Behavior of Single Pile in Unsaturated Clayey Soils

Dr. Mohammed Y. Fattah
Building and Construction Engineering Department, University of Technology/ Baghdad
Dr. Nahla M. Salim
Building and Construction Engineering Department, University of Technology/Baghdad
Isra'a Mohammed Mohsin
Building and Construction Engineering Department, University of Technology/Baghdad
Email:eng.civil_r@yahoo.com

Received on: 12/3/2013 & Accepted on: 5/9/2013

ABSTRACT

The mechanical behavior of partially saturated soils can be different from that of fully saturated soils. It has been found that for such soils, changes in suction do not have the same effect as changes in the applied stresses, and consequently the effective stress principles is not applicable.

A finite element analysis was carried out on a single pile with a diameter (0.6 m) and (12) m length embedded in fully and partially saturated clayey Iraqi soils within Baghdad city. The partially saturated parameters were calculated using laboratory methods; the filter paper method was utilized to estimate the soil water characteristic curve (SWCC) from which the H-Modulus function was obtained. The program (SoilVision) was used to make a fit of the SWCC. The finite element programs SIGMA/W and SEEP/W are then used in the analysis. A parametric study is carried out and different parameters are changed to study their effects on the behavior of partially saturated clay. These parameters include the degree of saturation, depth of water table and shear strength of clay. The study reveals that when the soil becomes partially saturated by dropping water table at different depths with different degrees of saturation, the pile capacity increases. It is concluded that the change in the water table level and the degree of saturation has a great effect on the behavior of partially saturated clay. 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 pile capacity in partially saturated soil is approximately (3-5) times higher than the capacity of piles in the same soil under saturated conditions.

Keywords: Partially Saturated Soil, SWCC, Soil Suction, Pile Capacity, Clay.

https://doi.org/10.30684/etj.32.3A.15
2412-0758/University of Technology-Iraq, Baghdad, Iraq

تصرف ركيزة مفردة في الترب الطينية غير المشبعة

الخلاصة

التصرف الميكانيكي للترب غير المشبعة يختلف بدرجة كبيرة عن تصرفها في الحالة المشبعة وقد وجد أن التغيير في تصرف التربة نتيجة التغير في ضغط الماء السالب للتربة له تأثير مختلف عن التغيير الناتج عن تسليط الاجهادات وبالتالي فأن مبدأ الاجهاد الفعال غير قابل للتطبيق في الترب غير المشبعة. استخدمت مبادئ ميكانيك التربة غير المشبعة في تحليل ركائز بقطر (0.6 م) و طول (12 م) في ترب أخذت نماذجها من مدينة بغداد , اعتبرت مشبعة مرة وغير مشبعة مرة أخرى اثناء التحليل بطريقة العناصر المحددة , حيث أن خصاص التربة والدوال المتعلقة بالحالة غير المشبعة تم قياسها مختبريا وذلك للحصول على المعامل (H) من منحني خصائص الرطوبة الذي تم الحصول عليه بطريقة ورقة الترشيح. ومن خلال برنامج (Soil Vision) بعد تحديد الخصائص الرئيسية للتربة, ثم تحويل علاقة منحني خصائص الرطوبة الى علاقة نسبة الفجوات وضغط الماء السالب وبعد تعيين مماسات العلاقة, استخدمت قيمة الميل لهذه المماسات في أيجاد(H-Modulus) .استخدم في التحليل برنامج العناصر المحددة (SIGMA/W) و (SEEP/W)حيث تم استخدام عناصر رباعية بثماني عقد لتمثيل هيكل التربة وضغط ماء المسام وقد تم تغيير عدة معاملات لدراسة تأثيرها على سلوك التربة غير المشبعة, من هذه المعاملات درجة التشبع و عمق منسوب الماء و مقاومة القص. تضمنت هذه الدراسة تأثير درجة التشبع الجزئي على قيمة أقصى مقاومة احتكاك بين التربة والركيزة, قيم αمعامل الالتصاق بين التربة والركيزة لكل عمق منسوب ماء ولكل درجة تشبع . أثبتت الدراسة أنه عندما تصبح التربة مشبعة جزئيا بمناسيب مياه بعيدة عن سطح التربة يحدث أختلاف كبير في تصرف التربة, حيث وجد أن انخفاض منسوب المياه الجوفية يؤدي الى زياده بقابلية التحمل للركائز3-5 مرات عن قابلية التحمل للركائز بترب مشبعة كليا.

INTRODUCTION

Engineering problems involving unsaturated soil span numerous sub disciplines and practices within the general field of civil engineering. Quantitative evaluation of moisture flux at the atmosphere-subsurface boundary requires not only knowledge of the relevant soil and pore water properties but also the predominant environmental conditions at the soil-atmosphere interface (Lu and Likos, 2004). Soil shrinkage is a well recognized problem which is associated with suction increase, on the other hand, soil swelling and soil structure collapse are considered as main engineering problems during suction which decrease under constant load, and these phenomena would affect the foundations if no special measures would have been taken during the design process (Nelson and Miller, 1992).

In the past, many empirical procedures have been proposed to predict soil volume changes due to suction variations but during the last fifteen years, research attention have shifted to more theoretical models. In combination with robust constitutive models, the finite element method gives the designer a nice tool to understand the mechanical behavior of unsaturated soils. It offers the opportunity to reach better design criteria. The design of a foundation is significantly influenced by the bearing capacity and settlement behavior of soils. There are several procedures or techniques available for the interpretation of the bearing capacity and settlement behavior of saturated soils (Poulos and Davids, 1980). These procedures or techniques are also conventionally used by the practicing engineers towards the estimation of the bearing capacity and the settlement behavior of soils that are in a state of unsaturated condition.

Vanapalli et al. (2008) suggested that such a practice is due to the following reasons; (i) the estimated bearing capacity and settlement of the unsaturated soils based on conventional soil mechanics for saturated soils provide conservative analysis, and (ii) the lack of a valid framework to interpret the bearing capacity and settlement behavior of unsaturated soils (Oh and Vanapalli, 2008).

