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Design of Single Piles Using the Mechanics of Unsaturated Soils

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ABSTRACT The load carrying capacity of single piles are commonly estimated using the well known α [1], β [2-3] and λ [4] methods. These methods are also used in engineering practice for unsaturated soils even though the α, β and λ methods are based on conventional saturated soil mechanics. In this study, a series of single model pile tests were conducted in a laboratory environment to study the influence of matric suction on the pile shaft capacity in a statically compacted fine-grained soil. The results of the study show that the shaft capacity of single piles is significantly influenced by the contribution of matric suction. Based on the experimental results, the conventional α, β and λ methods were modified to estimate the total shaft resistance of piles in unsaturated soils by including the influence of matric suction. The modified methods can also be used for estimating the variation of shaft capacity of single piles with respect to matric suction using the Soil-Water Characteristic Curve (*SWCC*) and the saturated soil shear strength parameters. The modified α, β and λ methods are promising for use in engineering practice to estimate the ultimate shaft bearing capacity of single piles placed in unsaturated soils.

Keywords: Unsaturated soils, pile design, modified α, β and λ methods, *SWCC*, matric suction

1. INTRODUCTION

In geotechnical engineering practice, conventional soil mechanics principles are used for the design of pile foundations assuming the soil is in a state of saturated condition [5], [6]. However, in many situations, natural soils are found in a state of unsaturated condition as the ground water table is at a great depth. This is particularly true for soils in arid and semi-arid regions. Several geotechnical structures such as highways, embankments, dams are constructed on or with compacted unsaturated soils in which pile foundations may be placed. The stresses associated with these foundations are distributed within the unsaturated soil zone above the ground water table.

Several recent studies on shallow foundations [7]-[10] have shown that the bearing capacities of both coarse and fine-grained soils are significantly influenced due to the contribution of matric suction. However, limited numbers of studies are reported in the literature [11]-[14] that consider the influence of matric suction or capillary stresses on the load carrying capacity of pile foundations. Typically, pile foundations are designed assuming saturated, dry or submerged soil conditions.

In this paper, the α method by Skempton [1], β method by Chandler and Burland [2], [3] and λ method by Vijayvergiya and Focht [4] are modified such that they can be used for estimating the ultimate shaft resistance of piles in unsaturated soils. The modified α, β and λ methods are similar to the conventional techniques 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 estimating the variation of the shaft capacity of the single piles 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.

A series of single model pile tests placed in statically compacted unsaturated glacial till with various degrees of saturation were performed in a laboratory environment to study the influence of matric suction on the shaft resistance. The results of these experimental studies were interpreted using the modified α, β and λ methods. Reasonably good comparisons were observed between the measured ultimate shaft capacity of the single model piles and those estimated using the proposed methods (i.e., modified α, β and λ methods).

2. BACKGROUND

The reliable determination of soil-structure interaction parameters requires cumbersome laboratory or field tests. Alleviating the need of such cumbersome tests; empirical methods are proposed to estimate the skin friction, f_s based on the conventional shear strength parameters and the information related to the variation of effective stresses along the length of the piles.

$$f_s = f\left(\sigma'_v, \phi', c_u\right) \quad (1)$$

where, σ'_v = vertical effective stress, ϕ'= effective friction angle, and c_u = undrained shear strength.

The functional form of (1) suggests that the skin friction, f_s can be analyzed in terms of either total or effective stress approach considering the loading and drainage conditions (i.e., *TSA* or *ESA*), respectively.

Experimental programs were planned to determine the contribution of matric suction on the shaft resistance and not the end bearing resistance. In other words, the contribution of end bearing capacity is not measured in the present study.

2.1 The β Method (*ESA*)

In both coarse and fine-grained soils, the skin friction, f_s mobilized along the length of the pile is a key parameter that is required in the estimation of the load bearing capacity of pile foundations. If a pile is loaded at a relatively slow rate (i.e., to achieve drained conditions) the skin friction resistance can be estimated using (2) [2].

$$f_s = c' + K_0 \sigma_v' \tan\phi' \tag{2}$$

where, K_0 = mean lateral earth coefficient at rest, c' and ϕ' = effective cohesion and internal friction angle of soil, respectively, and σ'_v = vertical effective stress along the pile length.
The shear strength of soils associated with cohesion decreases significantly due to the remolding and softening effects during pile installation. This leads to an assumption that effective cohesion can be neglected along the pile shaft, particularly in coarse-grained soils and other soils with low percentage of fines such as silty sands and normally consolidated clays. Hence, (2) can be incorporated in (3) with the introduction of a coefficient, β [2], [3], [15].

