# AN UNSATURATED-SOILS APPROACH TO THE BEARING CAPACITY OF FOUNDATION STRUCTURES

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**Abstract**

*Unsaturated soils are maintaining their importance for researchers and there is still much need to investigate the many engineering aspects of these soils. A new technique is proposed here to predict the variation of the bearing capacity of unsaturated soils with matric suction. The proposed method is an extension of conventional bearing-capacity theories and conceptually based on the logarithmic model of the shear strength of unsaturated soils, which only include one unknown, unsaturated parameter (the air-entry value, AEV). The possibility of predicting the unsaturated bearing capacity of soils is shown by the saturated effective shear-strength parameters c' and Ø' and the AEV from the soil-water retention curve (SWRC). Considering the necessity of validating new methods with other researchers' data, the proposed equation is tested using the published unsaturated experimental study by the author, in addition to some reported experimental studies on the shear strength for unsaturated soils and also a model footing loading on unsaturated sand under controlled suction conditions. The results of the study indicate that there is a good comparison between the "unsaturated bearing capacities" obtained via predicted and measured unsaturated strength parameters ($c_{total}$, Ø) and also between the measured/calculated bearing values of a model footing loading. Consequently, it is shown that, without needing complex unsaturated testing facilities, the proposed equation is capable of predicting the unsaturated bearing capacity for both fine-grained and sandy soils, requiring only one unsaturated parameter, which can be obtained from the SWRC or predicted using the basic soil-index properties.*

## 1 INTRODUCTION

One of the important engineering properties required for the design of shallow foundations is the bearing capacity. Several approaches are available in the literature for a determination of the bearing capacity of soils based on the saturated shear-strength parameters ([1], [2]). However, in some situations, shallow foundations are located above the ground-water table where the soil is under capillary tension and thus in a state of unsaturated condition. Besides, many kinds of natural soils, such as desiccated silts and clays, transported soils, residual soils and artificial compacted soils, are found in the unsaturated condition where $u_w<0$. Nevertheless, the bearing capacities of soils are often determined by assuming fully saturated conditions, ignoring the influence of the capillary stresses or the matric suction. Therefore, a bearing-capacity estimation of the shallow foundations using conventional approaches may not be reliable, leading to uneconomic designs.

Several researchers performed investigations on the bearing capacity of unsaturated soils ([3], [4], [5], [6], [7]) All these studies have shown that there is a significant contribution of the matric suction to the bearing capacity of unsaturated soils. However, limited theoretical research work is reported in the literature with respect to the interpretation of the bearing capacity of unsaturated soils ([3], [8]).

In this study, a semi-empirical equation is proposed to predict the variation of the bearing capacity of unsaturated soils with matric suction, using the saturated shear-strength parameters $c'$ and $Ø'$ and the air-entry value. The equation presented in this paper is developed by extending the concepts for predicting the shear strength of unsaturated soils proposed by Kayadelen et al. [9]. The equation proposed here is exercised for other studies reported in the literature that include a variation of the cohesion with the matric suction for fine-grained soils and also a sand-box model footing bearing capacity test results of unsaturated coarse-grained soils. In the content of this study, benefiting from the previously reported, unsaturated test results, unsaturated bearing capacities for a typical square footing (B=L=1m) were calculated based on unsaturated, experimental soil properties and ones obtained with the theoretical equation proposed here and a comparison was made between the bearing capacities. The studies presented in this paper show that there is a good comparison between the bearing capacities of an example square footing via theoretically and experimentally obtained soil parameters.

## 2 REVIEW OF THE BEARING CAPACITY OF UNSATURATED SOILS

Meyerhof [2] proposed an equation for predicting the bearing capacity of shallow strip footings for the soil failure mechanism. This equation is valid for strip footings resting in a homogenous soil and subjected to a vertical loading.

$$q_u = c'N_c\varepsilon_c + qN_q\varepsilon_q + 0{,}5B\gamma N_\gamma\varepsilon_\gamma \qquad (1)$$

where:

$q_u$ = ultimate bearing capacity, kPa
$q$ = overburden pressure, kPa
$c'$ = effective cohesion, kPa
$\varepsilon_c$ , $\varepsilon_q$ , $\varepsilon_\gamma$ = shape factors due to cohesion, overburden and unit weight
$N_c$ , $N_q$ , $N_\gamma$ = bearing capacity factors due to cohesion, surcharge and unit weight, respectively
$\gamma$ = soil unit weight, kN/m$^3$
B = footing width, m

As in the case of saturated soil, the bearing capacity of unsaturated soils is similarly calculated using two different methods, which are the 'effective stress approach' (ESA) and the 'total stress approach' (TSA). Oloo [4] proposed a method to predict the bearing capacity of surface footing on unsaturated fine-grained soils as extending the effective stress approach (ESA) as follows:

$$q_{ult(unsat)} = \{c' + (u_a - u_w)_b \tan Ø' + [((u_a - u_w) - (u_a - u_w)_b] \tan Ø^b\}N_c + 0{,}5B\gamma N_\gamma \qquad (2)$$

where;