Wong et al. (1998) made use of the computer programs SEEP/W and SIGMA/W to undertake their analysis, the first being used to undertake the seepage analysis while the second deals with stress-deformation behavior. They presented analysis of an unsaturated triaxial test, to investigate the effects of the gradient of the soil water characteristic curve, then go on to model a (2 m) high column of soil, with the phreatic surface at mid-height, subjected to an applied surface load. Their results indicated that while applied loads cause a significant change in the pore water pressure within saturated soil, the effects on the suctions within the unsaturated soil are all but negligible. The most significant effect was the movement of the phreatic surface. Also they concluded variations of vertical displacement with elevation, applying the pressure results in immediate and almost uniform incremental settlement in the unsaturated zone with little or no volume change below the initial water Table.

In this paper, the finite element method is utilized to analyze a single pile in sataurated and unsaturated soils. The soil suction is measured in the laboratory by the filter paper method. The distribution of shear stresses along the pile length is investigated.

Experimental work and Soil Properties

Three undisturbed soil samples were collected from three sites within Baghdad city Al-Rasafa region; namely, Sahat Al – Wathiq from depth (3.5 m), in this study referred to as (Rasafa 1), Bab Al – Muadham from depths (9.5 m, and 3.5 m) referred to as (Rasafa 2) and (Rasafa 3), respectively. Figure (1) shows that all these soils are classified as silty clay according to "ASTM" classification, and as (CL) for Rasafa 1 and Rasafa 2, and (CH) for Rasafa 3 according to the Unified Soil Classification System, the index properties of the soils are shown in Table 1.

Unconfined compression test was carried out on undisturbed samples in accordance with ASTM-D-2166-00 specification. The stress-strain relations are shown in Figure (2) from which the unconfined compression strength (q_u) and undrained shear strength of cohesive soil (Cu) are obtained.

Table (1) Index properties of the soils.

Site	Natural Water Content W (%)	Degree of Saturation S (%)	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)	Specific Gravity Gs	% Clay
Rasafa 1	24.32	100	34	19	15	2.74	68.3
Rasafa 2	25.12	95	45	27	18	2.76	66.5
Rasafa 3	31.3	96	54	27	27	2.78	80.3

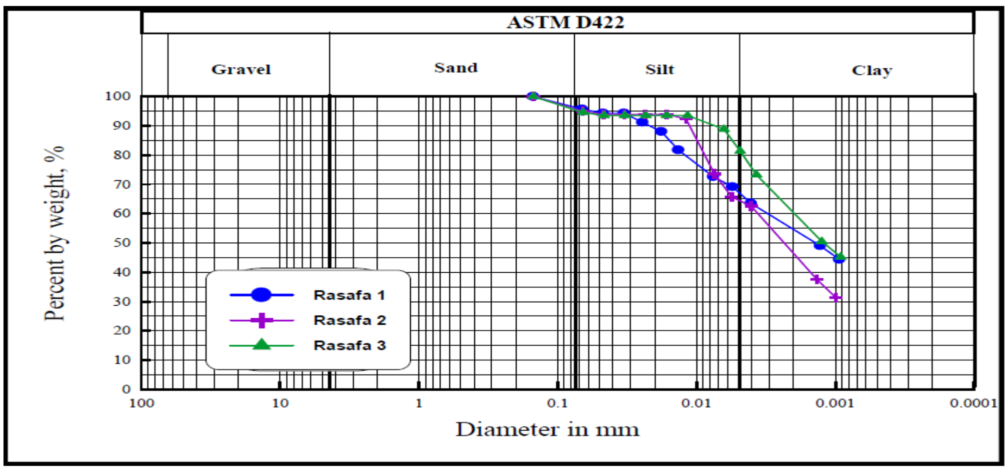


Figure (1) Grain size distribution.

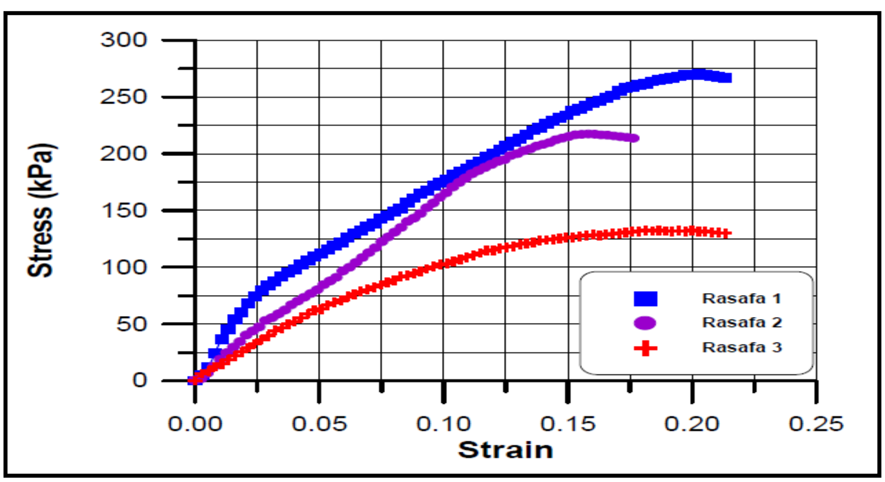
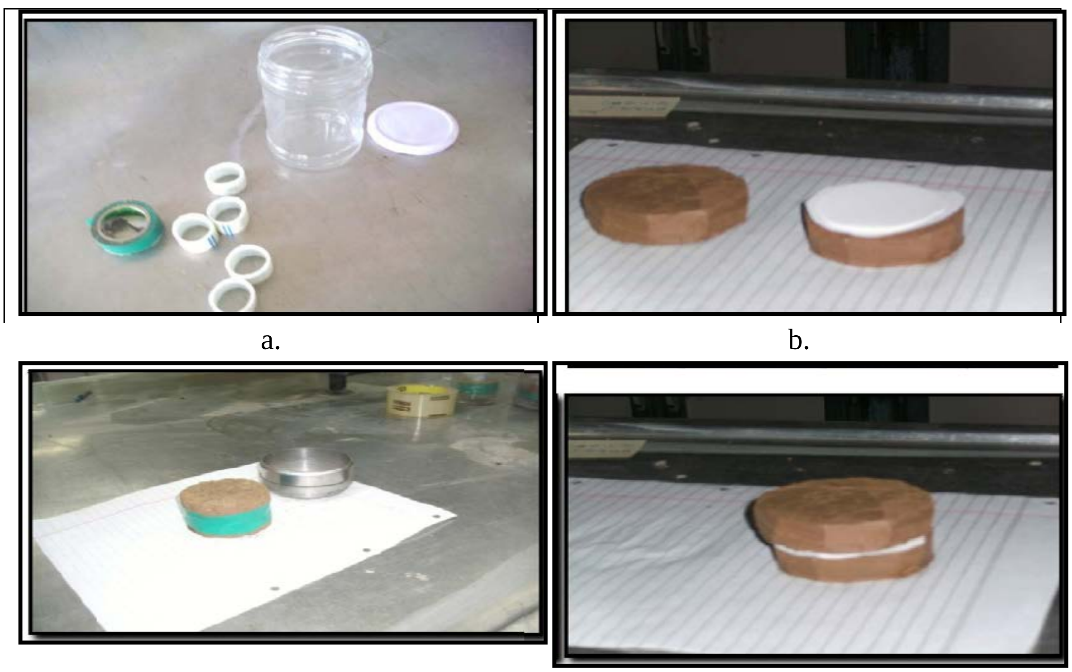