$$Q_f = f_s A_s = \beta \sigma_v' \pi d\, L \tag{3}$$

where, β = Burland-Bjerrum coefficient is a coefficient which is equal to $K_o \tan \delta'$, δ'= effective angle of friction along the soil/pile interface, A_s = surface area of the pile, σ'_v = vertical effective stress at the mid of the pile shaft, L = length of pile, and d = diameter of pile.
The coefficient, β values typically vary from 0.30 to 0.60 for fine and coarse-grained soils [2], [3].

2.2 The α Method - (*TSA*)

Undrained loading conditions can be assumed when a pile is loaded at a relatively fast rate in saturated fine-grained soils. The ultimate shaft resistance can be estimated for such loading conditions extending the *TSA*. In other words, the ultimate shaft capacity of a pile, Q_f is dependent on the undrained shear strength, c_u of the soil. Hence, the unit skin resistance, f_s can be expressed as (4) using undrained shear strength, c_u.

$$f_s = \alpha c_u \tag{4}$$

where, α = adhesion factor between soil and pile.
There is a large data base of in-situ pile load tests including bored and driven piles supporting this method dating back to 1950s. This method is commonly referred in the literature as the α method. The studies show that adhesion factor, α is not constant but decreases with increasing undrained shear strength, c_u of the soil and varies from close to unity for low strength soft clays and reach almost to a value of 0.4 for stiff clays for c_u values greater than150 kPa [16], [1]. The ultimate shaft capacity, Q_f for cylindrical piles using the α method can be estimated as (5).

$$Q_f = f_s \times A_s = \alpha c_u \pi d\, L \tag{5}$$

where, d = pile diameter, and L = length of pile.
The adhesion factor, α can be computed from correlation charts published in literature by several researchers [16]-[24] which are given as a relationship between the adhesion factor and the undrained shear strength. Alternatively, (6) can also be used for estimating the α value [25].

$$\begin{aligned} \alpha &= 0.5\psi^{-0.5} \quad \text{if } \psi \le 1 \\ \alpha &= 0.5\psi^{-0.25} \quad \text{if } \psi > 1 \end{aligned} \tag{6}$$

where $\psi = c_u/\sigma'_v$ and σ'_v = vertical effective stress [17].

2.3 The 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 fine-grained soils [4]. This technique is useful in reducing the sensitivity of the shear strength parameters measured using the *TSA* and *ESA*. The total shaft capacity is calculated using the relationship shown in (7).

$$Q_f = \lambda\left(\sigma_v' + 2c_u\right)\pi dL \tag{7}$$

where, σ'_v = 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 coefficient λ varies from 0.12 to 0.5 for pile penetration of 0 to 70 m based on the 42 piles load test data gathered and presented by [4].

3 ESTIMATION OF THE ULTIMATE SHAFT CAPACITY (*USC*) OF PILES IN UNSATURATED SOILS

3.1 Modified β Method

Researchers ([26], [27]) proposed a model (8) to predict the variation of shear strength with respect to matric suction using the *SWCC* and the effective shear strength parameters (i.e., c' and ϕ') as given below.

$$\tau = \left[c' + (\sigma_n - u_a)\tan\phi'\right] + \left[\left(u_a - u_w\right)(S^{\kappa})(\tan\phi')\right] \tag{8}$$

where, c' = effective cohesion, $(\sigma_n - u_a)$ = net normal stress, ϕ' = effective internal friction angle, $(u_a - u_w)$ = matric suction S = degree of saturation, κ = fitting parameter used for shear strength.
The contribution of matric suction towards the shear strength, τ_{us} can be expressed as (9) which is the second part of (8).

$$\tau_{us} = \left[\left(u_a - u_w\right)(S^{\kappa})(\tan\phi')\right] \tag{9}$$

The contribution of matric suction, towards the ultimate shaft capacity of a single pile, $Q_{(ua-uw)}$ can be estimated using (10) as given below.