$(u_a - u_w)_b$ = Air – entry value of soil
$(u_a - u_w)$ = Matric suction

Due to the limitations that the bearing capacity varies linearly and decreases beyond the residual water content for the coarse-grained soils, and converges to a certain value for fine-grained soils, which is not the general behaviour for the equation proposed by Oloo [4], Vanapalli and Mohammed [6] proposed a relationship that contains a nonlinear variation of the bearing capacity of unsaturated soils with respect to the matric suction for surface footings extending the ESA approach. The term $S^\varphi \tan Ø'$ considers the non-linear variation of the shear strength of unsaturated soils using a fitting parameter, φ. Equation (3) can be used to predict the bearing capacity of unsaturated soils that desaturate on the application of a matric suction.

$$q_u = [c' + (u_a - u_w)_b(1 - S^\varphi \tan Ø') + (u_a - u_w)_{AVR}S^\varphi \tan Ø']N_c\varepsilon_c + 0.5B\gamma N_\gamma\varepsilon_\gamma \qquad (3)$$

where:

φ = bearing capacity fitting parameter
$\varepsilon_c$ , $\varepsilon_\gamma$ = shape factors due to cohesion and unit weight
$(u_a - u_w)_{AVR}$ = Average matric suction below the foundation

The evaluation of change in pore water pressure within the effective stress zone of a foundation is relatively complex and depends on many factors, such as climatic changes, the amount of influx and outfluxes of water, soil properties, depth of the underground water table, etc. The hydrostatic line relative to the groundwater table represents an equilibrium condition where there is no flux to ground at the ground surface. During dry periods, the pore water pressure becomes more negative than that represented by hydrostatic line, and the opposite condition occurs during wet periods [7].

In arid and semi-arid areas the underground water table is found at a relatively deeper part of the soil profile, and thus soils are under a highly negative pore-water condition. The assumption of a shallower groundwater table and a hydrostatic line in such climatic conditions results in lower suction and thus lower unsaturated bearing capacity than the actual case, which causes it to remain on the safe side for foundation design.

The average matric suction below the footing can be found in Fig. 1 (Vanapalli and Mohammed, [6]).

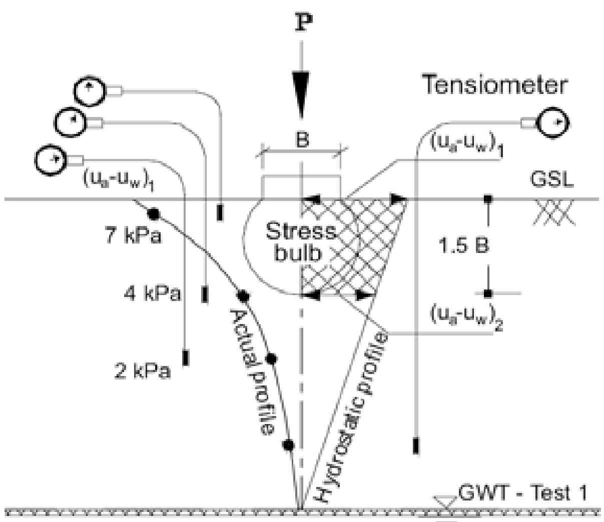


**Figure 1**. Procedure used for determining the average matric suction below the footing ([6]).

Vanapalli and Mohamed [6] extended Eq. (3) for an estimation of the bearing capacity of unsaturated fine-grained soils and suggested that the fitting parameter, φ, is a function of the plasticity index, $I_p$ , as shown in Eq. (4) (φ = 1 for $I_p$ = 0). They also experimentally found that for coarse-grained soils that φ has a value of 1. The advantage of this model is that it is capable of modelling “decrease attenuation” beyond the residual water content for some soils.

$$\varphi = -0{,}003\left(I_p\right)^2 + 0{,}3988\left(I_p\right) + 1 \qquad (4)$$

Vanapalli and Oh [10] analysed two more sets of in-situ plate load test results ([5], [11]) and showed that the φ value is constant (i.e., φ = 3.5) for $I_p$ values greater than 8%.

Some researchers performed an unsaturated loading test on site to investigate the characteristics of an unsaturated bearing capacity. Among them, Schnaid et al. [12] performed in-situ plate (0.3, 0.45, 0.6, 0.7 and 1 m) load tests on unsaturated fine-grained soils. They found that the bearing-capacity values that they calculated by the ESA were 4 to 6 times greater than the measured values. Similar trends were also observed for the in-situ plate (Dia. = 0.8 m) load tests results by Costa et al. [5]. Most researchers, for the ESA approach, interpreted the discrepancy between the measured and the predicted values as resulting from the poorly-defined drainage conditions of the pore air and water of unsaturated conditions and also due to not observing a well-defined “general shear failure” mode, which is not the most common case for unsaturated soils for both in-situ plate load and model footing tests ([4], [13], [12], [5], [11], [14]).

