Behavior of Partially Saturated Cohesive Soil under Strip Footing

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ABSTRACT

In this paper, a shallow foundation (strip footing), 1 m in width is assumed to be constructed on fully saturated and partially saturated Iraqi soils, and analyzed by finite element method. A procedure is proposed to define the H – modulus function from the soil water characteristic curve which is measured by the filter paper method. Fitting methods are applied through the program (SoilVision). Then, the soil water characteristic curve is converted to relation correlating the void ratio and matric suction. The slope of the latter relation can be used to define the H – modulus function.

The finite element programs SIGMA/W and SEEP/W are then used in the analysis. Eight nodded isoparametric quadrilateral elements are used for modeling both the soil skeleton and pore water pressure. A parametric study was carried out and different parameters were changed to study their effects on the behavior of partially saturated soil. These parameters include the degree of saturation of the soil (S) and depth of water table.

The study reveals that when the soil becomes partially saturated by dropping water table at different depths with different degrees of saturation, the bearing capacity of shallow foundation increases about (4 – 7) times higher than the bearing capacity of the same soil under saturated conditions. This result is attributed to matric suction value (i.e negative pore water pressure). The behavior of soil in partially saturated condition is like that of fully saturated condition but with smaller values of displacement. It is found that the settlement is reduced when the water table drops to a depth of 2 m (i.e. twice the foundation width) by about (92 %).

KEYWORDS: unsaturated soil, soil water characteristic curve, H-modulus function, matric suction.

تصرف الترب المتماسكة و المشبعة جزئيا بالماء أسفل الأساس الشريطي

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الخلاصه

في هذا البحث، تم تحليل أساس سطحي (أساس شريطي بعرض ١ م) أنشئ على تربة عراقية مشبعة كليا مرة و مشبعة جزئيا مرة اخرى، بواسطة طريقة العناصر المحددة. حيث إن الطريقة افترضت إيجاد دالة (H – Modulus) من منحني خصائص الرطوبة للتربة الذي أوجد بواسطة طريقة ورقة الترشيح، ومن خلال البرنامج (Soil Vision) وبعد تعريف الخواص الأساسية للتربة مثل حدود أتربيك، توزيع حجم الحبيبات، الوزن النوعي، المسامية والكثافة الوزنية الرطبة والجافة. ومن خلال تحويل منحني خصائص الرطوبة للتربة الى منحني العلاقة بين نسبة الفجوات ومقدار الامتصاص للتربة، ومن ميل العلاقة الأخيره تم إيجاد دالة (H – Modulus).

أستخدم في التحليل برنامج العناصر المحدده (SIGMA/W) و(SEEP/W) حيث تم إستخدام عناصر رباعية بثماني عقد لتمثيل هيكل التربة و ضغط ماء المسام. وتم تغيير قيم المعاملات التالية [درجة التشبع (S)، عمق منسوب الماء ودراسة تأثيرها على سلوك التربة غير المشبعة.

لقد بينت الدراسة إن انخفاض منسوب المياه الجوفية إلى أعماق مختلفة وبدرجات تشبع مختلفة يزيد من قابلية التحمل للأساس السطحي بحوالي (⍰ – ⍰) مرات عن قابلية التحمل لنفس التربة في حالة التشبع الكلي وهذه النتيجه تنسب الى ضغط الماء المسامي السالب المتولد من قابلية المص للتربة.

تم إستنتاج أن تصرف التربة غير المشبعة يشبه تصرف التربة المشبعة لكن بقيم أقل للهبوط الشاقولي حيث وجد إن الهبوط يقل عند انخفاض منسوب المياه أسفل الاساس الى عمق ⍰م (مرتين من عرض الاساس) بمعدل (⍰⍰%).

الكلمات الرئيسية: تربة غير مشبعة، منحني خصائص التربة – الرطوبة ، دالة معامل H ، قابلية المص للتربة.

INTRODUCTION

The mechanical behavior of partially saturated soils is different from that of fully saturated soils. A common engineering problem which often involves partially saturated soils is that of a shallow foundation resting above the ground water table. In many cases, a capillary zone exists above the ground water table, where the soil is partially saturated and which can be very large depending on the soil type. Typical footing analyses ignore this zone and assume that the soil above the ground water table is dry. The bearing capacity is one of the key parameters required in the design of shallow foundations. Several approaches are available in the literature for determination of the bearing capacity of soils based on the saturated shear strength parameters. However, in many arid and semi-arid regions, shallow foundations are usually located above the ground water table where the soil is typically in a state of unsaturated condition. Nevertheless, the bearing capacity of soils is commonly determined assuming fully saturated conditions ignoring the influence of capillary stresses or the matric suction. Due to this reason, estimation of the bearing capacity of shallow foundations using the conventional approaches may not be reliable leading to uneconomical designs **(Vanapalli and Mohammed, 2007)**.

Limited research work has been performed so far on shallow foundations in which the negative pore-water pressures of the soil were explicitly accounted for. **Rahardjo and Fredlund (1992)** presented example demonstrated the role of matric suction in affecting the value of undrained shear strength (Cu) and consequently the bearing capacity of the soil. They showed that the initial bearing capacity for the strip and the square footing was 257 and 309 kPa, respectively. The initial bearing capacity was observed to increase by 27 % when the matric suction increased by an amount equals to the undrained shear. **Fredlund and Rahardjo (1993)** proposed an extension of bearing capacity formulations to account for the increase in bearing capacity due to soil suction. The increase in bearing capacity is considered as an additional cohesive component due to matric suction, which can be estimated as $\{(u_a - u_w)\ \tan\o^b\}$. The angle $\o^b$, represents the increase in shear strength contribution due to matric suction. **Costa et al. (2003), and Mohamed and Vanapalli (2006)** showed that the bearing capacities of unsaturated soil are significantly influenced by the matric suction from their investigations on model footing tests or in situ plate load tests. **Costa et al. (2003)** used plate load test with diameter (0.8 m) and thickness (25 mm) on clayey sandy soil. **Mohamed and Vanapalli (2006)**, used model footings of different sizes (i.e., 100 mm x 100 mm and 150 mm x 150 mm) on sandy soil classified using USCS as poorly graded sand (SP) with internal friction angle of (35.3°) from direct shear test. The bearing capacity of a surface footing on saturated and unsaturated, compacted coarse-grained soil was measured using the University of Ottawa Bearing Capacity Equipment (UOBCE) that was specially designed and built for this research program at the University of Ottawa student work shop. It was shown that the matric suction values in the range of 2 to 6 kPa contributes to an increase in the bearing capacity of soil by 4 to 7 times in comparison to bearing capacity values under saturated condition.

