Bearing capacity of piles in unsaturated soil from theoretical and experimental approaches

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Abstract. Research in unsaturated soil mechanics has considerably developed in the past decades, through the simultaneous development of experimental investigations and theoretical analyses. A fundamental property of unsaturated soil is the ability to store and release water.

In this study, an attempt was made to compare the results of bearing capacity of model pile groups constructed in saturated soil prepared at two dry densities and unsaturated soil, with results from theoretical approach (conventional and modified) α, β and λ methods. Square aluminum model piles of 20 x 20 mm in cross section and 200 mm in length were used. The piles were arranged in six group configurations, single, 2x1, 3x1, 2x2, 3x2, and 3x3, groups in addition to pull out test at which the pile is designed to verify this purpose. All groups have the same spacing, which is equal to 3 pile diameters (60 mm). The results showed that using the β method gives the value of ultimate capacity close to the experimental results for saturated and unsaturated tests, while the theoretical results showed overestimation when using other two methods. The results of load displacement curves for piles embedded in soil having three different properties indicate an increase in the ultimate pile load carrying capacity with increase in the number of piles for different soil properties. This increase however, is not linear and gives a high value when the soil becomes in unsaturated state compared to the soil in saturated state.

Keywords
Bearing capacity, pile, model, unsaturated clay, experiment, shaft capacity, tip resistance.

1. Introduction

There are two usual approaches to the calculation of the ultimate load capacity of piles: the “static” approach, which uses the normal soil mechanics method to calculate the load capacity from measured soil properties; and the “dynamic” approach, which estimates the load capacity of driven piles from analysis of pile driving data (Poulus and Davis, 1980).

The strength and deformation characteristics of the unsaturated soil are generally influenced by the degree of saturation, therefore, a change in soil degree of saturation due to seasonal variation can affect the engineering properties of the unsaturated soil and thus, the overall behavior of the piled superstructure supported on it.
The bearing capacity of shallow foundations and piles in this region will not follow the conventional theories and require reassessment of the general behavior of foundation in the condition of partial saturation.

Georgiadis (2003) investigated the influence of the presence of a partially saturated soil zone above the groundwater table and of fluctuations of the groundwater table on the behavior of shallow and deep foundations in a uniform soil, using two new generalized constitutive models for partially and fully saturated soils. The pile was 20 m length and 1 m in diameter located at different depths of water table: 0 m (fully saturated) -2 m, -4 m, -6 m, -8 m, -10 m and -25 m, two sets of analyses were performed. The results of analysis showed that the bearing capacity of the pile increases with the increase in the depth of the ground water table, and this increase refers mainly to the increase in the shaft resistance. Once the ultimate shaft resistance is reached, at approximately 10 mm ~ 20 mm displacement, (1% ~ 2% of the pile diameter), the load displacement curves for all analyses are close to parallel. Although the shaft resistance for all analyses was reached at small displacements (less than 1% ~ 2% of the pile diameter), the base resistance continues to increase even at high values of vertical displacement. The load-displacement curves were predicted by the conventional and partially saturated analyses of the ground water at 25 m below ground level. The partially saturated analysis predicted approximately 75% higher ultimate load than the conventional analysis.

Vanapalli and Taylan (2011, 2012) performed a series of model pile load tests 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 key objective of the testing program was to determine the influence of matric suction on the ultimate shaft capacity of model piles under drained and undrained loading conditions for saturated and unsaturated compacted soil in specially designed test 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 using a conventional triaxial test loading frame. 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 model pile made out of stainless solid steel cylindrical rod with 20 mm diameter 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 pile and the soil. A gap with 20 mm 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 the measurement of shaft resistance without any contribution from the end bearing resistance. The matric suction values of the tested compacted soils were measured using the axis-translation technique with a modified null pressure plate. The measured matric suction values were 205 kPa, 110 kPa and 55 kPa for water contents of 13%, 16% and 18%, respectively.

The measured and predicted shaft bearing capacity results are graphically presented. 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. Such a behavior can be attributed to the effect of loading rate and also due to the difficulties associated with opening a hole using the thin wall tube during which some disturbance may have occurred.

The test results of the study, showed significant increase in shaft capacity due to the contribution of matric suction. The modified α, β and λ methods provide reasonably good comparison with the model pile load test results conducted in a laboratory environment. Vanapalli and Taylan (2011, 2012), suggested more experimental and numerical studies in progress to check the validity of the modified α, β and λ methods for different coarse and fine-grained soils.