$$Q_{(u_a-u_w)} = \tau_{us} A_s = \left[(u_a - u_w)(S^{\kappa})(\tan\delta') \right] \pi d L \qquad (10)$$

Equation (10) suggests that the variation of ultimate shaft capacity with respect to matric suction can be estimated using the *SWCC* and effective interface friction angle, δ'.
A general expression for estimating the ultimate shaft capacity of piles in unsaturated soils, $Q_{f(us)}$ can be obtained by combining (3) and (10) as given below in a more generalized form:

$$\begin{aligned} Q_{f(us)} &= Q_{f(sat)} + Q_{f(u_a-u_w)} \\ &= \left[\beta\sigma'_v + \left\{ (u_a - u_w)(S^{\kappa})(\tan\delta') \right\} \right] \pi d L \end{aligned} \qquad (11a)$$

The relationship between the fitting parameter, κ and plasticity index, I_p for predicting the shear strength of unsaturated soils [28] can be used for estimating the ultimate shaft capacity of the pile. The fitting parameter, $\kappa = 2$ is used for the soil tested in the present study. More details of this method are available in [14]. Equation (11a) shows that there is a smooth transition between the ultimate shaft capacity of a single pile from an unsaturated to saturated condition. This relationship will be the same as (3) when matric suction is equal to zero (i.e., for saturated soils).
The contribution of cohesion component associated with the adhesion, c_a' under drained loading condition may not be negligible for evaluating the pile capacity of fine-grained (i.e. over-consolidated) soils for the β method (see (11b). In other words, there will be some contribution of adhesion, c_a' towards the ultimate shaft capacity which will be mobilized with time after the installation of the pile. Therefore, the ultimate shaft capacity of piles in unsaturated fine-grained soils under drained loading conditions can be estimated by modifying (11a) as given below.

$$Q_{f(us)} = \left[c'_a + \beta(\sigma'_z) + (u_a - u_w)(S^{\kappa})(\tan\delta') \right] \pi d L \qquad (11b)$$

where, c_a' = adhesion component of cohesion for saturated condition, δ'= effective angle of interface along the soil/pile.

3.2 Modified α Method

Several investigators related the load bearing capacity of a single pile to the undrained shear strength, c_u of the fine-grained soils ([16]-[24]). In the present study, the conventional α method is modified such that it can be extended for interpreting the results of model piles tested under unsaturated soil condition. In addition, a model is proposed for estimating the variation of ultimate shaft capacity of model piles with respect to matric suction.
Equation (12) [9] can be used to estimate the variation of undrained shear strength with respect to matric suction using the *SWCC* and undrained shear strength for saturated condition, $c_{u(sat)}$.

$$c_{u(unsat)} = c_{u(sat)} \left[1 + \frac{(u_a - u_w)}{(P_a/101.3)} (S^{\upsilon}) / \mu \right] \qquad (12)$$

where, $c_{u(sat)}$, and $c_{u(unsat)}$ = undrained shear strength under saturated and unsaturated conditions, respectively, P_a = atmospheric pressure (i.e. 101.3 kPa), and ν, and μ = fitting parameters.
The fitting parameter ν is dependent on the soil type (i.e., coarse or fine-grained soils) and is equal to 1 for coarse-grained soils and 2 for fine-grained soils. The fitting parameter μ however is a function of plasticity index, I_p.

$$\begin{aligned} &\mu = 9 && (8.0 \le I_p(\%) \le 15.5) \\ &\mu = 2.1088\, e^{0.0903(I_p)} && (15.5 \le I_p(\%) \le 60) \end{aligned} \qquad (13)$$

Following the procedure described in section 3.1, the ultimate shaft capacity of piles in unsaturated soils under undrained loading conditions can be estimated by combining (4) and (12) as given below.

$$Q_{f(us)} = \alpha c_{u(sat)} \left[1 + \frac{(u_a - u_w)}{(P_a/101.3)} S^{\upsilon} / \mu \right] \pi d L \qquad (14)$$

The undrained shear strength under saturated condition, $c_{u(sat)}$ and the *SWCC* are required to estimate the variation of ultimate shaft capacity of pile, $Q_{f(us)}$ with respect to matric suction. Equation (14) will be the same as (4) when the matric suction value is set equal to zero.

