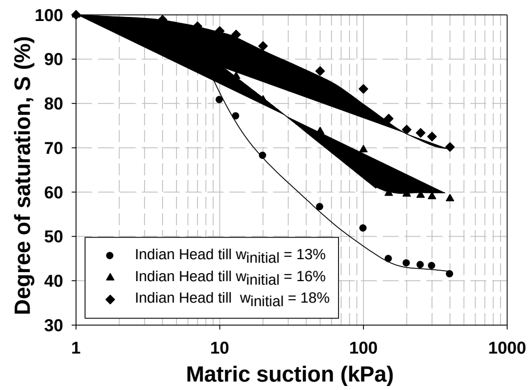

Figure 6. Measured Soil-Water Characteristic Curves for three different water contents.

Table 2. Summary of the soil properties and matric suction values of the compacted soils tested.

Test Cond.	ψ	γ	γ_d	e	w	S	v
	kPa	kN/m^3	kN/m^3	-	%	%	mm/sec
US-UD1	203	16	14.3	0.85	13	43	1.14
US-D	203	16	14.3	0.85	13	43	0.01
S-UD	0	16	14.3	0.85	31	96	1.14
S-D	0	16	14.3	0.85	31	96	0.01
US-UD2	110	18.6	16.2	0.64	16	65	1.14
US-UD3	53	19.2	16.4	0.61	18	76	0.01

where, ψ = matric suction, γ = total unit weight,
γ_d = dry unit weight, e = void ratio, w = water content,
S = degree of saturation, v = loading rate,
US/S = Unsaturated/Saturated soil sample,
D/UD= Drained/Undrained loading conditions.

The residual adhesion ratio which is defined as t_{res}/t_{max}, is typically between 0.7 to 0.9 for clays (API Recommended Practice 2000). The t_{res}/t_{max} values vary from 0.75 to 0.9 from the tests performed on saturated and unsaturated samples in the present study. Samples tested with higher water contents (i.e., some saturated samples tested) however did not fall in this group. This behavior may be attributed to the disturbance occurred while loading piles in compacted soils with higher water contents.

The load versus deflection data show that the peak load is achieved typically between 0.2 to 0.3 mm of pile penetration which corresponds to 1% of the pile diameter (i.e., 20-30 mm). These results are consistent with the failure criteria which is defined as the ultimate shaft capacity by the ratio of Z/d = 0.01 where Z (mm) is the local pile deflection and d (mm) is the pile diameter in API 2000.

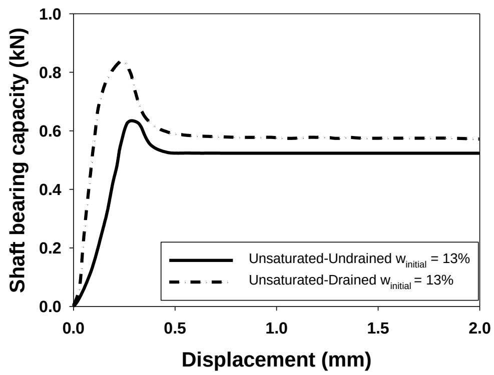

Figure 7. Model pile test results in an unsaturated soil compacted at an initial water content of 13% under drained and undrained loading conditions.

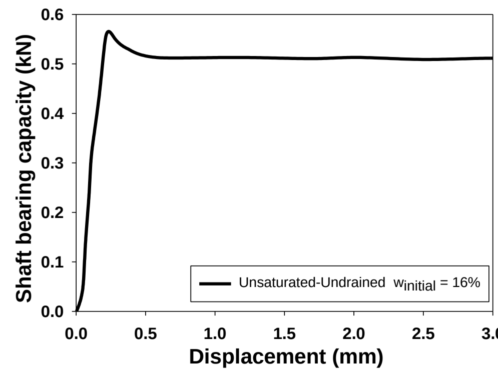

Figure 9. Model pile test results in an unsaturated soil compacted at an initial water content of 16% under undrained loading conditions.

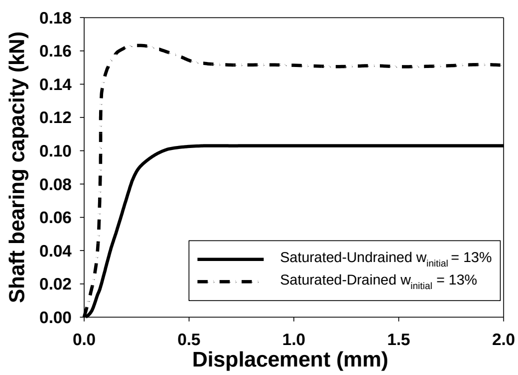

Figure 8. Model pile test results in a saturated soil compacted at an initial water content of 13% under drained and undrained loading conditions.