Mohsen (2012) and Fattah et al., (2014) investigated the behavior of a single pile in unsaturated soils using a pile foundation with (0.6 m) diameter and (12 m) length, embedded in fully saturated and
partially saturated Iraqi soils, within Baghdad city. The analysis was carried out using the finite element programs SIGMA/W and SEEP/W. The study revealed that when the soil becomes partially saturated due to the dropping of water table and consequently negative pore water emerges, the bearing capacity of pile is approximately (3-5) times higher than the capacity of piles in the same soil under saturated conditions. It was found that the increase in the pile capacity due to change in water table level is greater than the increase due to increase in matric suction and there is a linear increase in the capacity of piles obtained because of lowering of water table and nonlinear increase due to change in matric suction for the same depth of water table.

Predicting ultimate axial bearing capacity of pile foundations is an important and complicated problem in geotechnical engineering. Cone penetration test (CPT) is a reliable in situ test widely used in the analysis and design of pile foundations. Ebrahimian and Movahed (2016) presented a new CPT-based axial pile bearing capacity models for both cohesionless and cohesive soils using evolutionary polynomial regression (EPR), a branch of evolutionary approaches. A relatively comprehensive database was gathered and divided into training and testing sub-sets to avoid over-fitting. This database includes both coarse and fine grain soils, cone tip resistance and sleeve friction of CPTs, geometry and bearing capacity of piles. The presented models were compared to some previously published ones and their preferences are demonstrated statistically and probabilistically. Proper applicability of the models in predicting axial pile bearing capacity is then confirmed by field verification, compared to analytical and empirical models available in the literature.

**Conventional and Modified Methods of Pile Analysis**

The conventional soil mechanics principles are used for the design of pile foundations assuming the soil is in a state of saturated condition. However, in many situations, natural soils are found in a state of unsaturated condition as the ground water table is at a low depth, this is particularly true for soils in arid and semi-arid regions.

Several recent studies on shallow foundations have shown that the bearing capacities of both coarse and fine-grained soils are significantly influenced by the contribution of matric suction. However, limited numbers of studies are available 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 (Vanapalli and Taylan, 2012).

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. Vanapalli and Taylan (2012) modified these methods such that they can be used to estimate variation of bearing capacity of single pile with respect to matric suction using the SWCC and the conventional shear strength parameters as shown below.

*• Modified α Method*

The ultimate shaft resistance for undrained loading conditions when a pile is loaded at a relatively fast rate in saturated fine-grained soil using undrained shear strength, $c_u$, can be estimated:

$$ Q_{uf} = A_s (\alpha c_u) $$

(1)

where:

- $c_u$ = undrained shear strength,
- $A_s$ = surface area of the shaft of embedded length of pile in soil and
- $\alpha$ = adhesion factor between soil and pile which can be computed from correlation chart, alternatively, $\alpha$ can also be estimated as:

$$ \alpha = 0.5 \psi^{-0.5} \quad \text{if } \psi \leq 1 $$

$$ \alpha = 0.5 \psi^{-0.25} \quad \text{if } \psi > 1 $$

(2)
\[ \psi = \frac{c_u}{\sigma'_v} \] and 
\[ \sigma'_v = \text{vertical effective stress} \]

Equation (1) can be employed to estimate the ultimate shaft capacity of piles in unsaturated soils:

\[ Q_{f(us)} = \alpha c_{u(sat)} A_s \left( 1 + \left( \frac{u_a - u_w}{P_a/101.3} \right) S/\mu \right) A_s \]  
(3)

where:
- \( c_{u(sat)} \) = undrained shear strength under saturated conditions,
- \( P_a \) = atmospheric pressure (i.e. 101.3 kPa), and
- \( \mu = \) fitting parameter.

The fitting parameter \( \mu \) 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 \( \mu \) however is a function of plasticity index, \( I_p \).

\[ \mu = \begin{cases} 9 & (8.0 \leq I_p \% \leq 15.5) \\ 2.1088 e^{0.0903 (I_p)} & (15.5 \leq I_p \% \leq 60) \end{cases} \]  
(4)

The undrained shear strength under saturated condition, \( c_{u(sat)} \) and the soil water characteristic curve (SWCC) are required to estimate the variation of the ultimate shaft capacity of pile, with respect to matric suction.

- **Modified \( \beta \) Method**

  The conventional method for ultimate shaft capacity is reported as (Vanapalli and Taylan, 2012):
  \[ Q_{af} = A_s \beta \sigma'_v \]  
(5)

  The contribution of matric suction, towards the ultimate shaft capacity of a single pile, \( Q_{(u_a - u_w)} \) can be estimated as given below:
  \[ Q_{(u_a - u_w)} = \tau_{u_a} A_s - [(u_a - u_w)(S^*)(\tan \delta')]A_s \]  
(6)

  Equation (6) suggests that the variation of the ultimate shaft capacity with respect to matric suction can be estimated using the SWCC and effective interface friction angle, \( \delta' \).