The behaviour of the bearing mechanism for unsaturated, fine-grained soils below footings was considered by some researchers ([13], [15]) as an occurring punching shear failure (PSF) mechanism under a total stress condition (TSA). For PSF conditions, a compressible block of soil beneath the footing is taken into consideration and slip surfaces below the footings are typically not extended to the ground surface, but instead limits to the vertical planes of that soil block. For fine-grained soils, Vanapalli et al. [13] extended the above concept and proposed a method to estimate the bearing capacity using unconfined compression-test results, as shown in Eq. (5).

$$q_{ult(unsat)} = \left[\frac{q_{u(unsat)}}{2}\right]\varepsilon_{cv}N_{cw} \qquad (5)$$

where

$q_{ult(unsat)}$ = ultimate bearing capacity for unsaturated soil,
$q_{u(unsat)}$ = unconfined compressive strength for unsaturated soil,
$N_{CW}$ = bearing-capacity factor with respect to the constant water-content condition
$\varepsilon_{cv}$ = shape factor with respect to the constant water-content condition.

Using fine-grained soils, Vanapalli et al. [13] carried out small-scale model footing tests (B × L = 50 × 50 mm) for varying matric suction values of the foundation soil (0, 55, 100, 160, 205 kPa) to study the validity of Eq. (5) and to determine the bearing-capacity factor, $N_{cw}$. They found that the calculated bearing capacities using Eqn 5 were in good agreement with the measured values as $N_{cw}$ was taken as 5.14 that is used for the Skempton [16] bearing-capacity theory. Using the in-situ plate load tests results by Costa et al. [5], Vanapalli [13] also showed the comparison between the measured bearing-capacity values and those also extending both the ESA (i.e. Eq. (2) along with the reduction factors approach and the TSA (Eq. (5)) towards the bearing capacity. The results showed that the bearing-capacity values estimated by extending the TSA are conservative and reasonable, whereas those estimated by extending the ESA are significantly overestimated.

Consoli et al. [14] performed in-situ plate (1 m × 1 m) load tests in a residual homogeneous, cohesive soil ($I_p$ = 20%). The bearing-capacity values estimated using the ESA were obtained overestimated by 1.5–2.5 times compared to the measured values. On the other hand, the bearing capacity calculated by the TSA using the average unconfined compressive strength (i.e., 50.2 kPa) was obtained with approximately the same as measured value of 1 m square concrete footing.

Oh and Vanapalli [17] proposed a model to predict the variation of shear strength of the "unsaturated fine grained" soils with respect to suction using the shear strength derived from an unconfined compression test for the specimens under saturated conditions and the SWCC as presented below. After obtaining the unsaturated cohesion for the interested matric suction value it will become possible to calculate the bearing capacity of footing benefiting from Eqn. 5 in the context of the TSA.

$$c_{u(unsat)} = c_{u(sat)}\left[1 + \frac{(u_a - u_w)}{P_a/_{101,3}}(S^v)/\mu\right] \qquad (6)$$

The studies performed by various researches ([17], [16], [10]) have shown that either by laboratory or in-situ tests, the measured unsaturated bearing-capacity values of a footing resting on unsaturated soils are in good agreement with the predicted results calculated by TSA, while it is noticeably overestimated by ESA. It can be concluded that more theoretical/laboratory works are still needed for more accurately predicting the unsaturated bearing capacities of footings, especially by ESA.

Therefore, in the content of the current study a semi-empirical model were presented for predicting the variation of unsaturated bearing capacity for both coarse- and fine-grained soils. The model is simple, requires only one unsaturated parameter (air entry value) from the soil-water characteristic curve (i.e., SWCC). The proposed model can have practical use and it enables a smooth transition between the unsaturated and saturated soil behaviour. That means the proposed semi-empirical models converts to conventionally used equations when the matric suction value is zero (i.e., the saturated condition).

## 3 AN EQUATION FOR THE BEARING CAPACITY OF UNSATURATED SOILS

Several investigators reported that the behaviour of the shear strength due to suction has a non-linear character. We previously proposed a non-linear equation for a variation of the shear strength with respect to the matric suction, matching experimental data with a matching function and assumed *logarithmic* relation between the suction strength and the matric suction ([9]). The suction contribution to shear strength was offered in a relation, as stated below:

$$\tau_{us} = \tan \emptyset'(u_a - u_w)_b + P_{at}) \ln \left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right] \qquad (7)$$

Equation (7) reflects the contribution of the matric suction to the shear strength using only one additional parameter of unsaturated properties, which is the air-entry value. This contribution might be thought to be a part of the total cohesion of unsaturated soils. Therefore, the total cohesion can be expressed as shown below:

$$c_{Total} = c' + \tan \emptyset'(u_a - u_w)_b + P_{at}) \ln \left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right] \qquad (8)$$

As can be seen, the total cohesion is composed of two parts, which is the effective cohesion (c') and the suction contribution to the cohesion $\tan \emptyset'(u_a - u_w)_b + P_{at}) \ln \left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right]$, respectively. For normally consolidated saturated cohesive soils, both the effective cohesion (c') and the suction part of the total cohesion are approximately zero and as the cohesive soils move away from saturated conditions, the suction-contribution part becomes effective and the soil gains cohesion. At this stage, the magnıtude of the cohesion is greatly enhanced due to the level of suction. For the granular soils, the effective cohesion for granular soil is approximately null, while the second part of the cohesion, which is due to suction, forms the total cohesion for the unsaturated condition, and this can also be considered as apparent cohesion for the granular soil under unsaturated conditions.