Figure (2) Stress – strain relationship from unconfined compression test for undisturbed samples.

Measurement of soil suction

The soil water characteristic curve (SWCC) defines the relationship between the amount of water in the soil and soil suction. The SWCC has been used as a tool either directly or indirectly in the prediction of the shear strength parameter and coefficient of permeability. The filter paper method is adopted to measure the total and matric suction according to (ASTM D 5298) specification.

Glass jars that are between 250 to 500 ml volume sizes are readily available and can be easily adopted for suction measurements. Glass jars, especially, with 3.5 to 4 inch (88.9 to 101.6 mm) diameter can hold the 3 inch (76.2 mm) diameter Shelby tube samples. A testing procedure for total suction measurements using filter papers is outlined following the procedure adopted by Bulut et al. (2001) and Mohsin (2012). Figures (3) and (4) show the test procedure.



a. b.

c. d.

Figure (3) Steps of the matric suction measurements (after Mohsin, 2012).

Figure (4) Steps of the total suction measurements (after Mohsin, 2012).

Description of the Problem

All the analyses involve a single concrete pile in uniform soil. The pile is 12 m long and has 0.6 m diameter with the material properties shown in Table (2).

Table (2) Concrete pile properties (from Cheong and Alvery, 2000).

Modulus of elasticity, Ec (kPa)	Poisson's ratio (ν)	Unit weight (kN/m^3)	Cohesion (kPa)
21250 * 10^3	0.2	23.5	2700

Finite element description and constitutive model

The finite element mesh for the axisymmetric problem is shown in Figure (5). Eight nodded isoparametric quadrilateral elements are used for modeling all the cases. Due to symmetry, only half of the mesh is considered. The right and left hand edges of the mesh are restricted horizontally and the bottom of the mesh is restricted in both horizontal and vertical directions, the top edge is free in both directions.

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

The undrained shear strength (Cu) of each soil was measured by carrying out unconfined compression test through remolding the samples 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 the degree of saturation (S), and consequently increase of undrained shear strength (Cu); the results of unconfined compression test are shown in Table (3) and Figure (6) for Rasafa1 soil. Similar relations were obtained for Rasafa2 and Rasafa3 soils.

The pile is assumed to be constructed in saturated and unsaturated soils. The undisturbed soil samples obtained from three sites in Baghdad having different degrees of saturation, the undisturbed samples have material properties shown in Table (4) as obtained from laboratory tests carried out on these undistributed samples.

Table (3) Results of unconfined compression test on remolded samples at different degrees of saturation.

Type of Soil	S (%)	q_u (kPa)	Cu (kPa)	E (kPa)
Rasafa 1	100%	270	135	*135000*
	90%	287	143.5	*143500*
	80%	311	155.5	*155500*
	70%	329	164.5	*164500*
Rasafa 2	100%	205	102.5	*102500*
	90%	227	113.5	*113500*
	80%	238	119	*119000*
	70%	252	126	*126000*
Rasafa 3	100%	130	65	*65000*
	90%	151	75.5	*75500*
	80%	164	82	*82000*
	70%	*176*	*88*	*88000*

Required Relationships for Unsaturated Soils

There are some relationships that are required in dealing with partially saturated soil characteristics, these are:

1. Suction with degree of saturation

Total and matric suction of each soil sample were measured by remodeling the samples at different degrees of saturation (70%, 80%, 90% and 20%) using filter paper method (Whatman No. 42) according to the procedure of (ASTM D 5298-03). Figures (7) and (8) show the relationship between total and matric suction and the degree of saturation, respectively.

From these figures, it can be noticed that the suction of soil decreases with the increase in the degree of saturation and the rate of increase in matric suction of Rasafa1 is greater than the rate for Rasafa2 and Rasafa3 for the same degree of saturation. This is due to the difference in physical properties for each soil. Rasafa1 has a value of density greater than the other two sites, high value of density results in high values of suction. This is due to increase in clay content and decrease in the distance among the soil particles (Fattah et al., 2013).