In this paper, the finite element method is used to simulate the behavior of strip footing on unsaturated soil.

SOIL WATER CHARACTERISTIC CURVE

The soil water characteristic curve (SWCC) defines the relationship between the amount of water in the soil and soil suction. The amount of water can be a gravimetric water content, w, volumetric water content, θ, or degree of saturation, S. The SWCC is also called the water retention curve, (WTC) or the capillary pressure curve. The SWCC divides soil behavior into three distinct stages of desaturation as shown in **Fig. 1**. The stages of desturation are referred to as the "boundary effect stage" at low soil suction, the "transition stage" at intermediate soil suction, and the "residual stage" at the high soil suction that extend to 1,000,000 kPa **(Fredlund, 2006).**

There are two defining breaks along most SWCC and these are referred to as the “air entry value” of the soil and the “residual value” of the soil. These points are illustrated in **Fig. 1**, the air entry value is the point at which the difference between the air and water pressure becomes sufficiently large such that water can be displaced by air from the largest pore space in the soil. The residual degree of saturation is the point at which a further increase in suction fails to displace a significant amount of water **(Brooks and Corey, 1964)**.

The general shape of the SWCC for various soils reflects the dominating influence of material properties including pore size distribution, gain size distribution, density, organic material content, clay content, and mineralogy on the pore water retention behavior **(Lu and Likos, 2004)**.

THE PROGRAM (SIGMA/W)

SIGMA/W is a finite element software product that can be used to perform stress and deformation analyses of earth structures. Its comprehensive formulation makes it possible to analyze both simple and highly complex problems. For example, one can perform a simple linear elastic deformation analysis or a highly sophisticated nonlinear elastic-plastic effective stress analysis. When coupled with SEEP/W, another GEO-SLOPE software product, it can also model the pore-water pressure generation and dissipation in a soil structure in response to external loads. SIGMA/W has applications in the analysis and design for geotechnical, civil, and mining engineering projects **(Krahn, 2004)**.

Constitutive Models

SIGMA/W includes eight different soil constitutive models. It may be difficult to decide which model to select for a particular application, but the model which is selected must be consistent with the soil conditions and the objective of the analysis. SIGMA/W is formulated for several elastic and elastic-plastic constitutive soil models. All models may be applied to two-dimensional plane strain and axisymmetric problems.

Two constitutive models are used to study the bearing capacity of the unsaturated soils:

1. Linear elastic model

he simplest SIGMA/W soil model is the linear elastic model for which stresses are directly proportional to the strains. The proportionally constants are Young's Modulus, (E), and Poisson's Ratio, (ν). The stress and strain are related by the eq. (1):

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1-\nu)(1-2\nu)} \begin{matrix} 1-\nu & \nu & \nu & 0 \\ \nu & 1-\nu & \nu & 0 \\ \nu & \nu & 1-\nu & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} \end{matrix} \begin{matrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \end{matrix} \qquad (1)$$

For two – dimensional plane strain analysis, (ε_z) is zero.

2. Elastic – plastic model

The elastic – plastic model in SIGMA/W describes an elastic perfectly – plastic relationship. A typical stress – strain curve for this model is shown in **Fig. 2** where stresses are directly proportional to strains until the yield point is reached. Beyond the yield point, the stress – strain curve is perfectly horizontal. The material properties required for this model are given in **Table 1**.

Coupled Consolidation

A fully coupled analysis requires that both the stress – deformation and seepage dissipation equations be solved simultaneously. SIGMA/W computes displacements and stresses while SEEP/W computes the changes in pore-water pressure with time. Running these two software products in a coupled manner makes it possible to do a consolidation analysis. When coupled, both SIGMA/W and SEEP/W contribute to forming a common global characteristic (stiffness) matrix. Three equations are created for each node in the finite element mesh. Two are equilibrium (displacement) equations formed by SIGMA/W and the third is a continuity (flow) equation formed by SEEP/W. Solving all the three equations simultaneously gives both displacement and pore-water pressure changes. When doing a coupled analysis, it is essential to recognize that all equilibrium (force and displacement) conditions are defined in SIGMA/W and all hydraulic (flow) conditions are specified in SEEP/W. In SIGMA/W, the usual force and displacement boundary conditions have to be specified together with soil properties. In SEEP/W, the head and flow boundary conditions have to be specified together with hydraulic

Conductivity and volumetric water content functions.

ADDITIONAL MATERIAL PROPERTIES FOR UNSATURATED COUPLED ANALYSIS

H-Modulus Function

H is the unsaturated modulus that relates the volumetric strain of the soil to a change in negative pore-water pressure or change in suction. The H modulus may be defined as a function of negative pore-water pressure. At saturation, H is related to the elastic constants E and ν by eq. (2):

$$H = \left(\frac{E}{1-2\nu}\right) \qquad (2)$$

Therefore, H must be set to *E/(1-2ν)* at zero pore-water pressure when defining an H-Modulus versus pore-water pressure function. As a soil dries and the pore-water pressure becomes highly negative, the soil becomes very stiff. This increase in stiffness can be represented by an increase in H.

Fig. 3 illustrates a potential increase in H as a function of the negative pore-water pressure. The H modulus cannot be specified less than E/(1-2ν) . If an H modulus function is defined with an H value less than E/(1-2ν), SIGMA/W will automatically set H to E/(1-2ν) during the analysis. Consequently, when an H modulus function is defined, the lowest H value should be E/(1-2ν) at the point where the pore-water pressure is zero.

For a coupled analysis involving unsaturated soils, two additional material properties H and R need to be defined. H is a modulus relating to the change of volumetric strain in the soil structure to a change in suction. R is another modulus relating the change in volumetric water content to suction; therefore, it is given by the inverse of the slope of the soil water characteristic curve.

In this section, a procedure to obtain the H modulus parameter from the slope of a void ratio (e) versus matric suction ($u_a - u_w$) curve is described. For a soil element, a change in its volume can be decomposed into two parts:

$$dV = dV_s + dV_v \qquad (3)$$

where dV_s = the change in volume of the soil particles, and
dV_v = the change in the volume of voids.