3.3 Modified λ Method

The λ method was modified to propose (15) to include the influence of matric suction in the estimation of shaft resistance of piles in unsaturated soils.

$$Q_{f(us)} = \lambda \left[\sigma'_{v(avg)} + 2c_{u(sat)} \left(1 + \frac{(u_a - u_w)}{(P_a/101.3)} S^{\upsilon} / \mu \right) \right] \pi d L \qquad (15)$$

The form of (15) will be same as the conventional λ method once the matric suction is set to zero. Equation (15) can also be used to estimate the variation of total shaft resistance of pile, $Q_{f(us)}$ with respect to matric suction. The required information for (15) are the undrained shear strength under saturated condition, $c_{u(sat)}$ and the *SWCC*. The term, $P_a/101.3$ is a normalization factor for the modified α and λ methods for maintaining consistency with respect to dimensions and units on both sides of the equation. More details of this method are discussed while analyzing the results.

4 TESTING PROGRAM

A series of model pile load tests were performed in saturated and unsaturated compacted fine-grained soil under drained and undrained loading conditions. The soil chosen for this study is a glacial till obtained from Indian Head, Saskatchewan, Canada. The key objective of the test program is to determine the influence of matric suction on the ultimate shaft capacity of model piles.

4.1 Soil properties

The properties of the tested soil are summarized in Table I. Procedures followed for determining some of the test results summarized in Table I are not detailed in this paper due to space limitations. The shaft bearing capacity of model piles were proposed to be determined at three different water contents; 13% (dry of optimum), 16% (dry of optimum) and 18% (close of optimum). These water contents were chosen from the compaction curve data. The dry densities of the compacted soil at these water contents were respectively equal to 14.5 kN/m^3, 16.1 kN/m^3 and 16.7 kN/m^3. The matric suction values of the tested compacted soils were measured using the axis-translation technique [29] with a modified null pressure plate [30]. The measured matric suction values were 205 kPa, 110 kPa and 55 kPa for water contents of 13%, 16%, 18% respectively. The experiments were not conducted for the water contents on the wet of optimum side since the degree of saturation values were greater than 90%, which resulted in significantly low matric suction values.
The measured *SWCC*s of the specimens prepared with initial water contents of 13%, 16% and 18% are presented in Fig. 1. These *SWCCs* were measured following the drying path using the pressure plate apparatus. More details of the matric suction measurements using both the modified null pressure plate and the *SWCC* using pressure plate are discussed in [31], [32].

Table I. Properties of the tested soil

Soil Properties	Indian Head till
Optimum water content, w_{opt} (%)	18.6
Maximum dry unit weight, γ_{dmax} (kN/m^3)	16.7
Saturated unit weight, γ_{sat} (kN/m^3)	18.5
Sand *(%)*	28
Silt *(%)*	42
Clay *(%)*	30
Liquid limit, *LL* (%)	32.5
Plastic limit, *PL* (%)	17
Plasticity index, I_p (%)	15.5
Effective cohesion, c' (kPa) (Sat)	15
Effective friction angle, ϕ' (deg.) (Sat)	23
Undrained shear strength, c_u (kPa)	11.5

4.2 Testing Methodology and Equipment Details

Special testing procedures were followed to determine the ultimate shaft capacity of the model pile placed in the statically compacted soil. The model piles were loaded in saturated/unsaturated compacted soils for both drained and undrained loading conditions. The soil sample collected from the field was air-dried for several days, subjected to gentle pulverization, passed through a sieve with an opening size of 2 mm (i.e., #10 sieve), and oven-dried.
The oven dried soil, after reaching the room temperature in the laboratory, was mixed with distilled water at predetermined initial water contents. The prepared soil-water mixture was placed in sealed double plastic bags and then stored in a humidity controlled box for at least 3 days to ensure uniform water content conditions throughout the sample.

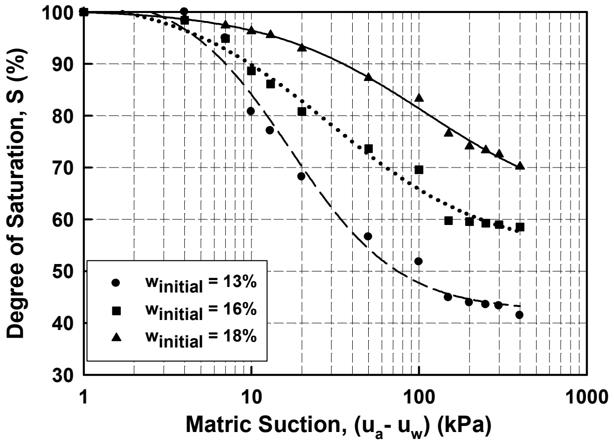

Fig. 1. *SWCCs* for the Indian Head till prepared at three different initial water contents.