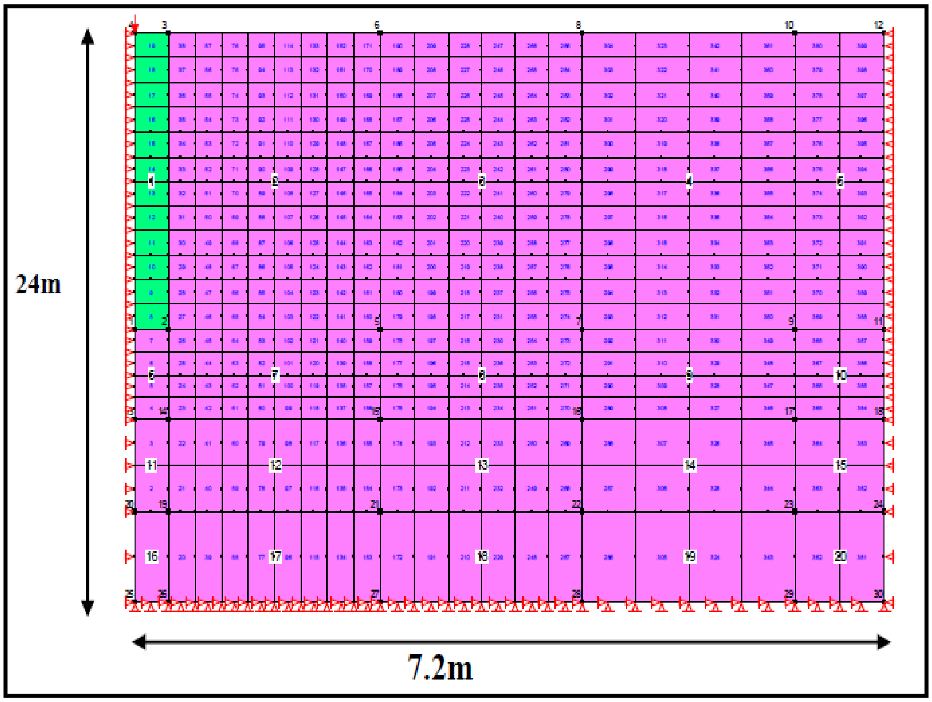


Figure (5) Typical finite element mesh of the pile-soil system.

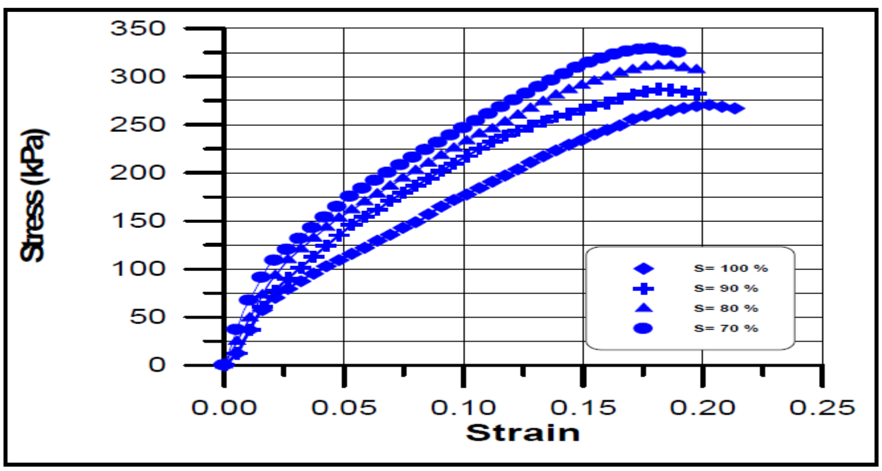


Figure (6) Results of unconfined compression test on remolded samples from (Rasafa 1) site at different degrees of saturation.

Table (4) Material properties for three soils of study.

Type of Soil	Parameter	Value	Unit
Rasafa 1	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)	2.55×10^{-10}	m/sec
	Void ratio, (e)	0.666	—
	Coefficient of volume change (m_v)	0.646	m^2/MN
Rasafa 2	Total unit weight, (γ_t)	19.57	kN/m^3
	Dry unit weight, (γ_d)	15.64	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)	2.78×10^{-10}	m/sec
	Void ratio, (e)	0.73	—
	Coefficient of volume change (m_v)	0.58	m^2/MN
Rasafa 3	Total unit weight, (γ_t)	18.82	kN/m^3
	Dry unit weight, (γ_d)	14.33	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)	2.85×10^{-10}	m/sec
	Void ratio, (e)	0.903	—
	Coefficient of volume change (m_v)	0.716	m^2/MN

* Assumed values (according to Bowles, 1996).

2. H-Modulus function

The 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 υ by the equation:

$$H = \frac{E}{1-2\vartheta} \qquad \text{... (1)}$$

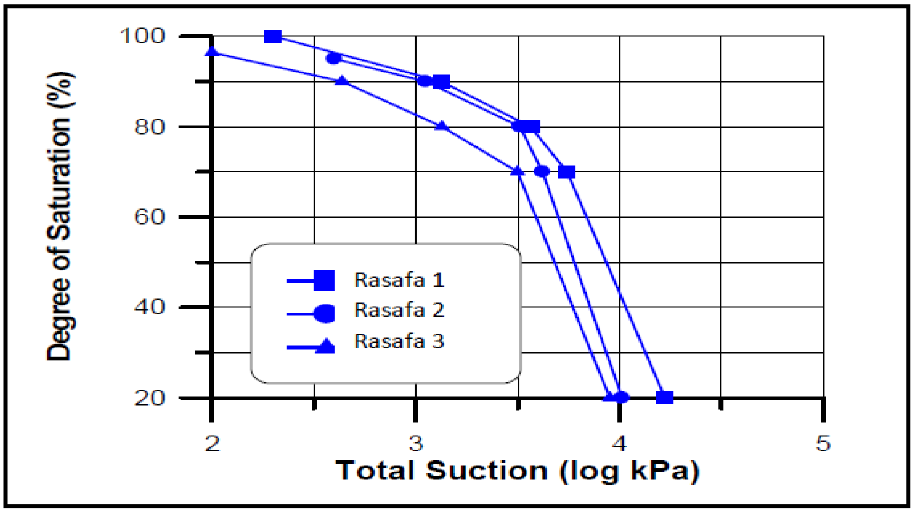


Figure (7) Relationship between the total suction and degree of saturation for the three soils.