If the volume change of the soil particles, dV_s, is small and thus neglected, the volumetric strain can be approximated as follows eq. (4):

$$\varepsilon_v = \frac{dV}{V} \approx \frac{dV_v}{V} \qquad (4)$$

From the definition of void ratio, e, a change in void ratio, *de*, is given by eq. (5):

$$de = d\left(\frac{V_v}{V_s}\right) = \frac{dV_v}{V_s} = \frac{dV_v}{(1-n)V} = \frac{d\varepsilon_v}{(1-n)} \qquad (5)$$

where: n = the porosity of the soil.

The slope of a void ratio versus matrix suction curve can be written as eq.(6):

$$\frac{de}{d(u_a - u_w)} = \frac{d\varepsilon_v}{(1-n)d(u_a - u_w)} \qquad (6)$$

In an unsaturated soil element, when only a change in matric suction occurs, the incremental volumetric strain, $d\varepsilon_v$, can be written as:

$$d\varepsilon_v = d\varepsilon_x + d\varepsilon_y + d\varepsilon_z = \frac{3d(u_a - u_w)}{H} \qquad (7)$$

$$\text{or:} \quad \frac{d\varepsilon_v}{d(u_a - u_w)} = \frac{3}{H} \qquad (8)$$

After substituting Eq. (8) into Eq. (6), it can be seen that the slope of a void ratio versus matric suction curve is: **(Wong, et al., 1998, and Krahn, 2004)**.

$$\text{Slope} = \frac{3}{(1-n)H} \qquad (9)$$

Definition of Hydraulic Conductivity

A conductivity function defines the relationship between pore water pressure and hydraulic conductivity. **Fig. 4** shows a typical conductivity function.

As soil desaturates and the water content decreases when the pore water pressure becomes negative; the ability of the soil to conduct water decreases as the water content decreases. The soil hydraulic conductivity consequently decreases as the pore water pressure becomes increasingly negative. A conductivity function is defined by specifying a series of discrete data points and fitting a weighted spline curve to the data points in order to create a continuous function.

Conductivity functions can be defined in the program SEEP/W in any of the following ways:

- Specifying each data point in the function by typing the coordinates or by clicking on the function graph.
- Estimating the function from an existing volumetric water content function.
- Importing an existing conductivity function from the SEEP/W function database or from another SEEP/W problem and modify it.

EXPERIMENTAL WORK

In this study, the aim of experimental work is to define the soil water characteristic curve (SWCC) by measuring of the soil suction.
Soil samples were collected from a three sites within Baghdad city – Al-Rusafa region namely, Sahat Al – Wathiq from depth (3.5 m), in this study referred to as (Rusafa 1), Bab Al – Muadham from depth (9.5 m, and 3.5 m) referred to as (Rusafa 2, and Rusafa 3), respectively. The physical and mechanical properties of these soil were studied by conducting a series of tests in the laboratory, these include: specific gravity, Atterberg limits, unconfined compression test, grain size distribution by sieve analysis and hydrometer, and consolidation test. **Table 2** shows the index properties of the soil. For each sample, the total and matric suction were measured by the filter paper method (Whatman No. 42) at different degrees of saturation according to **ASTM-D-5298**. With the aid of SOILVISION program, the fitted curve for the SWCC was predicted by **using Fredlund and Xing (1994)** fitting curve as shown in **Fig. 5**.

The result for Rusafa 1, soil will be presented here and shall be used in numerical analysis.

BEARING CAPACITY PROBLEM

A shallow foundation (strip footing) with width equals to 1 m is constructed on saturated and unsaturated soils. The strip footing is constructed on soil with dimensions (20 m) in width and (10 m) in height, to take into account the effect of the stress distribution below the footing. The finite element mesh is illustrated in **Fig. 6** Due to symmetry, 260 elements are used for modeling half of the footing and the soil beneath it. Eight nodded quadrilateral isoparametric elements are used for modeling the soil skeleton. The right and left hand edges of the mesh are restricted to move horizontally while the bottom of the mesh is restricted in both horizontal and vertical directions. The top edge is free in both directions. In addition, the side boundaries are assumed to be impermeable (i.e. no flow is allowed through these sides), and the top and bottom edges are assumed to be permeable.

In this work, two constitutive models are used to characterize the stress – strain behavior of the soil. Linear elastic model is used for the soil existing above the water table, while elastic – plastic model with Mohr-Coulomb failure criterion is used for modeling the soil existing below the water table.

Material Properties

The soil beneath the footing has the properties shown in **Table 3**, which were calculated from laboratory tests carried out on undisturbed samples. The soil is classified as silty clay according to the ASTM classification.

The undrained shear strength (Cu) of the soil was measured by carrying out unconfined compression test through remolding the sample at different degrees of saturation (100%, 90%, 80%, and 70%). The results demonstrate that the unconfined compressive strength (q_u) increases with the decrease of saturation (S), and consequently increase of undrained shear strength (Cu). The results of unconfined compression test are shown in **Table 4**. The initial tangent modulus of elasticity (E) was evaluated as given in **Table 4**.

H – Modulus Function

There are sets of steps considered to find the H-modulus function. These steps are proposed in this work in order to characterize the behavior of unsaturated soils:

1. The relation between gravimetric water content and suction is converted to relations correlating the void ratio and the matric suction based on the relation:

$$e = \frac{W_w \cdot G_s}{S} \qquad (10)$$

where w_w = gravitation water content,

G_s = specific gravity, and
S = degree of saturation.

Then, the slope of the void ratio versus the matric suction, m is predicted:

$$m = \frac{\Delta e}{\Delta h_m} \qquad (11)$$

where: $\Delta e = (e_2 - e_1)$, and
$\Delta h_m = (h_{m1} - h_{m2})$

h_{m1}, h_{m2} are the initial and final matric suctions, respectively.
e_1, e_2 are the initial and final void ratios, respectively.
Hence, five to seven values of the slope are predicted from this curve as show in **Table 5**.
Fig. 7 shows the steps followed to find the slope of the void ratio versus the matric suction relation the soil.