The soil-water mixture (hereafter referred to as soil) was placed in a tank (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. The compaction and model pile load tests were conducted using a conventional triaxial test loading frame (Fig. 2).

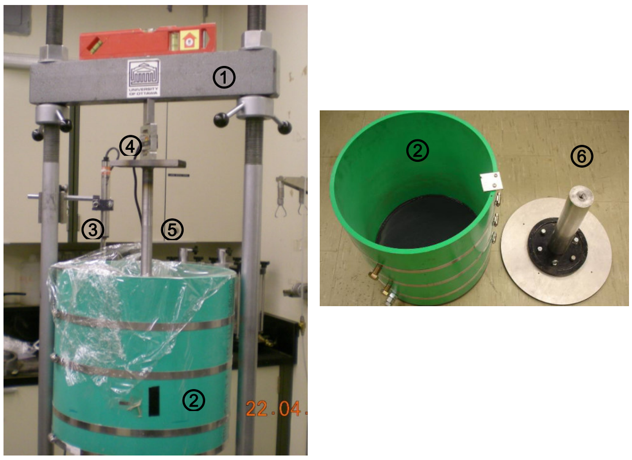

Fig. 2. Test setup for model pile loading test: ① Adjustable height loading frame ② Test tank ③ LVDT ④ Load cell ⑤ Model pile, ⑥ Compaction base plate.

After the soil was compacted under static loading conditions in five layers in the test tank, a thin wall sampling tube of 18.7 mm diameter with 1 mm of wall thickness was used to create a hole down to a depth of 220 mm. The sampling tube along with the soil column embedded into it was removed out of the compacted soil. The model pile used in the study was made out of stainless solid steel cylindrical rod with 20 mm diameter. The model pile (hereafter referred to as D-20 pile) was slightly larger in diameter in comparison to the diameter of sampling tube in order to obtain a good contact between the walls of the drilled shaft and the model pile. After the borehole drilling was completed, model pile was jacked down to a depth of 200 mm. A gap with 20 mm of length at the tip of the pile was intentionally left to eliminate the end bearing resistance while loading the model pile. In other words, the void was created to facilitate in the measurement of shaft resistance without any contribution from the end bearing resistance. The tests described were conducted under unsaturated (UNSAT) conditions.

However, when the pile was loaded under saturated (SAT) condition, the compacted unsaturated soil was gradually saturated by allowing downward flow of water from the top of the soil through the compaction base plate which had apertures. 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. After the saturation process was completed, the model pile was installed using same procedure described for the pile testing under unsaturated condition.

A piezometer attached to the side of the tank was used to check the saturation condition. The soil was assumed to be saturated as 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. In addition to these checks, small chunks of soil specimens were collected from the tank for water content measurements after the loading tests were completed. The average water content from these tests was 31% which corresponds to a degree of saturation equal to 96% calculated from mass-volume relationships. This value can be considered to be close to saturation conditions for the present study because there is other evidence to support the soil is saturated.

A strain rate of 0.0120 mm/min was chosen for loading the pile to achieve drained loading conditions [18],[33]. A relatively fast loading rate of 1.4 mm/min was used to simulate undrained loading conditions [34].

The soil samples prepared with an initial water content of 13% were tested under both unsaturated and saturated conditions considering both the drained and undrained loadings (i.e., SAT-Drained, SAT-Undrained, UNSAT-Drained, UNSAT- Undrained). The tests on unsaturated soil samples were conducted (i.e., UNSAT-Drained, UNSAT-Undrained) with initial compaction water contents of 16% and 18%. The details of the experimental program of the present study are summarized in Fig. 3 as a flow chart.