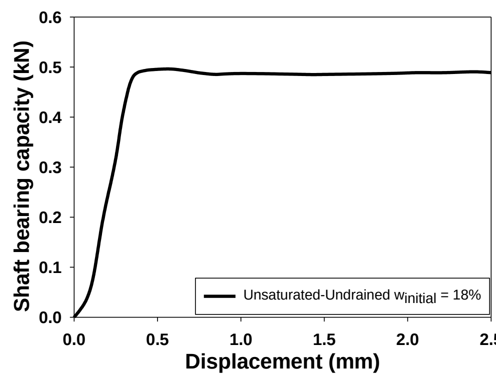

Figure 10. Model pile test results in an unsaturated soil compacted at an initial water content of 18% under undrained loading conditions.

(a) (b)

Figure 11. (a) Collection of soil samples using thin-wall tubes. (b) Extracted soil sample used for unconfined compression tests.

6 RESULTS AND ANALYSIS

The measured shaft bearing capacity test data of 20 mm diameter (D20) model pile were interpreted using the modified α, β and λ methods presented in the paper. In addition, comparisons are provided between the measured and estimated shaft bearing capacity values.

6.1 Interpretation of results using the modified α method

The ultimate shaft bearing capacity of tested model piles for undrained loading conditions on both saturated and unsaturated samples were estimated from the unconfined compression test results by using the modified α method. The unconfined compression tests were conducted on specimens prepared at different initial water contents.

After the model pile tests were completed, specimens were collected from the compacted soil using stainless steel thin-wall tubes 50 mm in diameter and 100 mm in height (Figure 11). Figure 12 summarizes the test results of the unconfined compression tests.

Several investigators provided relationships between the adhesion factor, α and the undrained shear strength, c_u values as discussed in earlier sections. Table 3 shows the comparison between the measured ultimate shaft capacity values and those estimated using the modified α method for the model pile, D20 that was tested in a compacted soil samples prepared with different initial water contents. The adhesion factor, α values were chosen for saturated and unsaturated conditions based on undrained strength values from Sowers and Sowers (1970). More details are available in Vanapalli and Taylan (2011a).

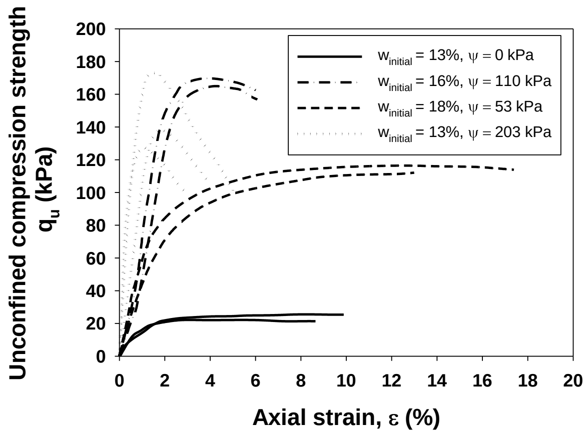

Figure 12. Unconfined compression test results.

The adhesion factor, α values were also back calculated from the model pile test results conducted on compacted soils with different initial water contents (i.e., w=13%, 16% and 18%) and summarized in Table 3. The shaft capacity was estimated using fitting parameters ν and μ in Eq. [1] which are equal to 2 and 9 respectively for the Indian Head till studied.

Table 3. Comparison between the measured and estimated ultimate shaft capacities using the α method.

W	ψ	c_u[1]	α[2]	Back Cal. α value	Cal[3]. $Q_{f(us)}$	Meas. $Q_{f(us)}$
(%)	kPa	kPa	-	-	kN	kN
13	0	11.5	0.90	0.70	0.13	0.10
18	53	58	0.82	0.68	0.59	0.50
13	203	68	0.75	0.79	0.64	0.68
16	110	80	0.67	0.55	0.67	0.55

[1] Undrained shear strength from unconfined compression tests.
[2] α value obtained from Sowers and Sowers (1970).
[3] Calculated shaft bearing capacity using Equation 1

6.2 Interpretation of the results using the modified β method

The model pile test results for fine-grained soils under drained loading conditions for compacted Indian Head till were interpreted using the conventional β method for saturated soils and the modified β method (Eq. [4]) for the unsaturated soils.