2. After finding the slope of the void ratio versus the matric suction, it can be seen that the slope, m is equal to $\frac{3}{(1-n)H}$ **(Krahn, 2004)**:
   Hence, the H-modulus function becomes:

$$H = \frac{3}{(1-n)m} \qquad (12)$$

where: n = porosity of soil,
m = the slope of the void ratio versus the matric suction.

In addition, the H must be set to E/ (1-2ν) at zero pore water pressure when defining it **(Krahn, 2004)**.

Fig.8 shows the relations between the H-modulus and the matric suction calculated for Rusafa 1 soil.

The relationship between the hydraulic conductivity and pore water pressure can be estimated from SEEP/W program as shows in **Fig. 9.**

RESULTS OF FINITE ELEMENT ANALYSIS AND DISCUSSION

At first, each type of soil was analyzed as fully saturated soil by the programs SIGMA/W and SEEP/W. The results as shown in **Fig. 10** and **Table 6** demonstrate that the failure mechanism is close to the general shear failure mode and the ultimate bearing capacity according to the criterion of the load corresponding to settlement equals to (10%) of the width of footing is in a good agreement with Trezaghi's bearing capacity equation for a surface strip footing:

$$q_u = Nc\ Cu \qquad (13)$$

where q_u = ultimate bearing capacity,
Cu = undrained shear strength, and
Nc = bearing capacity factor, which is equal to (5.7) when ø equals to zero.

Then, each type of soil was analyzed as partially saturated soil with different water table levels (2 m, 4 m, and 6 m) below the ground surface with the same degree of saturation. Later, each problem is re-analyzed with another degree of saturation. This means that for each case, the degree of saturation is changed from (90%) to (80%) and (70%) keeping the other parameters constant, and for each degree of saturation, the problem was re-analyzed with the same water table level.

In unsaturated soil (i.e. soil located above the water table), practically, the water content of this soil is varying with depth from the ground surface reaching to the water table level, and consequently the matric suction value is varied with depth above the water table level. In SIGMA/W program, it is difficult to measure the variation of matric suction with depth, therefore; in this work the matric suction is assumed constant with depth above the water table level.

Effect of Degree of Saturation and Water Table Level

Figs. 11 to 13 show the effect of dropping water table level on the behavior of unsaturated soil.
Fig.11 illustrates that the dropping of water table to depth of (2 m) leads to increasing the bearing capacity of the soil, and this increase continues when dropping the water table to 4 m, and 6 m depth. This can be attributed to increasing in matric suction value as a result of increasing of unsaturated zone and also increasing of overburden pressure.

The same trend is shown in **Figs. 12 and 13** for degree of saturation 80% and 70%, respectively.
But when comparing the three figures at same water table level with different degrees of

saturation, it can be noticed that when moving from degree of saturation 90% to 80% and 70%, the increase in bearing capacity becomes small due to small contribution of matric suction only.

The values of the ultimate bearing capacity which were obtained from these figures according to the criterion of a load corresponding to a settlement equal to (10 %) of the width of the footing are summarized in **Table 7**. From the table, it can be noticed that the ultimate bearing capacity of partially saturated soil is higher than that for fully saturated by about (4 to 7) times. This result is attributed to increasing in matric suction and overburden pressure as a result of dropping of water table. These results are consistent with the observation of **Mohammed and Vanapalli (2006)** who reported that the bearing capacity of coarse grained unsaturated soil to be (5 to 7) times higher than the bearing capacity of the same soil under saturated conditions.

From **Table 7**, it can also be noticed that at the same water table level, the increase in bearing capacity due to matric suction is only about (50 – 100) kPa.

Vertical Displacement

Fig. 14 shows the relation between the vertical surface displacement and distance from the center line of the model footing. The figure represents the soil in fully saturated and partially saturated conditions, and loaded to the same maximum value of footing stress.

Fig. 14 a illustrates that when the applied stress is equal to zero, the vertical displacement is zero along the distance from the center line, and this value is changed as the footing stress is increased. It can be noticed that with progress of applying stress, the vertical displacement starts to change, and heave at the footing end takes place.

It is also noticed that the vertical displacements near the center line of the footing are negative (downward movement), while at a distance far from the center line of the footing, they are positive (upward movement). The maximum value of vertical displacement occurs at the center line of the footing. The displacement increases with increase of the applied stress and reaches a value of (154 mm). This is due to concentration of stresses of the footing in this region. The small vertical displacement, observed under the far end away from the center line of the footing, is due to upward movement of the soil under the footing which reduces the downward movement.

In **Fig. 14 b**, the vertical displacement is traced when the soil is partially saturated and the water table is dropping to depth 2 m and the degree of saturation is 90 %. It is noticed that the distribution of vertical displacement is similar to that in condition of fully saturation state but with less values when compared at a certain value of loading. For example, when the value of stress reaches the maximum value (770 kPa), the maximum vertical displacement is (154 mm), and the maximum heave is (49 mm), when the soil is fully saturated, but the maximum vertical displacement is only (9.8 mm), and the maximum heave is (2.1 mm) when the soil is partially saturated. This is due to existing of negative pore water pressure which increases the shear strength of the soil and consequently reduces the settlement.

It is also, noticed in **Fig. 14** that the heave continues to the end of the problem mesh, another run was carried out in which the mesh was extended to a distance of 20 m, the heave was noticed to decrease gradually at about 15 m from the foundation center.

The percentage of reduction in settlement can be defined as:

Reduction in settlement (%) =

$$\frac{S_{sat} - S_{unsat}}{S_{sat}} \times 100\% \qquad (13)$$

where S_{sat} = settlement for fully saturated soil, and
S_{unsat} = settlement for partially saturated soil.

It is found that the settlement decreases when the water table drops to depth 2 m (i.e. 2 B) by about (94 %). These results approximately agree with those of **Agarwal and Rana (1987)**, who reported that when the water table is at surface, the settlement is 95 % higher than when the water table is at depth (1.5 B).

Variation of Bearing Capacity with Matric Suction

Fig. 15 shows the variation of the bearing capacity with respect to matric suction for the model footing.

These relationships demonstrate that there is significant increase in the bearing capacity of the model footing due to the contribution of suction. The results also suggest that the bearing

Capacity approximately increases linearly with matric suction up to the air – entry value and there is a non – linear increase in the bearing capacity with respect to matric suction beyond the air – entry value.