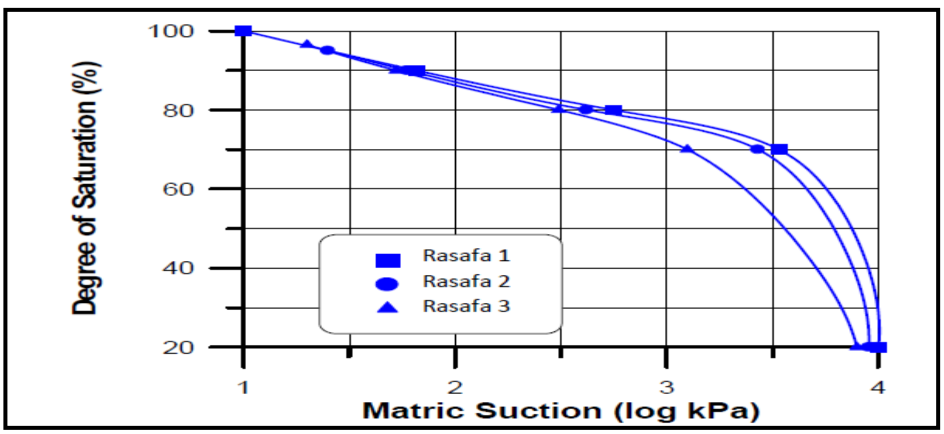


Figure (8) Relationship between the matric suction and degree of saturation for the three soils.

Therefore, H must be set to E / (1 – 2 υ) at zero pore water pressure (Krahn, 2004). When defining an H-Modulus with 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 is represented by an increase in H.

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. From the program (Soil Vision), and after inputting all the required properties of the soils used in this analysis, (i.e., total unit weight, dry unit weight, liquid limit, plasticity index, void ratio, porosity, matric suction value, degree of saturation, and grain size distribution), the soil water characteristic curve is predicted (relation between the gravitation water content and the matric suction) through applying fitting methods, such as the method proposed by Fredlund and Xing (1994) and Van Genuchten (1980) for fitting the soil water characteristic curve see (Figure 13).

2. The previous relations are converted to relations correlating the void ratio and the matric suction based on the relation:

$$e = \frac{wGs}{S} \qquad \text{.... (2)}$$

where

w= gravitation water content,

G_s = specific gravity of soil solids, and

S = degree of saturation.

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

$$m = \frac{\Delta e}{\Delta h_m} \qquad \text{... (3)}$$

where: $\Delta e = (e_2 - e_1)$,

$\Delta h_m = (h_{m1} - h_{m2})$,

h_{m1}, h_{m2} are the initial and final matric suctions, respectively, and

e_1, e_2 are the initial and final void ratios, respectively.

Figure (10) shows the steps followed to find the slope of the void ratio versus the matric suction relation for Rasafa2 soil.

3. After finding the slope of the segments on the curve of void ratio versus the matric suction of different types of the soil, it can be seen that each slope, m is equal to $\frac{3}{(1-n)H}$ (Krahn, 2004):

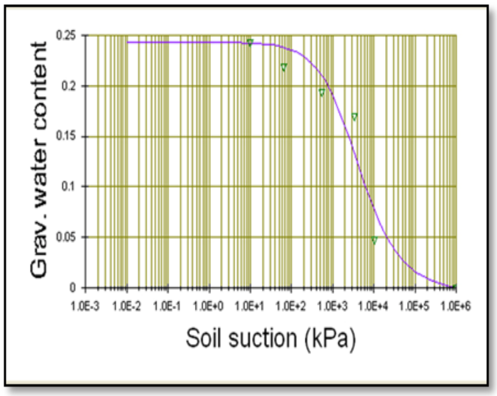
Hence, the H-modulus function becomes:

$$H = \frac{3}{(1-n)\,m} \qquad \text{... (4)}$$

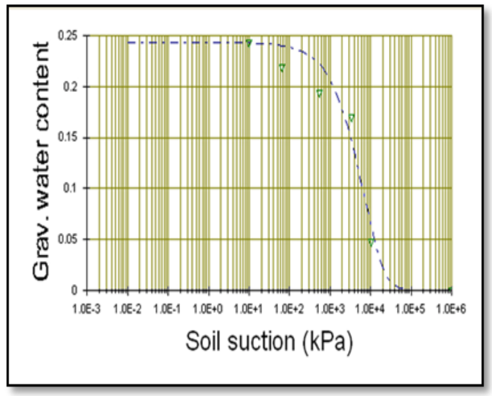
where: n = porosity of soil, and

m = the slope of the void ratio versus the matric suction.

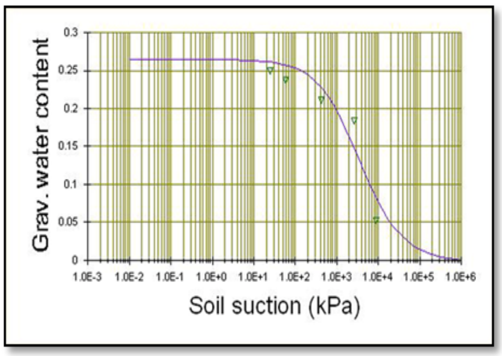
The H-modulus functions for the three soils are shown in Figure (11).