  A general expression for estimating the ultimate shaft capacity of piles in unsaturated soils, \( Q_{f(us)} \) can be obtained by combining equations (5) and (6) in a more generalized form:
  \[ Q_{f(us)} = Q_{f(sat)} + Q_{(u_a - u_w)} \]  
(7)

  where \( \kappa = \beta \sigma'_v + \left\{ (u_a - u_w)(S^*)(\tan \delta') \right\}A_s \) is a fitting parameter which is a function of the plasticity index \( I_p \). The relationship between the fitting parameter \( \kappa \), and plasticity index, \( I_p \) for predicting the shear strength of unsaturated soils can be used for estimating the ultimate shaft capacity of the pile. (\( \kappa = 1 \) for \( I_p = 0 \)), as suggested by Vanapalli and Mohamed (2007):
  \[ \kappa = -0.0031 (I_p)^2 + 0.3988 (I_p) + 1 \]  
(9)

  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 \( \beta \) method. 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 equation (8) as follows:
  \[ Q_{(u_a - u_w)} = \left[ c_a + \beta \sigma'_v + \left\{ (u_a - u_w)(S^*)(\tan \delta') \right\} \right] A_s \]  
(10)

  where \( c_a = \) adhesion component of cohesion for saturated condition.

- **Modified \( \lambda \) Method**

  The conventional \( \lambda \) method is given as:
  \[ Q_{af} = A_s \lambda (\sigma'_v + 2c_a) \]  
(11)
The equation was modified by Vanapalli and Taylan (2012) to include the influence of matric suction in the estimation of shaft resistance of piles in unsaturated soils as shown below:

\[
Q_{f(u_s)} = A_s \lambda \left[ \sigma' \nu + 2c_{u(sat)} \left( 1 + \frac{(u_a - u_w)}{P_a / 101.3} \right) S / \mu \right]
\] (12)

The form of equation (12) will be the same as that of the conventional \( \lambda \) method once the matric suction is set to zero. Equation (12) can also be used to estimate the variation of the total shaft resistance of pile, \( Q_{f(u_s)} \) with respect to matric suction. The required information for equation (12) 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 \( \alpha \) and \( \lambda \) methods for maintaining consistency with respect to dimensions and units on both sides of the equation.

In this work, an attempt has been made to compare the load carrying capacity of single pile and pile group embedded in saturated soil prepared at two dry densities and unsaturated soil, these results are compared with the results obtained from theoretical approaches.

**Experimental Work**

The soil used is clayey soil brought from a region east of Baghdad city in Iraq. The grain size distribution curve is shown in figure 1. The physical and chemical properties are illustrated in table 1. According to the Unified Soil Classification System (USCS), the soil can be classified as (CL – ML) with 38% sand, 28% silt and 34% clay. These soil percents were selected at the early stage of soil model preparation in order to facilitate emerging of negative soil pressure during desaturation process as described earlier.

![Figure 1: Grain size distribution of the soil used.](image-url)
Table 1: Physical and chemical properties of the soil used.

| Index property                  | Index value |
|---------------------------------|-------------|
| Optimum moisture content (OMC)% | 13.3        |
| Liquid limit % (LL)             | 25          |
| Plastic limit % (PL)            | 19          |
| Plasticity index% (PI)          | 6           |
| Activity (Ac)                   | 0.19        |
| Specific gravity (Gs)           | 2.68        |
| Gravel (larger than 4.75 mm)%   | 0           |
| Sand (4.76-0.074 mm)%           | 38          |
| Silt (0.074-0.005 mm)%          | 28          |
| Clay (less than 0.005mm)%       | 34          |
| Gypsum content %                | 0.8         |
| Total dissolved salts TDS%      | 1.3         |
| SO$_3$ content %                | 0.41        |
| pH value                        | 8.73        |
| CaCO$_3$ content %              | 30.7        |
| Soil symbols (U.S.C.S.)         | CL-ML       |

Two sets of containers were used in the experimental work. These containers are designed to serve the saturation process and can be subdivided into three types according to the pile group tested as follows:

Container 1 with internal dimensions of 200 mm length, 20 mm width and 350 mm height was used for single pile test (compression and pull out test).

Containers 2 with internal dimensions of 300 mm length, 300 mm width and 350 mm height was used for pile of (2x1) and (2x2) group configuration.

Container 3 with internal dimensions of 400 mm length, 300 mm width and 500 mm height was used for pile groups of (3x1), (3x2) and (3x3) configuration.

It should be noted that the spacing between piles is the same for all group, the spacing between piles = 3 pile diameters (60 mm).