The adhesion component of cohesive strength, c_a', and the internal friction angle, δ', between the soil and the pile material was measured by conducting interface direct shear tests for both saturated and unsaturated soil specimens under drained loading conditions (Table 4). The shearing rate used for direct shear tests was the same as the rate of loading the model piles (i.e., 0.0120 mm/min).

Table 4. Comparison between the measured and estimated ultimate shaft capacities using the β methods.

Test Condition	β	Ψ	δ'	c'_a	Cal. $Q_{f(us)}$	Meas. $Q_{f (us)}$
	-	kPa	°	kPa	kN	kN
S-D	0.3	0	27	20	0.11	0.16
US-D	0.3	203	30	102	0.73	0.80

*S: Saturated, US: Unsaturated, UD: Undrained, D: Drained;
Ψ = matric suction

The fitting parameter κ in Eq. [4] is equal to 2.4 for the soil studied in the present research with a plasticity index, I_p of 21.2 (Vanapalli and Fredlund, 2000). The β value was calculated for the soil-pile interface friction angle, δ' using Eq. [4] (see Table 1), which is equal to 0.3. Burland (1973) reported similar values for soft clays. Since the internal friction angle, δ' did not vary much with respect to matric suction, the β coefficient value of 0.3 was used for both saturated and unsaturated conditions and the reduction factor, ε is chosen as 0.4.

6.3 Interpretation of results using the modified λ method

The λ value is a function of pile length which can be determined from Figure 1 for estimating the load capacity of piles in-situ. The data of Vijayvergiya and Fotch (1972) is revisited and plotted differently as a relationship between the λ and the ratio of pile diameter, d to pile penetration depth, L (Fig. 13). A best-fit linear curve is plotted through the data which exhibits some scatter. This relationship is useful for interpreting model pile results compared to the relationship shown in Figure 1. The λ value for interpreting the model pile, D20 results is equal to 0.32 for the d/L ratio of 0.1. The shaft capacity of the model pile is estimated using Eq. [6]. The comparison between the measured shaft capacity of the model pile and the estimated values were summarized in Table 5. The results are encouraging as there is a reasonably good comparison.

Table 5. Comparison between the measured and estimated ultimate shaft capacities by using the λ method

w	Ψ	Meas. c_u	λ	Cal. $Q_{f(s),(us)}$	Meas. $Q_{f(s),(us)}$
(%)	kPa	kPa	-	kN	kN
13	0	11.5	0.32	0.09	0.10
18	53	58	0.32	0.47	0.50
13	203	68	0.32	0.55	0.68
16	110	80	0.32	0.64	0.55

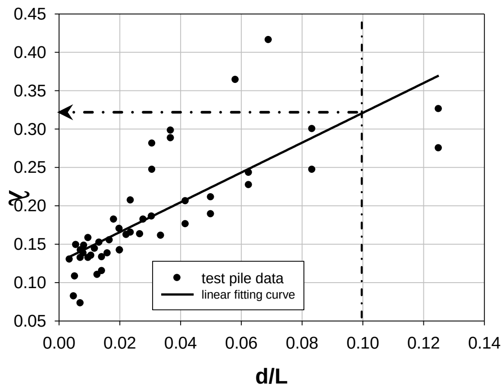

Figure 13. Relationship between the variation of λ coefficient and the ratio between pile diameter, d to pile penetration, L using the data from Vijayvergiya and Fotch, (1972).

7 SUMMARY

Model pile load tests were conducted to determine the ultimate shaft bearing capacity of single piles in statically compacted Indian Head till in the laboratory on saturated and unsaturated soil samples under drained and undrained loading conditions. The test results were interpreted using the modified α, β and λ methods presented in this paper for unsaturated soils. The approach presented for interpreting the data is similar to the conventional α, β and λ methods. The modified methods revert to the same form as the conventional α, β and λ methods if the matric suction, $(u_a - u_w)$ value is set to zero. There is a good comparison between the measured and estimated values of shaft capacity of model piles under both the drained and undrained loading conditions using the modified α, β and λ methods.

The total shaft resistance of piles in unsaturated conditions is significantly higher in comparison to saturated conditions for both drained and undrained loading conditions. The data suggests that ignoring the influence of matric suction is conservative. The present study shows that the proposed methods and models are of considerable promise. More studies are necessary to check the validity of the proposed methods on different fine-grained soils both in the laboratory and in the field with respect to the proposed modified α, β and λ methods.

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