From the SWCC **(Fig. 5)** fitting curve proposed by **Fredlund and Xing (1994)**, the air – entry values of the soil is 350 kPa. The trends of the results of the bearing capacity of unsaturated soil are similar to the shear strength behavior of unsaturated soils which were reported by **Vanapalli et al. (1996)** who found that there is a linear increase in shear strength up to the air – entry value.

Vanapalli et al. (1996), demonstrated a typical relationship between the shear strength and the SWCC in **Fig. 16**. There is a linear increase in shear strength up to the air – entry value. The rate of desaturation with respect to an increase in matric suction is greatest between the air – entry value and the suction corresponding to residual water content condition. There is a nonlinear increase in shear strength in this region. Beyond the residual suction condition, the shear strength of an unsaturated soil may increase, decrease, or remain relatively constant during further desaturation depending on the type of soil. In the clayey soil, the residual state may not be well defined that even at high value of suction; it could still be considerable water available to transmit suction along the soil particle or aggregate contents, which contributes towards increases in the shear strength. This phenomenon can occur for a large range of suction value for clay soil.

CONCLUSIONS

Based on the experimental results obtained from this research work and the analysis of the behavior of partially saturated soil beneath a strip footing by the finite element method, the following conclusions can be made:

1) From the soil water characteristic curve (SWCC) which was determined by experimental method (i.e. filter paper method) the matric suction value was found to increase with decrease of the degree of saturation, and the rate of increase is not equal to rate of decrease in degree of saturation. The values of matric suction also increase with decrease of the void ratio at the same degree of saturation.
2) The procedure of analysis of the bearing capacity of shallow foundation on partially saturated soil required a proposed procedure to define the H – modulus function (H is a modulus relating the change of volumetric strain in the soil structure to change in suction). The procedure is found to be successful.
3) The water table level and the degree of saturation have the great effect on the behavior of partially saturated soil. In this work, it is found that due to dropping of water table and contribution of matric suction (i.e. negative pore water pressure), the bearing capacity of partially saturated soil increases by about (4 – 7) times higher than the bearing capacity of the same soil under saturated conditions. But, at the same water table depth, the bearing capacity increases in a small value due to contribution of matric suction only.
4) There are two phenomena governing the behavior of footing represented by settlement (negative vertical displacement) and heave (positive vertical displacement). This behavior can be explained as follows; an increase of load on the foundation will increase the settlement and the failure surface will gradually extend outward from the foundation in heave behavior. The vertical displacement of fully saturated soil is greater than that of partially saturated soil.
5) The settlement reduces when the water table drops to a depth of 2 m (i.e. 2 B) by about (94 %).

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Table 1 Elastic – plastic material properties.

Property	Definition
Elastic Modulus, E	Initial linear – elastic stiffness of the soil
Poisson's Ratio, ν	Constant value
Cohesion, c	Cohesive strength of the soil
ϕ	Soil internal friction in degree
Dilation Angle, ψ	Soil dilation angle in degree ($0 \le \psi \le ø$)
$ø^b$	a value used to make the cohesive strength a function of soil suction (negative pore – water pressure)

Table 2 Index properties of the soils for undisturbed sample.

Natural water content, W %	24.32
Dgree of saturation, S %	100
Liquid limit, L.L	34
Plastic limit, PL %	19
Plasticity index, PI %	15
Specific gravity, Gs	2.74
% clay	68.3

Table 3 Material properties for the soils beneath the footing.

Parameter	Value	Unit
Total unit weight, (γ_t)	20.21	kN/m^3
Dry unit weight, (γ_d)	16.25	kN/m^3
Angle of internal friction, (ø)	0	Degree
Poisson's ratio, (ν)* for saturated soil	0.45	—
Poisson's ratio, (ν)* for unsaturated soil	0.3	—
Hydraulic conductivity, (k_s)	2.55×10^{-10}	m/sec
Void ratio, (e)	0.666	—
Coefficient of volume change (m_v)	0.646	m^2/MN

Table 4 Results of unconfined compression test on remolded samples at different degrees of saturation.

S (%)	q_u (kPa)	Cu (kPa)	E (kPa)
100%	270	135	108000
90%	287	143.5	114800
80%	311	155.5	124400
70%	329	164.5	131600

Table 5 Values of the slopes predicted from the void ratio versus matric suction curve.

Slope	e_1	e_2	h_{m1}	h_{m2}
m_1	0.143	0.096	20000	40000
m_2	0.096	0.07	40000	60000
m_3	0.07	0.06	60000	80000
m_4	0.06	0.051	80000	100000

Table 6 Results of bearing capacity analysis of fully saturated soils for remolded sample.

Soil name	q_u according to Trezaghi's equation (kPa)	q_u by the finite element analysis (kPa)
Rusafa 1	770	760
Rusafa 2	584	580
Rusafa 3	371	380

Table 7 Results of ultimate bearing capacity (kPa) for unsaturated soil obtained from finite element analysis.

W.T depth	Degree of saturation	Bearing Capacity (kPa)
0 m	100 %	760
2 m	90 %	3200
	80 %	3250
	70 %	3300
4 m	90 %	4700
	80 %	4750
	70 %	4800
6 m	90 %	5400
	80 %	5500
	70 %	5600

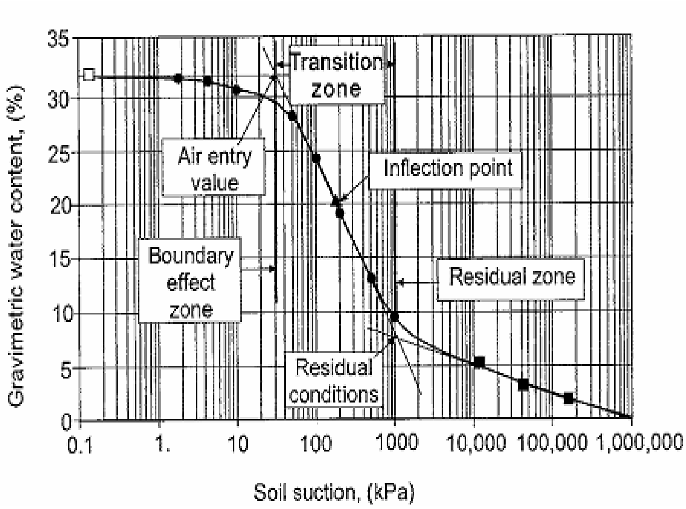


Fig. 1: Illustration of the in situ zones of desaturation defined by a soil – water characteristic curve (after Fredlund, 2006).