The steel containers are made from a steel angle (25.4 mm x 25.4 mm) with a thickness of 2 mm and steel plates of 2 mm thickness to form the walls and the base of container. The container sides were rigid enough to function as independent reaction frame. A thick glass panel of 10 mm thickness was inserted within a section of the container wall to function as a window to observe the level of the soil during the preparation of the soil model.

A 30 mm layer of clean aggregate was placed over the perforated steel base (the perforation consists of 3 mm openings at spacing of 25 mm) for every testing container. The aggregate layer was prepared by sieving the soil on sieve 3/4” (19 mm opening), and retained on sieve No. 4 (4.75 mm opening), covered with perforated nylon sheet, which was used as a porous barrier between the soil and the aggregate layer, and also to prevent the mix of the soil with aggregate. The main objective of these two layers (aggregate and nylon sheet) is to facilitate the free and gradual movement of the water into the box through the compacted soil layer as required by the testing requirements.
The water was supplied to the container through a main water supply plastic tube of 10 mm diameter, this tube is branched into two pipes of the same diameter on every side of the container to ensure gradual and uniform saturation process from the base of the container to the surface (saturation was progressed from the bottom to the top of the soil surface in order to expel any entrapped air during saturation process).

A drainage pipe with a valve was connected to the bottom of the test container to spell the water at the end of the test. A tube of 10 mm diameter was installed on one side of the test containerto monitor the elevation of water table during the saturation process.

As mentioned earlier, the program of the work includes tests on both saturated and unsaturated soil models. To prepare the unsaturated soil model, some researchers e.g. Vanapalli and Mohamed (2007) prepared the unsaturated soil (coarse grained) from the saturated model by dropping the water from the model (opening the bottom drainage valve) and consequently, the negative pore water pressure emerged due to this dropping (soil suction).

This process is found to be ineffective for the soil used in this research; it requires waiting for more than 14 days since there is no change in water content inside the soil model, consequently, no change in pore water pressure (zero reading). To overcome this problem, the trend was directed to another procedure to capture the negative pore water pressure, using a laboratory oven for a degree not exceeding (50°C) to protect the wires of the soil pressure and pore water pressure measurement devices from overheating. This process also continued more than 14 days, the reading of pore pressure tensiometer unchanged (zero reading). For these reasons, the decision was to prepare unsaturated soil model directly according to the water content calculated previously to give the desired degree of saturation and consequently the negative pore water pressure as calculated from CBR molds (results will be presented within this chapter). This procedure to prepare the unsaturated soil model (fine grained soil) from previously calculated water content was also conducted by Vanapalli and Taylan, (2011).

In this study, the soil suction was measured using a watermark model (900M - monitor), this logger is accompanied by seven soil moisture sensors named (200SS – 15) and one soil temperature sensor named (200TS) as shown in figure 2.

For these reasons, it is important to measure the soil suction using seven CBR molds for samples with different water contents to get a relationship between the soil suction and water content. The result of this test is shown in figure 3.

The following equation is obtained with a coefficient of determination $R^2 = 0.89$ from the test results:

$$\psi_t = 585546 w^{-3.977} \quad \text{for} \quad 10 \leq w \% \leq 16$$

(13)

where:

$\psi_t$ = soil suction (kPa) and $w$ = water content %.

The results of this test indicate that there is a distinct increase in the soil suction with decreasing the water content as indicated by most researches. However, this increase is not always rapid, but sometimes it may become asymptote or even decreases for some soils, coarse grained soil for example (Vanapalli and Oh, 2010).
Figure 2. 900M monitor with 8 probes.

Figure 3. Relationship between soil suction and water content obtained using sensors.

The model piles
Seven model pile groups were used, these are single pile with two types; one for compression and the other for pull out test, 2x1, 3x1, 2x2, 3x2 and 3x3 groups. The model piles used were made of aluminum metal with a square in cross section (20 mm x 20 mm) and 1.2 mm thickness. The pile model was closed at the toe with aluminum plate (closed end pile), and attached to the pile cap with two small aluminum angles (20 mm x 15 mm), 2 mm thick by two bolts and nuts. The pile ends were closed to prevent formation of soil plug since the plug has a considerable effect on pile load capacity and effect of plug removal was studied by Fattah et al. (2015). All piles have a length of 200 mm to give an L/D ratio = 10, with the same spacing for all groups s = 3 pile diameters (60 mm).