On the other hand, the equation proposed for the bearing capacity of saturated soils can be written as given below for adopting the bearing capacity of the surface footings, taking account of the influence of the shear strength contribution due to the matric suction for unsaturated soils:

$$q_u = \left[c' + \tan \emptyset'(u_a - u_w)_b + P_{at}) \ln \left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right]\right] N_c \varepsilon_c + $$
$$+ 0.5 B \gamma N_\gamma \varepsilon_\gamma \qquad (9)$$

where:

$(u_a - u_w)_b$ = Air-entry value of the foundation soil
$\varepsilon_c$ , $\varepsilon_\gamma$ = shape factors due to cohesion and unit weight (Meyerhof)
$(u_a - u_w)$ = matric suction (can be taken as the average matric suction below the footing within the effective stress zone).

The matric suction can be obtained as stated below:

$$(u_a - u_w) = (u_a - u_w)_{AVR} = {}^1\!/_2 \left[(u_a - u_w)_1 + (u_a - u_w)_2\right] \quad (10)$$

The hydrostatic water-pressure distribution that was given in Fig. 1 can be used to obtain the average matric suction below the footing, considering the effective stress zone, for practical engineering purposes. The average suction within the effective stress zone can also be measured via proper suction devices for more accurate values of the average suction.

The bearing-capacity contribution due to the matric suction can be obtained from a part of Equation (9), which is equal to

$$N_c \varepsilon_c \left[\tan \emptyset'(u_a - u_w)_b + P_{at}\right] \ln\left(\frac{(u_a - u_w) + P_{at}}{P_{at}}\right).$$

As can be seen, the AEV is the only unsaturated parameter in Eqn. (9), and it needs to be measured in the laboratory or on site, or obtained in any indirect way. The air-entry value (AEV) corresponds to the value of the negative pore-water pressure when the largest voids or pores begin to drain freely. It is a function of the maximum pore size in the soil and is also influenced by the pore-size distribution within a soil. Soils with large, uniformly shaped pores have relatively low AEVs, such as uniform sandy soils with a wider distribution of pore sizes, such as well graded silts that have a relatively higher AEV. The pores between the individual clay particles in clayey soil are small and this results in a higher value of AEV. The AEV values of soils are obtained from the volumetric water-content function of the soils and it generally varies in a narrow range, especially for sandy and silty soils, and therefore the predictions for AEV mostly do not give values that are far away from the measured values.

It is not especially difficult to obtain a direct measurement of a volumetric water-content function in a laboratory, but it requires time and finding special equipment. It is, however, standard practice to obtain a grain-size distribution curve and many soil laboratories have the facilities to obtain the grain-size distribution curves. Based on basic soil properties such as the soil grain size distribution, void ratio, Atterberg limits, several researchers presented various methods to predict the volumetric water-content function ([18], [19], [20], [21]). As an example, Aubertin et al.'s [20] method predicts the volumetric water-content function using basic soil properties such %10 and % 60 passing, void ratio and liquid limit.

Alternatively, there are some sample water-content function curves prepared for practical engineering purposes, and these curves can be used to provide an AEV value regarding the type of soils. Consequently, it is seen that with the proposed method with Eqn. 9 used here, the unsaturated bearing capacity can be calculated using saturated parameters (c', Ø') and basic soil parameters such as the grain size distribution and the index properties.

## 4 COMPARISON OF THE BEARING CAPACITIES OF UNSATURATED SOILS

In order to examine the performance of the unsaturated bearing-capacity equation, Eqn. 9, it benefited from the results of an experimental unsaturated shear strength study carried out by one previous experimental study by the author (Kayadelen et. al. [9]) and by some other researchers. Considering the difficulty of performing unsaturated tests and also the necessity of validating new methods with other previous study data, the current working methods were followed. The experimental saturated strength parameters, such as the effective cohesion c' and the internal friction angle Ø', were collected from previous published works carried out by the author and some other researchers and using Eqn. 8 the total cohesion, $c_{total}$, for unsaturated soils corresponding to various suctions were calculated. Based on calculated unsaturated strength parameters, the unsaturated bearing capacities of a typical square footing (1 m × 1 m) were calculated by the method proposed here ($q_{ult\ (with\ calculated\ parameters)}$) and also by means of the measured parameters ($q_{ult\ (with\ measured\ parameters)}$). Additionally, a sand-box measurement performed by Vanapalli et. al. [13] for the bearing capacity of the model footing on unsaturated sand with controlled suctions was also used to validate the proposed method. Bearing capacities were also calculated by the proposed Eqn. 9 and a comparison was made using the measured values obtained in the sand box.