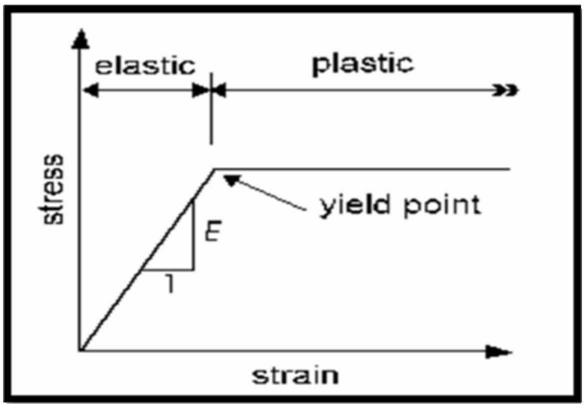


Fig.2 Elastic – perfectly plastic constitutive relationship (from Krahn, 2004).

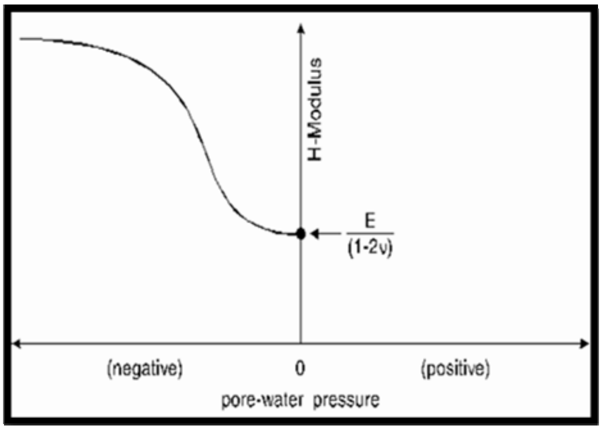


Fig.3 H-modulus as a function of pore-water pressure, (from Krahn, 2004).

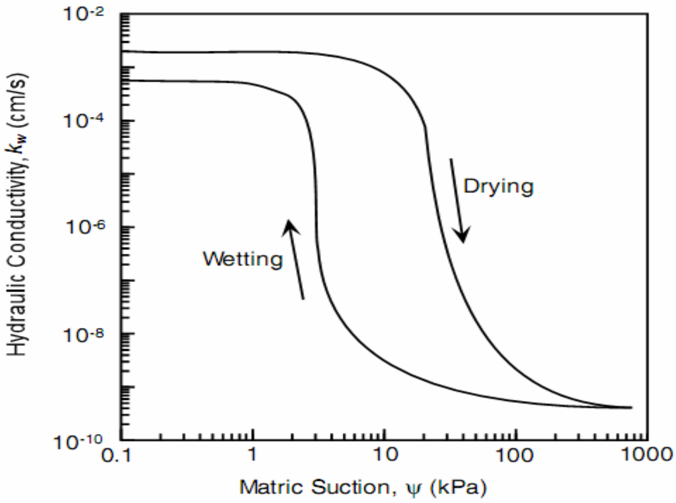


Fig. 4 Conductivity Function, (from Lu and Likos, 2004).

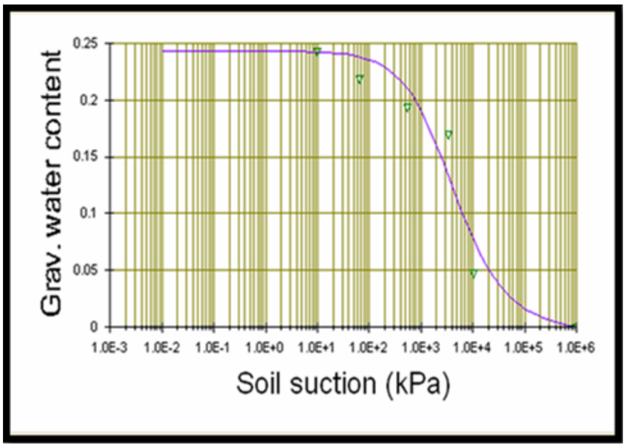


Fig. 5 Soil water characteristic fitting curve.

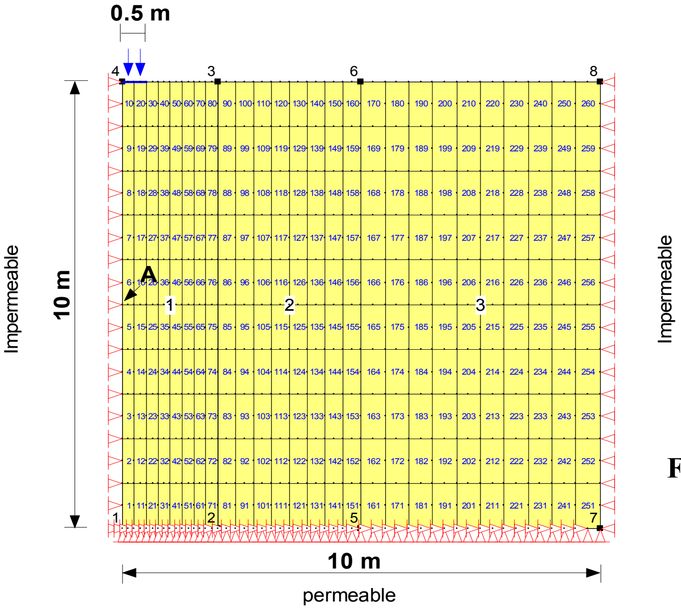


Fig.6 Typical finite element mesh of the soil beneath the footing.

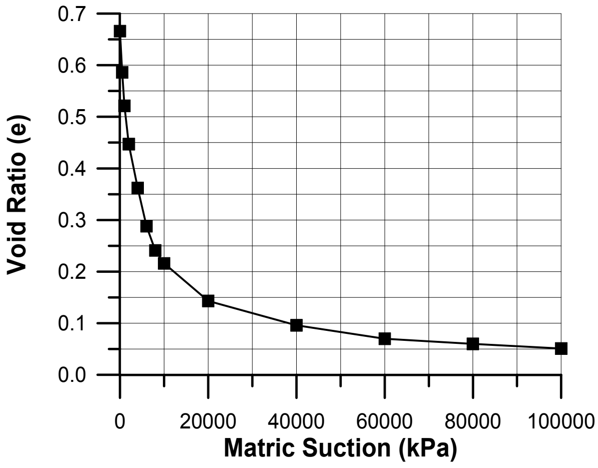


Fig. 7 Void ratio versus matric suction curve.