To facilitate and minimize the disturbance of the soil during pile inserting, another aluminum pile of square cross section (15 mm x 15 mm), was used, which is slightly smaller in cross section in comparison with the used pile. This pile was inserted prior to the pile installation to facilitate and minimize soil disturbance. After that, the pile group was jacked to the soil model slowly and checked within the jacking process to be in the horizontal alignment.
Test Preparation
The soil was prepared in accordance with the type of test (saturated or unsaturated), and the amount of soil according to the testing container adopted. The saturated soil was prepared according to the following steps:
1. The sieved soil was stored at room temperature at approximately 1% water content, then mixed with water about 11.5% water content, to get a water content equal to 12.5%, which is in the range of optimum moisture content.
2. Each 10 kgs of conditioned soil was mixed gradually and thoroughly with an amount of water corresponding approximately to the water content of 12.5% by hand for a period of 10 minutes to give a uniform distribution of moisture content.
3. After mixing with water, the wet soil was kept in double tightened polythene sheets and left for about 2-4 days as curing period. Two samples of the soil were extracted to check the actual water content, after that the pre-calculated amount of soil according to the box selected is spread to occupy 50 mm depth of the box. This quantity of soil was compacted to the desired depth using a special tamping steel hammer of (100 mm x 100 mm) in size. The soil was tamped according to the calculated dry density. Before placing the second layer using the same procedure, the surface of the first layer was scratched to give a good interaction with the next layer.

Experimental Setup
Figure 4 shows details of the equipment that was designed to serve the objective of the proposed testing program. The loading frame was constructed using two steel channels (150 mm x 50 mm x 8 mm), and 2 m length assupporting columns. They are connected with two other steel channels of the same dimensions, 1.2 m length. One of these channels was to fix the column channel against movement during the load application, while another channel was allowed to move vertically for about 50 cm according to the container length used during the test.

The main work in this study is to investigate the behavior of different pile groups in the soil model with three different soil properties, these are: i) saturated soil with two different dry densities ($S = 90\% \gamma_d = 15 \text{ kN} / \text{m}^3$ and $S = 90\% \gamma_d = 17 \text{ kN/m}^3$) and ii) unsaturated soil with ($S = 60\%$ and $\gamma_d = 15 \text{ kN} / \text{m}^3$). Some researchers consider that when the degree of saturation of a soil is greater than 85%, saturated soil mechanics principles can be applied. However, when the degree of saturation of a soil is less than 85%, it becomes necessary to apply unsaturated soil principles (Huat et al., 2005).

The vertical load was applied on the model piles by means of a hydraulic jack, the applied load was measured using a calibrated proving ring with 2 kN capacity. A dial gauge with 0.01 mm accuracy was used for measuring settlements of the pile group model.

At the end of seating time, the dead load was removed with the nylon sheet, the soil model container was positioned at the center of the loading frame. Then the steel channel which was carrying the loading frame was allowed to move a suitable distance from the testing container, then the hydraulic jack was moved with the proving ring until the base of the ring touches the pile cap, the displacement dial gauge is checked and positioned to measure the cap settlement.

The load was applied incrementally with a period of 5 minutes for every load increment as adopted in some pile load tests (U. S. Army Corps of Engineers, 1991). The loading rate was kept approximately constant at 2 mm/min for testing clayey soil.
Results and Discussion

The results ultimate bearing capacity and laboratory tests at the end of loading tests for all pile groups tested in three soil types mentioned previously ($S = 90\%$, $\gamma_d = 15 \text{ kN/m}^3$), ($S = 90\%$, $\gamma_d = 17 \text{ kN/m}^3$) and ($S = 60\%$, $\gamma_d = 15 \text{ kN/m}^3$) are shown in tables 2, 3, 4, 5, 6 and 7, while the results of load – displacements curves are presented in figure 5.

The results of single pile obtained from the experimental work are compared with results obtained from theoretical approaches, these methods are characterized for two sets:

1. Conventional $\alpha$, $\beta$ and $\lambda$ methods, these methods are illustrated by equations 1, 5, and 11. They are used to obtain the ultimate pile capacity for pile in saturated soil. These methods are used to obtain the pile capacity in saturated soil with ($S = 90$, $\gamma_d = 15 \text{ kN/m}^3$ and $S = 90$, $\gamma_d = 17 \text{ kN/m}^3$).

The value of $\alpha = 0.32$ as obtained from equation 2 for the value of $\psi = c_u/\sigma_v$ with $c_u = 8.8 \text{ kPa}$ and $\sigma_v = 1.5 \text{ kPa}$. The value of $\beta = 0.45$ which is the average between the selected value of 0.3 for fine grained soil and 0.6 for coarse grained soil (Vanapalli and Taylan, 2011).