For the current study, the saturated/unsaturated bearing capacities were calculated corresponding to various matric suction values (Ex: 0, 50, 100, 200, 300, 400 kPa) for typical model square footing. The total cohesion, $c_{total}$, (effective cohesion with suction strength contribution) were calculated for different suction values, while the internal friction angle, Ø', was taken as a constant for each interested soil. As can be seen from previous studies, the internal friction angle does not change considerably during the wetting/drying process for the unsaturated condition, especially for dealing with a range of suctions in most engineering practice (0–500 kPa). Among these studies, Vanapalli [22] showed results where Ø', independent of the suction for a glaciall till, was tested at various densities and initial water contents for a suction range of 0–500 kPa. Karube [23],

**Table 1**.Soil properties studied by various researchers.

| | | Strength Parameters | | |
|---|---|---|---|---|
| Reference | Soil Type | Ø'(°) | Air-entry value (kPa) | c' (kPa) |
| Vanapalli et. al. (1996) | Glacial Till compacted | 23 | 32 | 0 |
| Gan et. al. (1988) | Glacial Till | 25.5 | 35 | 10 |
| Miao et. al. (2002) | Nanyang expansive soil | 21.3 | 25 | 32 |
| Kayadelen et. al. (2007) | Residuel Clay | 21.9 | 40 | 14.82 |
| Vanapalli and Fathi (2007) | Sandy soil | 35 | 3 | 0 |

**Table 2**. Comparison of calculated and measured bearing capacities and total cohesions.

| Matric suction (kPa) | 0 | 50 | 100 | 250 | 400 | 500 |
|---|---|---|---|---|---|---|
| Calculated cohesion ($c_{total}$) | 0 | 14 | 38.47 | 70.36 | 90.48 | 100.77 |
| $q_{ult}$ (bearing capacity, Eqn 9, with measured parameters by Vanapalli et. al. (1996)) | 56 | 608 | 924 | 1975 | 2475 | 2764 |
| $q_{ult}$ (bearing capacity calculated by Eqn 9) | 56 | 424 | 1068 | 1906 | 2435 | 2705 |

reported similar results for a kaolinite. Drumright [24] reported that Ø' was slightly influenced by the suction. Escario and Juca [25] found that Ø' was independent of the suction for Madrid clayey sand. Therefore, for most engineering purposes it would apparent that can be assumed as constant between the suction values of 0–500 kPa.

The reported soil properties and explanations about testing programs given by various researchers were summarized in Table 1 and in the following paragraphs.

The unsaturated shear strength behaviour of a statically compacted glacial till at three different water contents and densities, which are represented by optimum, dry and wet of optimum, were studied by Vanapalli et al. [26]. The experimental results of the unsaturated shear strength were compared with the predicted shear strengths. The cohesions calculated by Eqn. 8 corresponding to various suctions, bearing capacities results by Eqn. 9 using measured /calculated unsaturated parameters ($c_{total}$ , Ø') are presented in Table 2 and Fig. 2 respectively.

Gun et al. [27] performed a series of consolidated, drained, single-stage and multi-stage direct shear tests on saturated/unsaturated compacted specimens prepared by Indian head glacial till at optimum conditions. The matric suctions ranged from 0 to 500 kPa. The cohesion calculated by Eqn. 8, with the bearing-capacity results using measured /calculated unsaturated parameters ($c_{total}$ , Ø') by Eqn. 9, are presented in Table 3 and Fig. 3, respectively.

Miao et al. [28] performed a series of tri-axial tests under saturated/unsaturated conditions on remoulded