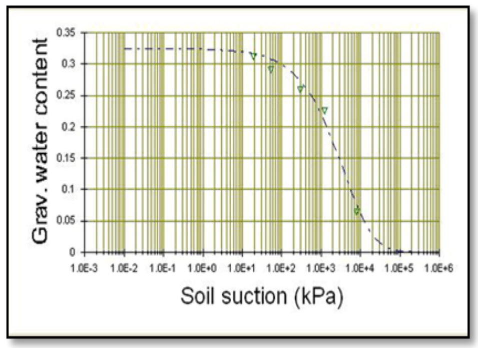
a. Using Fredlund and Xing (1994) fitting for Rasafa 1.



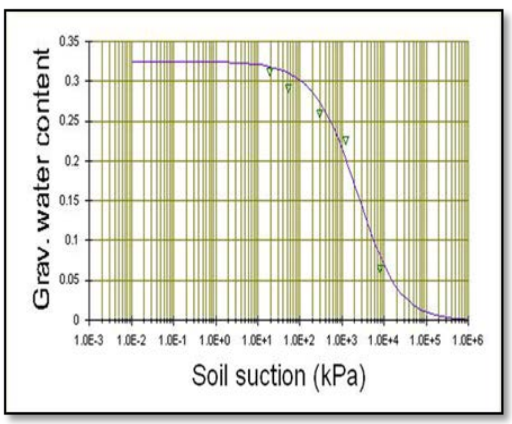
b. Using Van Genuchten (1980) fitting for Rasafa 1.



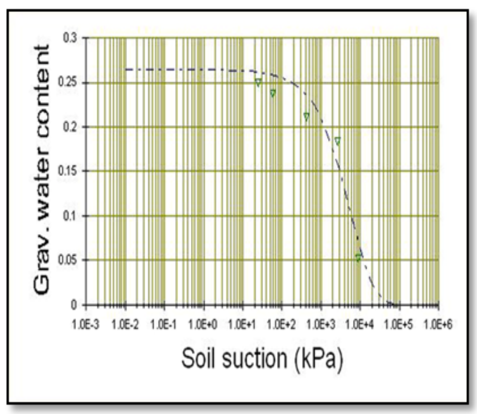
c. Using Fredlund and Xing (1994) fitting for Rasafa 2.



d. Using Van Genuchten (1980) fitting for Rasafa 2.



e. Using Fredlund and Xing (1994) fitting for Rasafa 3.



f. Using Van Genuchten (1980) fitting for Rasafa 3.

Figure (9) Relationships between the gravitational water content and the matric suction for different soil types obtained by the program Soil Vision.

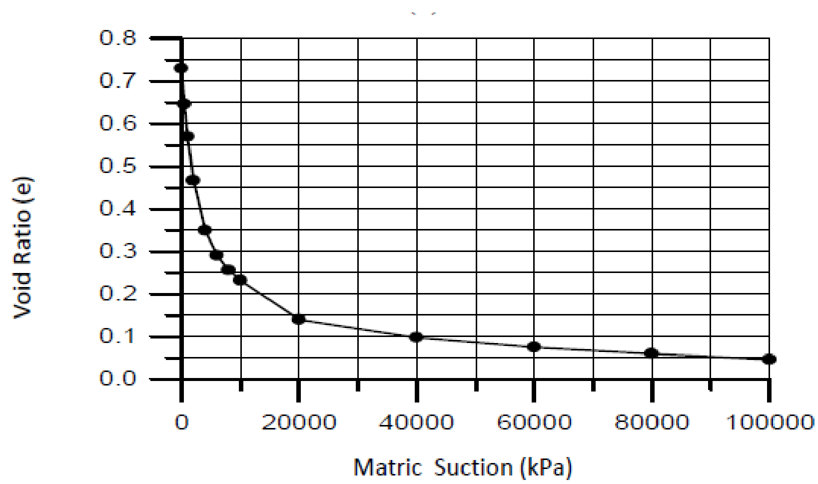
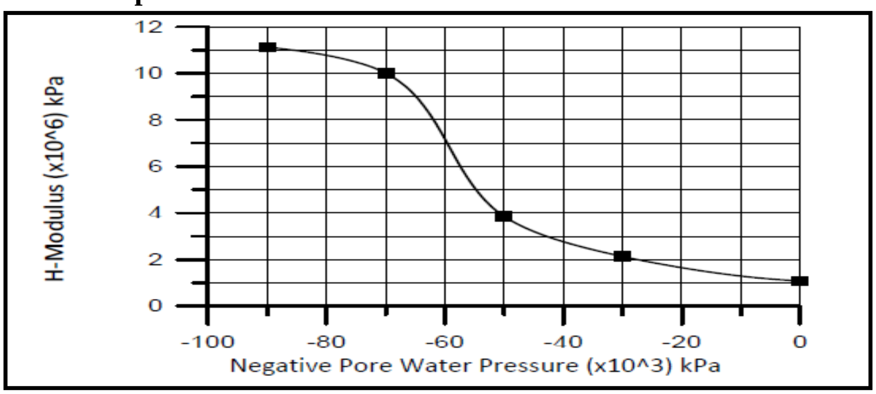
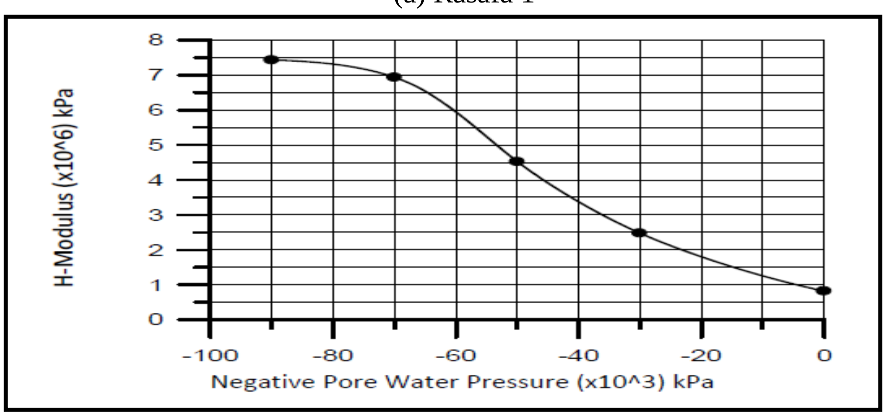