Table 2. Results of laboratory tests of saturated soil measured at the end of loading tests of pile groups ($S = 90\%$, $\gamma_d = 15 \text{ kN/m}^3$) with percentage increase compared to single pile.

| Pile group          | Pull out | Single | 2x1 | 3x1 | 2x2 | 3x2 | 3x3 |
|---------------------|----------|--------|-----|-----|-----|-----|-----|
| Qu,N                | 21.5     | 41     | 98  | 187 | 265 | 425 | 600 |
| (Qu_N - Qu single/Qu single) *100 | -48      | 100    | 139 | 356 | 546 | 936 | 1363|
| Efficiency, $E_e$   | 0.52     | 1      | 1.2 | 1.52| 1.61| 1.72| 1.62|

Figure 4. Diagram of setup configuration.
Table 3. Results of laboratory tests of saturated soil measured at the end of loading tests of pile groups (\( S = 90\% \), \( \gamma_d = 15 \text{kN/m}^3 \)).

| Vane shear results | Pile group | Mass volume parameters |
|---------------------|------------|------------------------|
| Su, kPa             | w %        | Type                   | S%  | w %   | \( \gamma_d \text{kN/m}^3 \) |
| Pull out            | 87.28      | 23.46                  | 15.28 |
|                     | 90.58      | 23.58                  | 15.48 |
|                     | 83         | 22.71                  | 15.16 |
| 10                  | 17.74      | Single pile            | 80.64 | 18.14 | 16.3 |
| 9.4                 | 18.54      | 78.83                  | 19.37 | 15.8  |
| 7.2                 | 18.4       | 85.28                  | 21.44 | 15.6  |
| 8.7                 | 19         | 2x1                    | 89    | 22.75 | 15.6  |
| 6.8                 | 18.93      | 94.5                   | 24.1  | 15.62 |
| 3.8                 | 19.8       |                        |       |       |
| 6.8                 | 22.02      | 3x1                    | 85.74 | 23.3  | 15.21 |
| 5.8                 | 23.55      | 85.82                  | 22.87 | 15.33 |
| 6.3                 | 22.89      | 90                     | 23.45 | 15.47 |
| 5.2                 | 23.06      | 2x2                    | 85.8  | 24.04 | 15.01 |
| 6                  | 23.17      |                        |       |       |
| 4.3                 | 24.01      |                        |       |       |
| 10.8                | 19.9       | 3x2                    | 91.88 | 21.56 | 16.14 |
| 10.5                | 19.27      | 88.5                   | 21.1  | 16.04 |
| 7.2                 | 18.56      |                        |       |       |
| 5.8                 | 22.16      | 3x3                    | 85    | 23.64 | 15.05 |
| 3.8                 | 22.13      | 84                     | 23.22 | 15.07 |
| 4                  | 22.22      |                        |       |       |

Table 4. Results of ultimate bearing capacity for saturated soil (\( S = 90\% \), \( \gamma_d = 17 \text{kN/m}^3 \)) with percentage increasing compared to single pile.

| Pile group | Pull out | Single | 2x1 | 3x1 | 2x2 | 3x2 | 3x3 |
|------------|----------|--------|-----|-----|-----|-----|-----|
| Qu, kPa    | 90       | 116    | 367 | 360 | 600 | 670 | 900 |
| (Qu− Qu single /Qu single) *100 | -22 | 100 | 216 | 201 | 417 | 477 | 676 |
| Efficiency \(E_g= Qu/N Qu single\) | 0.78 | 1 | 1.58 | 1.04 | 1.29 | 0.96 | 0.86 |

Table 5. Results of ultimate bearing capacity for saturated soil measured at the end of loading tests of pile groups (\( S = 90\% \), \( \gamma_d = 17 \text{kN/m}^3 \)).

| Vane shear result | Pile group | Mass volume parameters | Shear strength |
|-------------------|------------|------------------------|---------------|
| Su kPa            | w %        | type                   | S%  | w %   | \( \gamma_d \text{kN/m}^3 \) | c kPa | \( \phi' \) |
| 23                | 17.34      | Pull out               | 90.96 | 18 | 17.17 | 18.8 | 25.51 |
| 21                | 17.82      |                        | 90.92 | 18.33 | 17.07 | 18.27 | 25.41 |
| 21                | 18.33      |                        | 92.7 | 22.71 | 17.2 | 18.45 | 24.44 |
| 20.5              | 15.62      | Single                 | 98.69 | 22.71 | 17.41 | 22.23 | 24.44 |
| 23                | 18.67      | 2x1                    | 88.6 | 17.4 | 17.34 | 28.4 | 22.18 |
| 22                | 18.55      | 2x2                    | 94.6 | 17.22 | 17.36 | 28.4 | 22.18 |
| 26.3              | 17.42      | 2x2                    | 87.86 | 17.69 | 17.07 | 16.22 | 26.65 |
Table 6. Results of ultimate bearing capacity for unsaturated soil \((S = 60\%, \ \gamma_d = 15 \text{kN/m}^3)\) with percentage of increasing compared to single pile.