5 MODEL PILE TEST RESULTS AND ANALYSES

5.1 Test Results

The model pile test results obtained for both saturated and unsaturated soil samples are presented in Fig. 4 through Fig. 7. The shaft carrying capacity of the model piles loaded in the soils compacted with different compaction water contents (i.e., 13%, 16%, and 18%) is significantly different depending on the soil (saturated or unsaturated) and drainage (drained or undrained) conditions. The trends of the load versus displacement behavior of model piles from the present study are similar to the results published on results on other fine-grained clays in the literature [25].

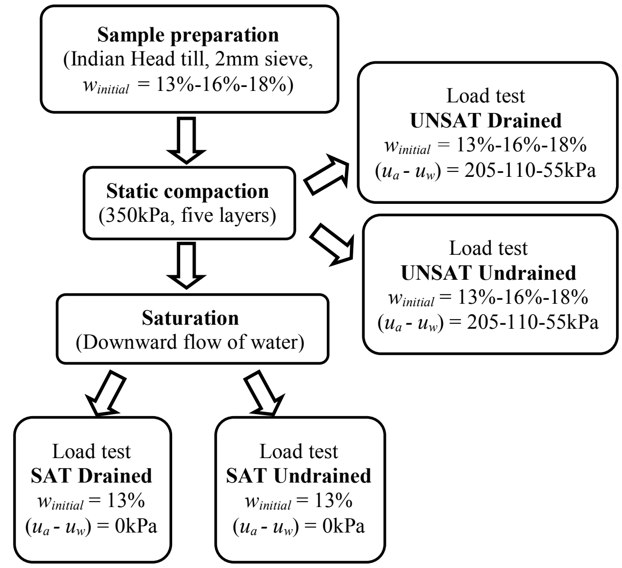

Fig. 3. Flow chart of the testing program.

5.2 Interpretation of the Test Results

The measured shaft bearing capacity values for the D-20 pile were interpreted using the modified α, β and λ methods proposed in this paper. In addition, comparisons are provided between the measured and estimated shaft bearing capacity values.

The ultimate shaft bearing capacities for the model piles was estimated using the modified α method assuming undrained loading conditions. The undrained shear strength values for the compacted soils required for the modified α method were determined by conducting unconfined compression tests on the samples collected from the testing tank after model pile tests. The undrained shear strength values were also estimated by using (12). The test results are summarized in Table II.

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

$w_{initial}$	$(u_a - u_w)$	Meas.(1) c_u	Est.(2) c_u	α (3)	Back Cal. α value	**Est.(4) $Q_{f(us)}$**	**Meas. $Q_{f(us)}$**
(%)	kPa	kPa	kPa	-	-	**kN**	**kN**
13	0	11.5	-	0.90	0.70	**0.13**	**0.10**
13	205	68	57	0.75	0.79	**0.64**	**0.68**
16	110	80	65	0.67	0.55	**0.67**	**0.55**
18	55	58	62	0.82	0.68	**0.59**	**0.50**

$(u_a - u_w)$ = matric suction
1 Undrained shear strength from unconfined compression tests
2 Undrained shear strength calculated by using (12)
3 α value obtained using the correlation charts [20]
4 Calculated shaft bearing capacity by using (14)

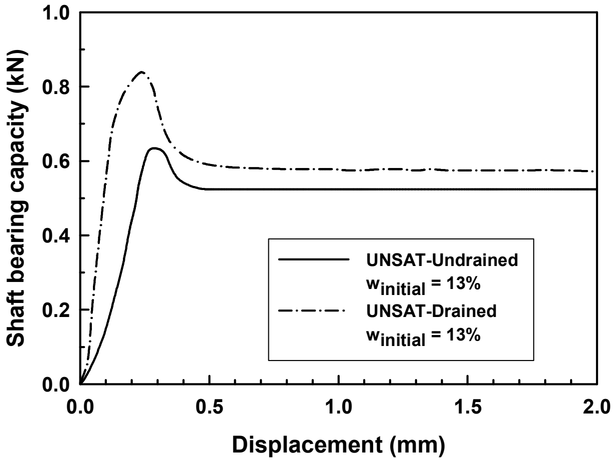

Fig. 4. Model pile test results in unsaturated soil sample compacted at an initial water content of 13% under drained and undrained loading conditions.