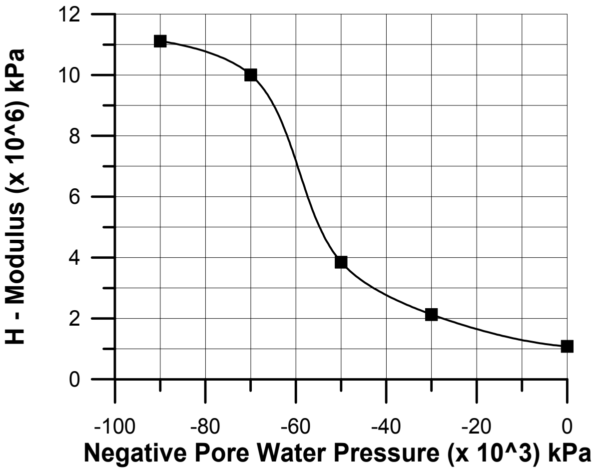


Fig. 8 H – Modulus function.

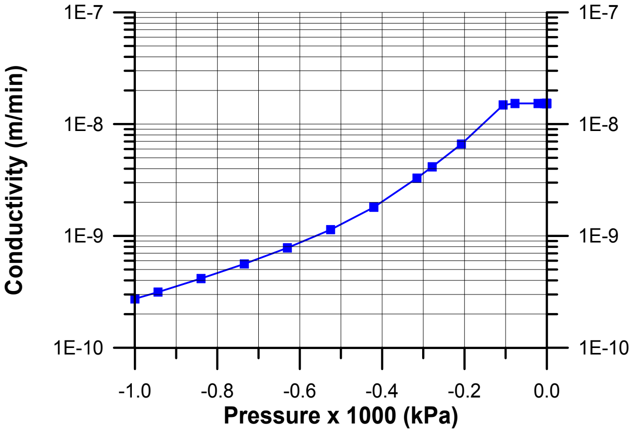


Fig. 9 Relation between the hydraulic conductivity and pore water pressure for partially saturated soils from Rusafa 1 as predicted from SEEP/W program.

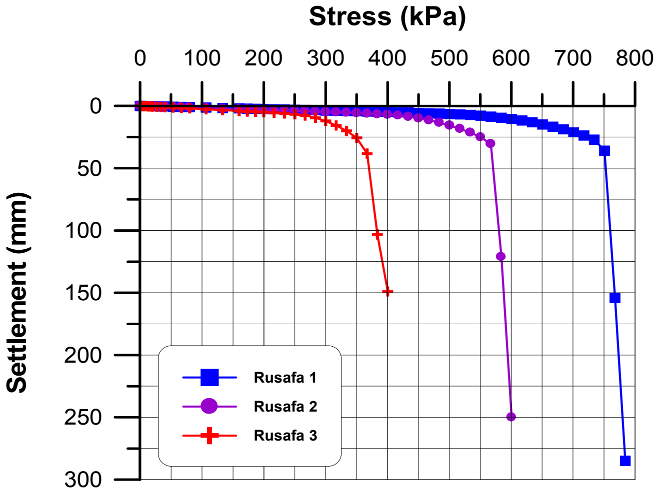


Fig. 10 Stress – settlement curve for a footing (1 m) wide over different types of fully saturated soil.

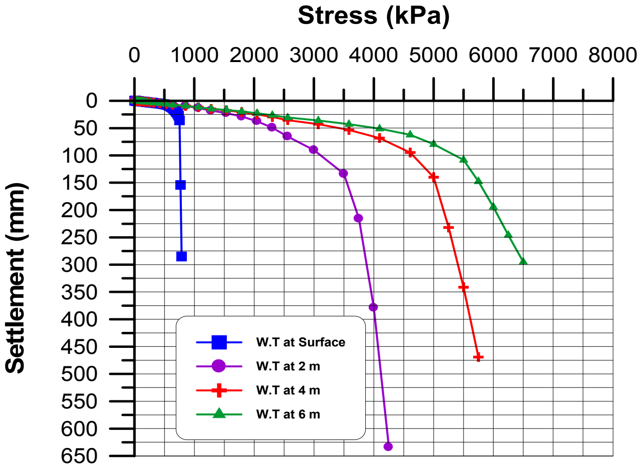


Fig.11 Stress – settlement curve for a footing (1 m) wide over Rusafa 1 soil with different conditions of water table depth at S = 90 %.

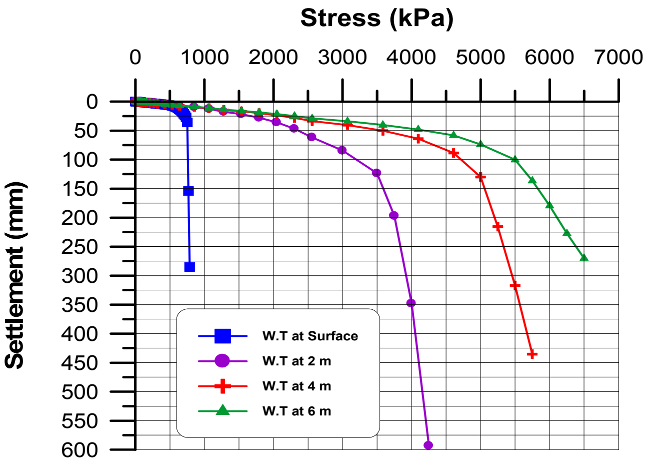


Fig 12 Stress – settlement curve for a footing (1 m) wide over Rusafa 1 soil with different conditions of water table depth at S = 80 %.