| Pile group | Pull out | single | 2x1 | 3x1 | 2x2 | 3x2 | 3x3 |
|------------|----------|--------|-----|-----|-----|-----|-----|
| Qu, kPa    | 16 325 545 680 840 1280 2400 |
| \(\text{(Qu-Qu single)/Qu single} \times 100\) | 95 100 67 110 158 294 638 |
| Efficiency \(E_g = \frac{\text{Qu}}{N \text{Qu single}}\) | 0.05 1 0.84 0.7 0.65 0.66 0.83 |

Table 7. Results of ultimate bearing capacity for unsaturated soil measured at the end of loading tests of pile groups \((S = 60\%, \ \gamma_d = 15 \text{kN/m}^3)\).

| Vane shear result | Pile group | Mass- volume parameters | Shear strength parameters | UC test results |
|-------------------|------------|-------------------------|---------------------------|----------------|
| Su kPa            | w % type   | S% w % \(\gamma_d\) kN/m\(^3\) c kPa \(\phi'\) Su kPa |
| 40.6              | 14.6 Pull out | 53.6 15.1 15 14.1 27.1 16 |
| 43.8              | 14.8       | 63.3 15.2 16 |
| 44                | 15.3       | 58.6 15.1 15.5 |
| 26                | 14.4 Single | 49.1 14.1 14.6 8.9 30.5 17.7 |
| 47                | 14.5 pile  | 57.6 14.9 15.5 |
| 45                | 14.4       | 53.2 15.2 14.9 |
| 32.4              | 15.7 2x1   | 55.7 15.5 15.1 |
| 30                | 15.8       | 62.8 15.7 15.5 |
| 30                | 15.5       | 66.8 15.9 16 |
| 24.1              | 16.3 2x2   | 60 15.7 15.4 10.4 29.4 14.2 |
| 31.2              | 15.9       | 59.1 16. 15.2 |
| 36.1              | 15.8       | 65.1 15.7 15.9 |
| 31.5              | 15.9 3x1   | 57 15.5 15.2 |
| 26                | 15.9       | 63.5 15.5 15.8 |
| 30                | 15.8       | 57.5 15.4 15.3 |
| 31.2              | 15.3 3x2   | 63.1 15.3 15.9 9.7 28.8 15.8 |
| 26.3              | 15.1       | 60.4 15.6 15.5 |
| 32                | 14.8       | 60.3 15.8 15.4 |
| 35.8              | 13.9 3x2   | 62.9 15.8 15.7 11.4 25 13.7 |
| 34                | 15.0       | 59.4 15.6 15.4 |
| 28                | 14.2       | 62.4 15.5 15.7 |

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Figure 5. Load - displacement curve for different pile group in saturated and unsaturated soils.

The value of $\lambda$ was presented in a figure as a function of pile length from 0 to 90 m, Vanapalli and Taylan (2011), revised and plotted the figure as a relationship between the $\lambda$ and the ratio of pile diameter $D$ to pile penetration depth $L$, a best fit linear curve was obtained. The $\lambda = 0.32$ for $D/L$ ratio = 0.1 with other soil properties is presented in tables 3 and 5 for the soil in saturated state, giving a value of $Q_u$ presented in table 8.
2. Modified $\alpha$, $\beta$ and $\lambda$ methods, these are illustrated by equations 3, 10 and 12. They are used to obtain the ultimate pile capacity for pile in unsaturated soil. These equations are applied to piles in unsaturated soil with the following properties: $S=58\%$ and suction $(u_a-u_w)=14.48$ kPa for the average water content $w=14.4\%$, see figure 3, and fitting parameter value of $\mu=9$ equation (4), for $Ip=6$. However, the equation gives the minimum value of $Ip=8$. The fitting parameter $\mu\gamma=1.5$ average of 1 for coarse grained and 2 for fine grained soil as suggested by Vanapalli and Taylan (2011). The value of $\delta=15$ was chosen as approximate value since the value of angle of internal friction obtained from direct shear test $=30^\circ$ for single pile and the value of cohesion $c=8.9$ kN/m$^2$. These values are used in addition to the values for conventional equations presented. The results are presented in table 8.

The calculated value according to these methods represents the shaft capacity, while the end bearing capacity $Q_b$ is calculated according to Terzaghi’s theory for square footing of width $B$:

$$Q_b=1.3 c N_c + q N_q + 0.4 \gamma B N_q$$

where:

$N_c$, $N_q$, $N_q$= Terzaghi’s bearing capacity factors, and

$q =$ surcharge load (overburden at the base of the pile) $= \gamma L + q_o$.

It should be noted that all these equations presented to determine the ultimate pile capacity are based on experimental field data and therefore, they should be adopted for site piles. Scale effect must be considered when applying these equations to model piles in the laboratory. Vanapalli and Taylan (2012), suggested more experimental and numerical studies to check the validity of the modified $\alpha$, $\beta$ and $\lambda$ 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 $\alpha$, $\beta$ and $\lambda$ methods in engineering practice to estimate the ultimate shaft capacity of single piles placed in unsaturated fine-grained soil.