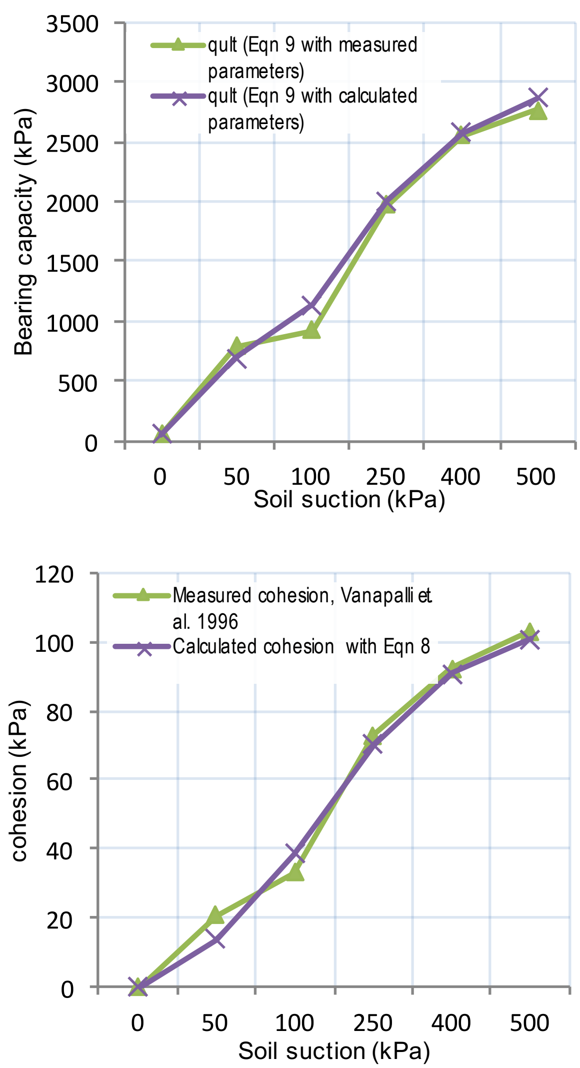


**Figure 2**. Comparison of calculated bearing capacities and total cohesions with measured values.

**Table 3.** Comparison of calculated and measured bearing capacities and total cohesions.

| Matric suction (kPa) | 0 | 50 | 100 | 200 | 300 | 400 |
|---|---|---|---|---|---|---|
| Calculated cohesion ($c_{total}$) | 10 | 36.08 | 54.64 | 80.86 | 100 | 113.96 |
| $q_{ult}$ (bearing capacity, Eqn 9, with measured parameters by Vanapalli et. al. (1996)) | 410 | 1216 | 1849 | 2765 | 3345 | 3797 |
| $q_{ult}$ (bearing capacity calculated by Eqn 9) | 410 | 1251 | 1850 | 2696 | 3313 | 3763 |

**Table 4.** Comparison of calculated and measured bearing capacities and total cohesions.

| Matric suction (kPa) | 0 | 50 | 80 | 120 | 200 |
|---|---|---|---|---|---|
| Calculated cohesion ($c_{total}$) | 32 | 51.75 | 60.66 | 70.44 | 85.67 |
| $q_{ult}$ (bearing capacity, Eqn 9, with measured parameters by Vanapalli et. al. (1996)) | 779 | 1221 | 1400 | 1677 | 2098 |
| $q_{ult}$ (bearing capacity calculated by Eqn 9) | 779 | 1233 | 1439 | 1665 | 2015 |