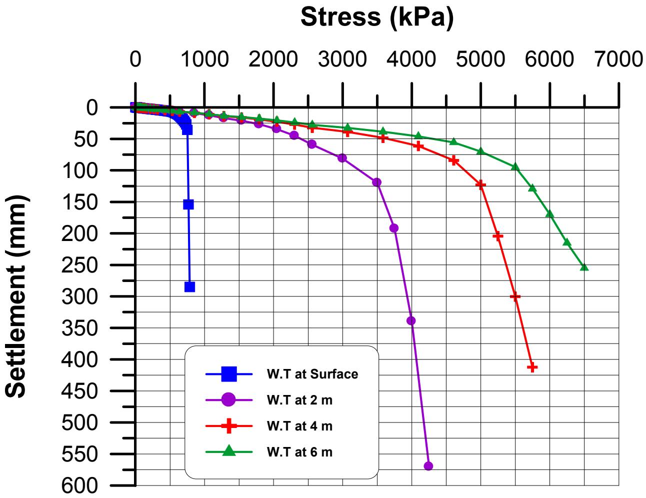
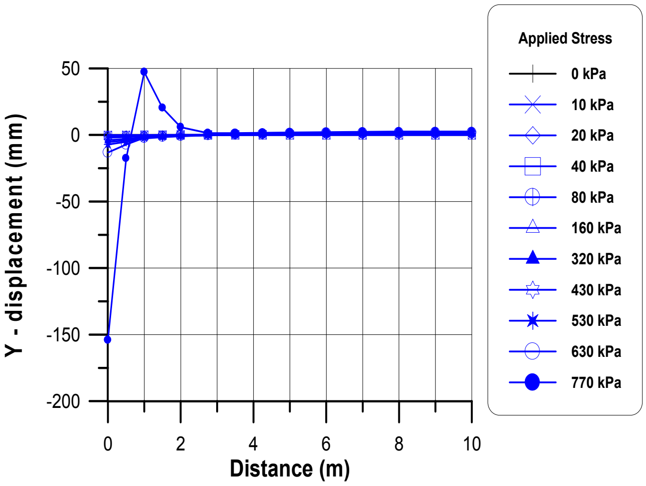
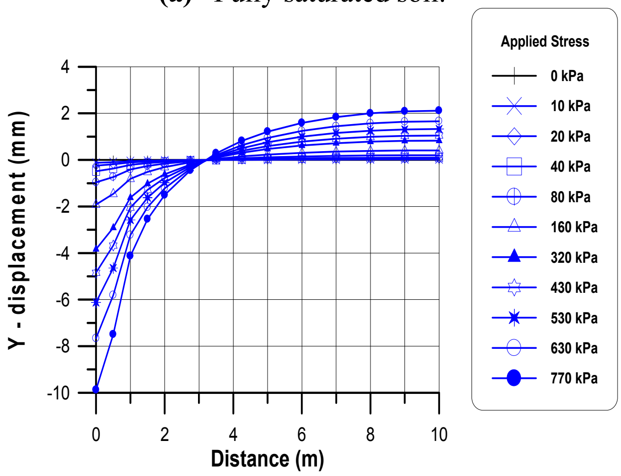


Fig.13 Stress – settlement curve for a footing (1 m) wide over Rusafa 1 soil with different conditions of water table depth at S = 70 %.



(a) Fully saturated soil.



(a) Partially saturated soil, water table at depth 2 m (S = 90%).

Fig. 14 Variation of the vertical surface displacement along the distance from the center line of the footing of Rusafa soil.

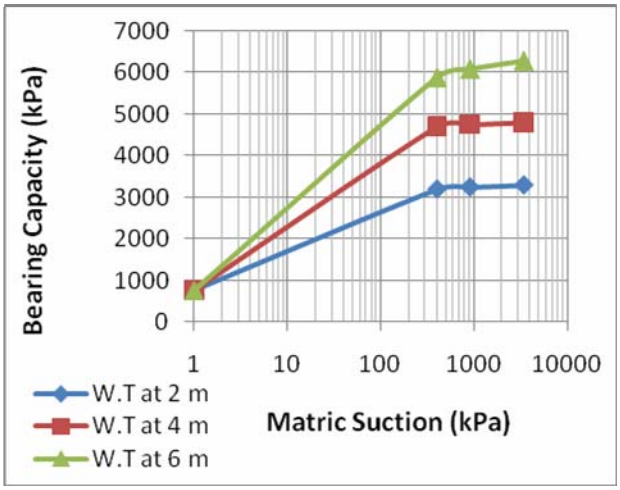


Fig. 15 Variation of the bearing capacity with respect to matric suction of Rusafa 1.

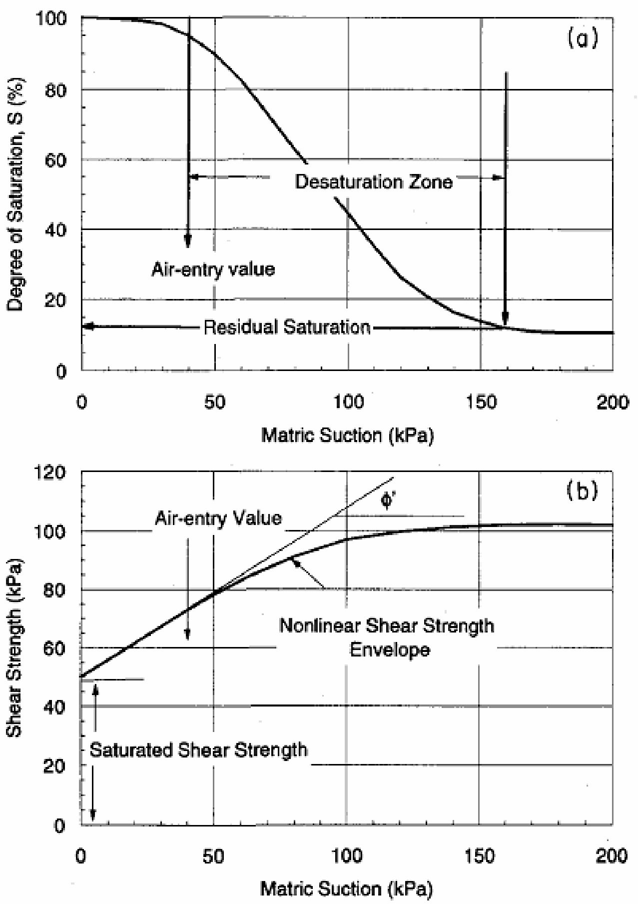


Fig. 16 Typical behavior of unsaturated soil.
(a) A typical soil water characteristic curve.
(b) Shear strength behavior of soil as it is related to the soil water characteristic curve, (from Vanapalli, et al., 1996).