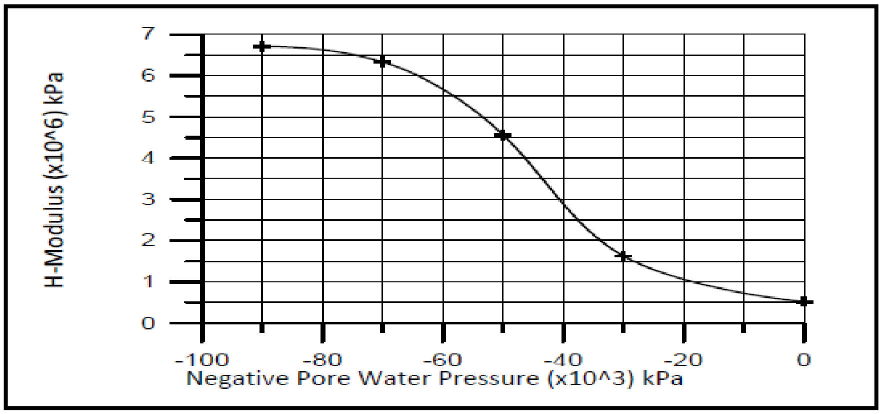
Figure (10) Relationships between void ratio and matric suction for Rasafa2 soil.



(a) Rasafa 1



(b) Rasafa 2



(c) Rasafa 3

Figure (11) Relations between the H-modulus and the matric suction for different soil types.

3. Volumetric water content

In soil science, volumetric water content is most commonly used. In geotechnical engineering practice, gravimetric water content *w*, which is the ratio of the mass of water to the mass of solids, is most commonly used. Fredlund and Rahardjo (1993), defined the volumetric water content as the ratio of volume of water, *Vw*, to the total volume of the soil,

$$\theta_w = \frac{V_w}{V} \qquad \dots (5)$$

The volumetric water content can also be expressed in terms of specific gravity, G_s, void ratio, e, and water content as a function of soil suction:

$$\theta_w = \frac{w(h)\, G_s}{1 + e} \qquad \dots (6)$$

where:

w(h) = gravimetric water content as a function of matric suction of soil.

One of required input data in SEEP/W program is relationship between volumetric water content and pore water pressure. SEEP/W can estimate this relationship from input data such as, volumetric water content at saturated condition, θ_s, and coefficient of volume change, m_v, and from closed form solution of Van Genuchten (1980), or Fredlund and Xing (1994).The four parameters *a*, *n*, *m* and h_r, can be obtained from a semi log plot of the soil water characteristic curve.

First, the suction corresponding to the residual water content h_r, is determined by locating a point where the curve starts to drop linearly in the high suction range. Next, the inflection point (h_i, θ_i) is located on the semi log plot and a tangent line is drawn through this point. Then the fitting parameters *a*, *n*, and *m* can be determined as follows:

$$a = h_i \qquad \text{..... (7)}$$

$$m = 3.67 ln\left[\frac{\theta_s C(h_i)}{\theta_i}\right] \qquad \text{.... (8)}$$

$$n = \frac{1.31^{m+1}}{mC(h_i)} 3.72 S^* \qquad \text{... (9)}$$

where:

θ_s = volumetric water content at saturated condition, and

h_i = the suction corresponding to infection point.

$$S^* = \frac{S}{\theta_s} - \frac{h_i}{1.31^m (h_i + h_r) \ln\left[1 + \left(1{,}000{,}0000/h_r\right)\right]} \qquad \text{... (10)}$$

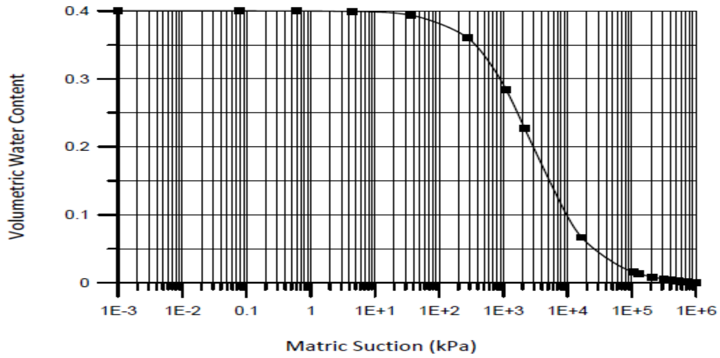
The slope, s, of the tangent line can be calculated as follows:

$$s = \frac{\theta_i}{\ln\left(h_p/h_i\right)} \qquad \text{... (11)}$$

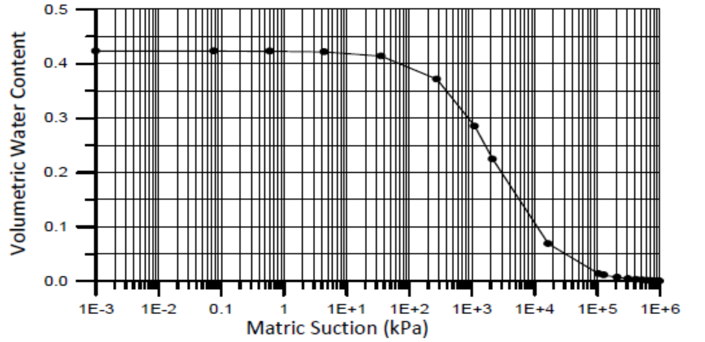
where:

h_p = intercept of the tangent line on the semi log plot on matric suction axis.