This increase is represented by the group efficiency: the ratio of cluster capacity to the sum of individual capacities, and the group efficiency of friction piles in clay is normally less than one, whereas the group efficiency for friction piles in sand is greater than one (Lambe and Whitman 1979).

The ultimate pull out test indicates a value of $Qu = 16$ N in table 6, which is less than the ultimate capacity for single pile under compressive load with a percent of -48%, the minus sign refers to the decrease in the ultimate load. This is due to the absence of the end bearing contribution, which has a significant value in single pile tested. Further, the results of laboratory tests at the end of each loading including laboratory vane shear and mass volume relationship revealed a value of undrained shear strength $Su$ less than 11 kPa and a value of degree of saturations $S$ and water content $w$ in the arrange of 85% and 22%, respectively as shown in table 3.

Further, the group efficiency depends on soil parameters, size and shape of pile group, pile length and spacing (Prakash and Sharma, 1990). The percentages of increase in pile capacity relative to single pile are shown in table 4., all the results indicate efficiency values greater than one for all pile groups tested. This finding may be attributed to low soil shear strength which gives a value of adhesion factor between soil and pile sometimes greater than one, and the group action is more pronounced and efficient as the number of piles increased for piles embedded in soil with these properties.

The adhesion force is too large when the soil becomes saturated as the most pile researchers agree with this justification (Lambe and Whitman 1979). The adhesion factor between the pile and soil reaches unity or even more than one when the soil is with soft consistency (Tomlinson, 1994).
The approximate range of pile group efficiency varies according to the pile group tested. These values are around unity and this is due to difficulty in ensuring the same soil consistency during the model preparation.

All the values of laboratory vane shear test and mass volume are obtained at the end of test at three different depths (sometimes two depths) these are: 10, 15 and 20 cm of the tested soil to give a whole picture of soil consistency. However, these values are not the same for all piles tested, and for the same pile. This is attributed to the accuracy of measurements, and due to difficulty of controlling the preparation of the same soil bed.

The results of laboratory tests using vane shear device for all pile groups tested, revealed values of undrained shear strength Su ranging from 19 to 25 kPa, while the mass-volume relationships give a value of degree of saturations range around to S = 90% and water content w with amounts of 18% as shown in Table 7.

### Table 8. Comparison between the measured and estimated single pile capacity using conventional and modified α, β and λ methods.

| Methods | Ultimate pile capacity, $Q_u$ (N) |
|---------|----------------------------------|
|         | α method | β method | λ method | Experimental |
|         | Shaft | Tip | Shaft | Tip | Shaft | Tip | Shaft | Tip |
| S = 90, $\gamma_d = 15$ kN/m³ | 45.0 | 67.7 | 19.8 | 35.5 | 98.0 | 122.5 | 21.5 | 41.0 |
| S = 90, $\gamma_d = 17$ kN/m³ | 91.7 | 153.0 | 12.0 | 74.0 | 233.0 | 295.0 | 90.0 | 116.0 |
| S = 60, $\gamma_d = 15$ kN/m³ | 78.0 | 281.0 | 28.0 | 231.0 | 163.0 | 366.0 | 16.0 | 325.0 |

**Conclusions:**

From the review of the test results and comparison between the results obtained from experimental work and the results according to the proposed equations, it can be concluded that:

1. The results of load displacement curves for piles embedded in soil having three different properties indicate an increase in the ultimate pile load carrying capacity with increase in the number of piles for different soil properties. This increase however, is not linear and gives a high value when the soil becomes in unsaturated state compared with soil in saturated state.

2. For saturated soil, the results obtained according to β method give a value of the ultimate bearing capacity close to the result obtained experimentally, while the other two methods give overestimated results.

3. The same finding is also obtained from the soil in unsaturated state using the modified equations.

4. The percentage of increase in pile group capacity tested in saturated soil with (S =90%, $\gamma_d$=17 kN/m³), compared with pile tested in saturated soil with (S =90%, $\gamma_d$=15 kN/m³) is: 183% for single pile, 274% for 2x1, 93% for 3x1, 126% for 2x2, 58% for 3x2 and 50% for 3x3 pile group.

The pull out results indicate a value of 318% as a percent of increase in the ultimate pile load capacity.

5. The ultimate pile capacity resulting from experimental tests for piles in unsaturated soil is compared with that of theoretical (conventional and modified) α, β and λ methods. The results indicate that using the β method gives the value of ultimate capacity close to the experimental results in saturated and unsaturated tests, while the theoretical results are overestimated when using the other two approaches.
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