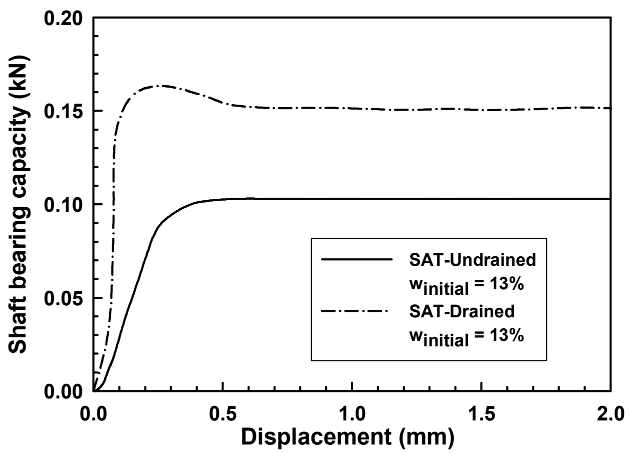

Fig. 5. Model pile test results in saturated soil compacted at an initial water content of 13% under drained and undrained loading conditions.

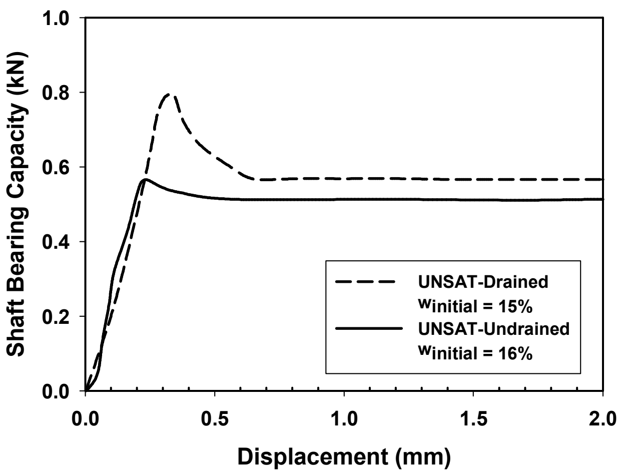

Fig. 6. Model pile test results in unsaturated soil sample compacted at an initial water content of 16% under drained and undrained loading conditions.

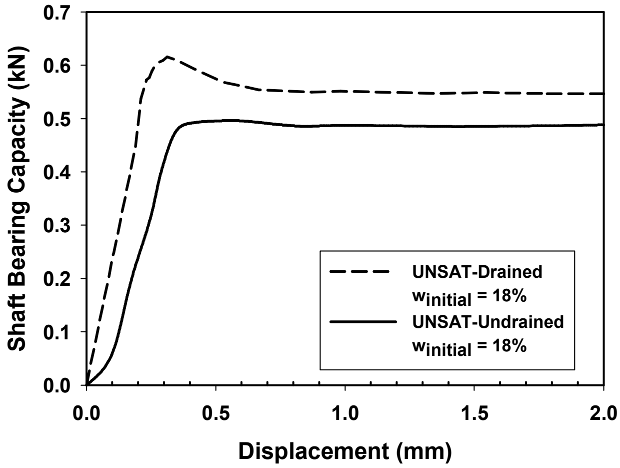

Fig. 7. Model pile test results in unsaturated soil sample compacted at an initial water content of 18% under drained and undrained loading conditions.

The measured ultimate shaft capacities under drained loading conditions and the predicted shaft bearing capacities from the conventional (i.e. (2)) and the modified (i.e., (11b)) β methods for the saturated and unsaturated soil conditions, respectively are summarized in Table III. The fitting parameter κ in (10) was determined using the relation given in [28]. The coefficient, $\beta = 0.3$ was used for both the saturated and unsaturated soils based on the soil-pile interface friction angle, δ' (see Table III) since the influence of matric suction on δ' is relatively less.

Table III. Comparison between the measured and estimated ultimate shaft capacities using the modified β method.

$w_{initial}$	$(u_a - u_w)$	β	δ' sat/unsat	c'_a sat/unsat	**Est. $Q_{f(us)}$**	**Meas. $Q_{f(us)}$**
%	kPa	-	°	kPa	**kN**	**kN**
13	0	0.3	25	20	**0.25**	**0.16**
13	205	0.3	27	100	**0.52**	**0.82**
15	150	0.3	23/25	12/21	**0.55**	**0.80**
18	55	0.3	22/23	12/21	**0.40**	**0.62**

The measured ultimate shaft capacities and the predicted values from the modified λ method (i.e. (15)) were summarized in Table IV. Vanapalli and Taylan [35] analyzed the data available in the literature [4] and suggested the relationship between λ and the ratio of pile diameter to pile penetration depth, d/L. A value of $\lambda = 0.32$ was used in the present study. More details with respect to using this value are detailed in [35].