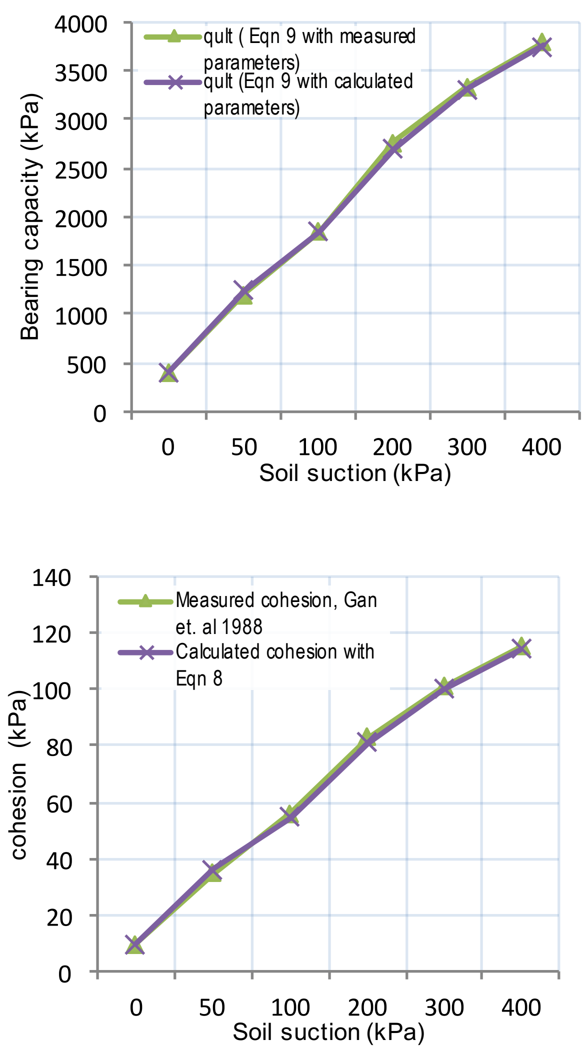


**Figure 3.** Comparison of calculated bearing capacities and total cohesions with measured values.

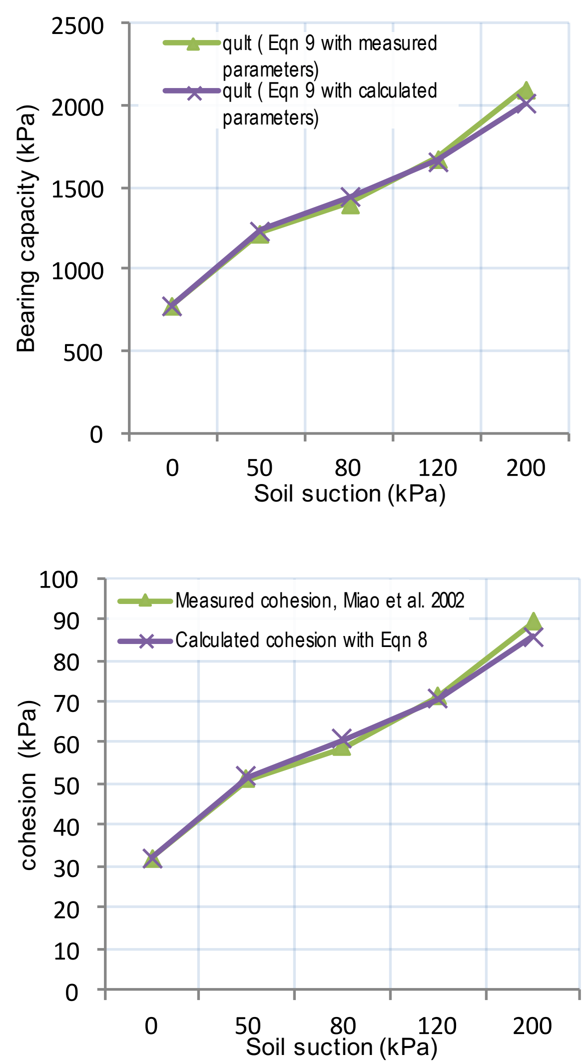


**Figure 4.** Comparison of calculated bearing capacities and total cohesions with measured values.

**Table 5.** Comparison of calculated and measured bearing capacities and total cohesions.

| Residuel clay (kPa) | 0 | 50 | 100 | 200 | 400 |
|---|---|---|---|---|---|
| Measured cohesion($c_{total}$) | 14.82 | 35.24 | 46.72 | 69.56 | 98.32 |
| Calculated cohesion $c_{total}$ () | 14.82 | 37.6 | 52.65 | 74.86 | 102.91 |
| $q_{ult}$ (bearing capacity, Eqn 9, with measured parameters by Kayadelen et. al. 2007) | 403,69 | 896 | 1173 | 1724 | 2417 |
| $q_{ult}$ (bearing capacity calculated by Eqn 9) | 403,69 | 953 | 1316 | 1852 | 2528 |

Nanyang expansive soil prepared with predetermined water contents using the static compaction effort. The unsaturated tests are performed by controlling the suction in $u_s = (u_a - u_w)$, = 50, 80, 120 and 200 kPa using unsaturated tri-axial apparatus. The cohesion calculated by Eqn. (8), bearing capacities results using measured / calculated unsaturated parameters ($c_{total}$ , Ø'), by Eqn. 9 are presented in Table 4 and Fig. 4, respectively.

The series of laboratory tests were performed by author (Kayadelen et. al. [9], author in)) using a tri-axial shear test on saturated/unsaturated residual clayey soil, including high contents of semectite and chlorite minerals. The tests were conducted on the undisturbed soil specimens under consolidated and drained conditions. A total of 12 unsaturated tests were performed and axis translation technique, as described by Fredlund and Rahardjo [7], was applied to the specimens. The air-entry value was also calculated by the method proposed by Aubertin et al [20] using %10 and % 60 passing in the grain size distribution chart and the liquid limit. The air-entry value was calculated as 40 kPa, the same as the air-entry value obtained from the experimental SWCC.

The shear strength tests were performed on both saturated and unsaturated soil specimens, which have varying matric suctions ranging from 50 to 400 kPa. The measured cohesion and calculated values with Eqn. (8), bearing capacities results, using measured/calculated unsaturated parameters (ctotal , Ø'), by Eqn. (9 were presented in Table 5 and in Fig. 5, respectively.)

Vanapalli and Fathi [6] performed a number of bearing-capacity tests by means of 100 mm × 100 mm square model footing in test tank by imposing matric suction to compacted coarse-grained soil in the range 0 to 6 kPa. By adjusting the water table level in the test tank, fully saturated and unsaturated conditions of the compacted sand in the test tank were achieved. In the testing program, they measured the bearing capacity of the model footing for 0, 2, 4 and 6 kPa imposed suctions of the foundation soil. They found that a considerable increase in the bearing capacity observed due to the contribution of matric suction for unsaturated condition.