Table IV. Comparison between the measured and estimated ultimate shaft capacities using the modified λ method.

$w_{initial}$	$(u_a - u_w)$	Meas. c_u	λ	**Est. $Q_{f(s),(us)}$**	**Meas. $Q_{f(s),(us)}$**
(%)	kPa	kPa	-	**kN**	**kN**
13	0	11.5	0.32	**0.09**	**0.10**
13	205	68	0.32	**0.55**	**0.68**
16	110	80	0.32	**0.64**	**0.55**
18	55	58	0.32	**0.47**	**0.50**

The measured and predicted shaft bearing capacity results are graphically summarized and presented in Fig. 8. Each circle shown in Fig. 8 represents the results of the three different methods with different matric suction and initial water contents. The difference between the measured and estimated shaft bearing capacities in terms of percentage varies between 6 to 36%. The difference is more significant for the results obtained using the modified β method (11b). Such a behavior can be attributed to the effect of loading rate and also due to the difficulties associated with the opening a hole using the thin wall tube during which some disturbance may have occurred.

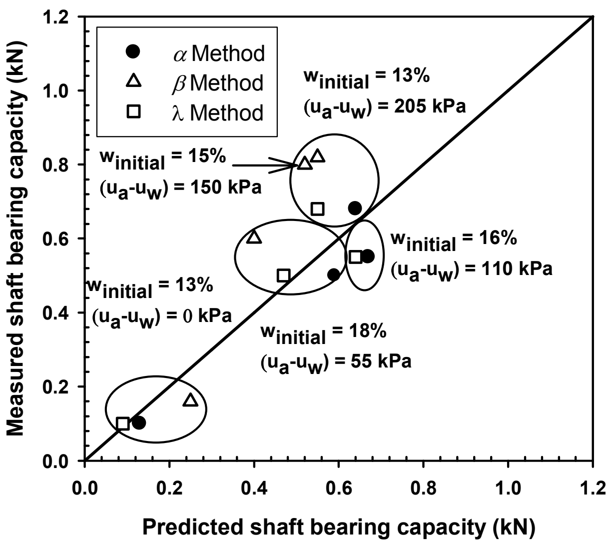

Fig. 8. Measured and estimated ultimate shaft bearing capacities calculated using the modified α, β and λ methods for compacted Indian Head till samples.

6 SUMMARY AND CONCLUSIONS

The conventional α, β and λ methods are commonly used in engineering practice for estimating the ultimate shaft bearing capacity of single piles in saturated soils. In the present study, these methods are modified such that they can be used to estimate the variation of ultimate shaft capacity of single piles with respect to matric suction using the *SWCC* and the conventional shear strength parameters. There is a smooth transition between the modified and conventional methods and are convenient to estimate the shaft capacity of piles in unsaturated and saturated soil conditions.

A series of model pile load tests were conducted on statically compacted fine-grained soil (i.e., compacted Indian Head till) in a laboratory environment to study the validity of the modified α, β and λ methods. The test results of the study presented in this paper show significant increase in shaft capacity due to the contribution of matric suction. The modified α, β and λ methods provided reasonably good comparison with the model pile load test results conducted in a laboratory environment.

The authors based on the experience of the present study suggest different techniques of testing to alleviate some experimental problems. Instead of drilling a hole into the initially compacted soil, it is suggested to compact the soil around the pile using a specially designed compactor. Such a technique would reduce disturbance during pile installation for tests and likely provide better correlation results as it eliminates the problems associated with the soil disturbance. In addition, this technique also provides better contact between the pile and the soil.

The results summarized in this paper are based on the studies undertaken using one compacted fine-grained soil. More experimental and numerical studies are in progress to check the validity of the modified α, β and λ methods for different coarse and fine-grained soils. These studies will be useful to better understand the influence of matric suction on the load carrying capacity of the piles. The results of the studies conducted to date are promising for using the modified α, β and λ methods in engineering practice to estimate the ultimate shaft bearing capacity of single piles placed in unsaturated fine-grained soils.

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