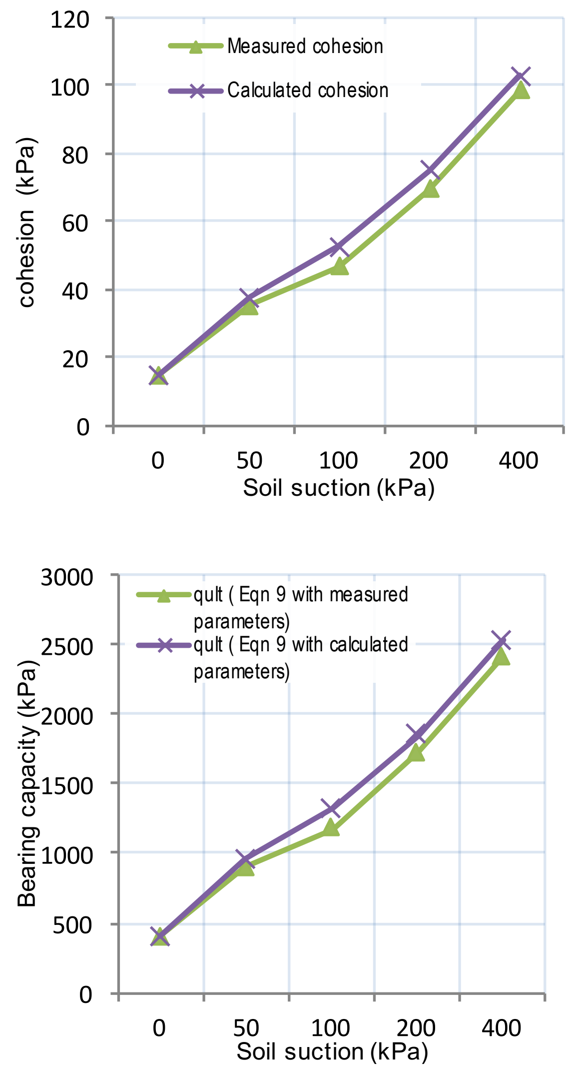


**Figure 5**. Comparison of calculated bearing capacities and total cohesions with measured values.

The cohesion calculated by Eqn. (8) and bearing capacities by Eqn. (9) are presented in Table 6 and measured/predicted cohesions values are given in Fig. 6

As the total cohesion is examined, it can be seen that it is composed of two parts, which are the effective cohesion (c') and the suction contribution to cohesion

**Table 6.** Comparison of calculated and measured bearing capacities and total cohesions.

| Matric suction (kPa) | 0 | 2 | 4 | 6 |
|---|---|---|---|---|
| Calculated cohesion(appearent) | 0 | 1.43 | 2.83 | 4.2 |
| $q_{ult,measured}$(model footing by Vanapalli and Fathi (2007)) | 100 | 575 | 700 | 860 |
| $q_{ult}$ (bearing capacity calculated by Eqn 9) | 483 | 598 | 710 | 820 |

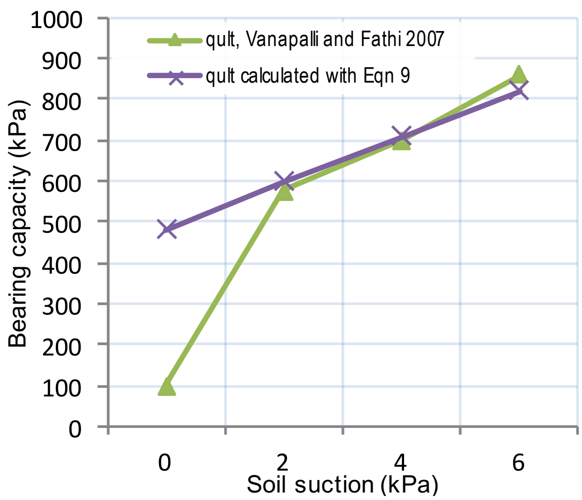


**Figure 5**. Comparison of calculated bearing capacities and total cohesions with measured values.

$(u_a - u_w) \tan Ø^b$, respectively. Since the effective cohesion for granular soil is approximately null, the second part of the cohesion, which is due to suction, forms the total cohesion and this can also be considered as the apparent cohesion for the granular soil under unsaturated conditions. In contrast to saturated soils, the cohesions calculated herein for the granular soil corresponding to various suction values should be considered in this context.

## 5 CONCLUSIONS

In this paper a simple technique is proposed for predicting the bearing capacity of unsaturated soils using the saturated shear strength parameters c' and Ø' and the air-entry value (AEV) of the soil for both coarse-and fine-grained soils. Based on the soil's grain size distribution, using several methods, such as the one proposed by Aubertin et al (2003), the AEV can be obtained from the volumetric water-content function with basic soil parameters by %10 and % 60 passing, the void ratio and the liquid limit. Another way to obtain the AEV is to use ready sample functions prepared for different types of soils. Therefore, a quite approximate AEV can be obtained without any complicated test, but only needing simple geotechnical laboratory index tests that are found in everywhere.

The new method proposed here is conceptually in the frame of effective stress approach (ESA). The results of the study indicate that there is a good comparison between the measured and predicted bearing capacity values. Eqn. 9 can also be used to calculate the unsaturated bearing capacity of foundations for practical engineering purposes, provided that we obtain the AEV from the basic soil properties.

Eqn.9 implies that the variations in the bearing capacity for unsaturated soils mainly depend on the total cohesion rather than internal friction angle, since as reported by many earlier researchers, the friction angle does not change noticeably in the unsaturated zone. Therefore, for the unsaturated zone the "total cohesion" and thus the matric suction contribution to the total cohesion become significant on the bearing capacity and it determines the magnitude of bearing capacity. Therefore, it can be said that the nonlinearity in the variation of the bearing capacity with suction is due to similar behaviour in the variation of the cohesion with suction (see Fig. 2 to Fig. 6).

Consequently, this study introduced a method of calculating the bearing capacity of unsaturated soils with a new approach, which only requires one more unsaturated parameter. This study introduced a new, simple method and validates it with various types of materials, but considering the complexity/uncertainty in behaviour of unsaturated soils, the author encourages more experimental works to encompass the method for widespread use.


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