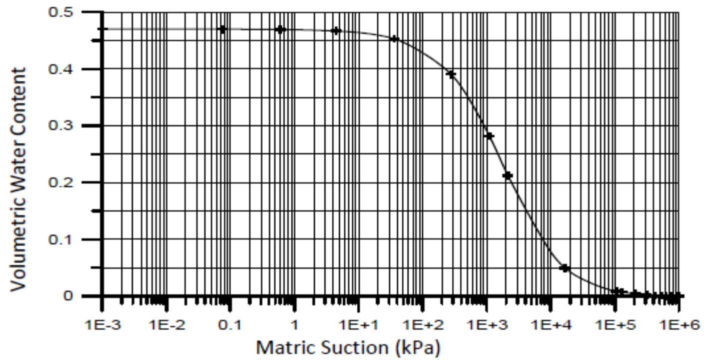
Figure (12) shows the estimated relation between the volumetric water content and matric suction (negative pore water pressure for the soils). After estimating the relation between the volumetric water content and pore water pressure, Figure (12), a relationship between the hydraulic conductivity and pore water pressure can be estimated. This relation is shown in Figure (13) for the three soils.



(a) Rasafa 1

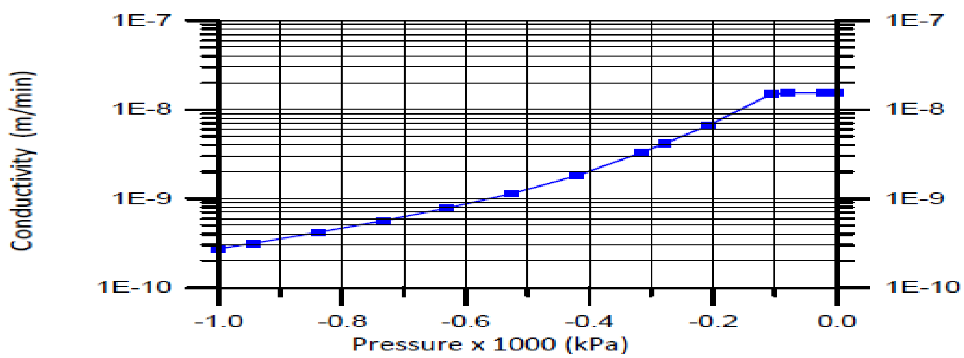


(b) Rasafa 2

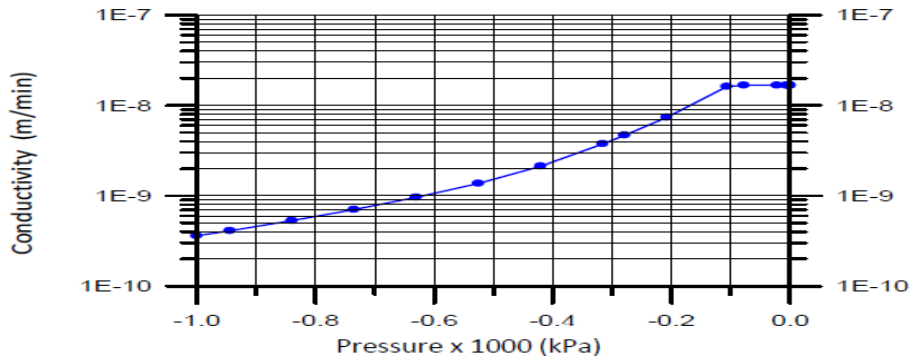


(c) Rasafa 3

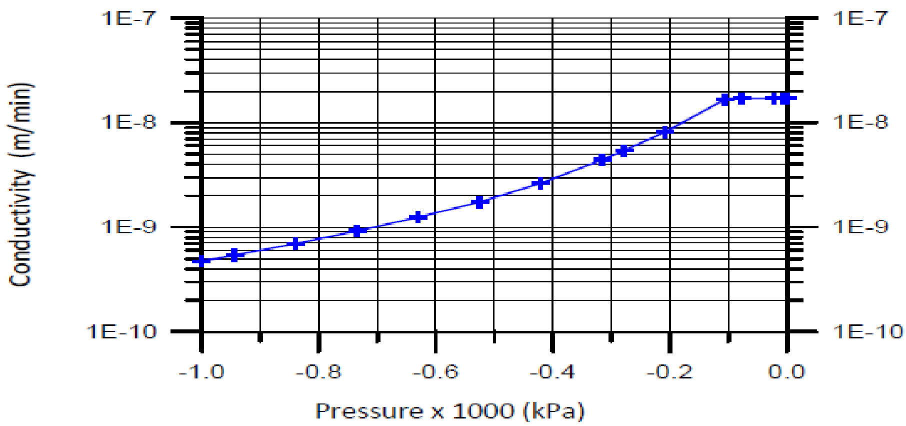
Figure (12) Relationships between volumetric water content and matric suction for the three soils.



(a) Rasafa 1



(b) Rasafa 2



(c) Rasafa 3

Figure (13) Relation between the hydraulic conductivity and pore water pressure for partially saturated soils of the three sites.

Finite Elements Analysis of Piles in Unsaturated Soils

Each type of soil was analyzed first as fully saturated soil by the programs SIGMA/W and SEEP/W. The results shown in Figure (14) and Table (5) demonstrate that the failure mechanism is close to the punching shear failure mode and the ultimate bearing capacity according to the criterion of the load corresponding to settlement equal to (10%) of the pile diameter is in a good agreement with bearing capacity equation for piles in cohesive soil. A modified Terzaghi bearing capacity equation is used to find the pile capacity:-

$$Pu = Qu + Su \quad \dots (12)$$

$$Pu = 9 \, . c . Ac + \alpha \, . c \, . Ap \quad \dots (13)$$

where:

Pu = ultimate pile capacity,

Qu = ultimate end bearing capacity,

Su = ultimate skin friction,
c = cohesion of the soil,
Ac = cross sectional area of the pile,
α =adhesion factor between pile and soil, and
A_p = shaft area along the pile.

Effect of water table and degree of saturation on the capacity of pile is studied for the three types of soil, for each type of soil, the depth of water table is varied (2 m,4 m,6 m, and 12 m) and (70%, 80%, and 90%) degrees of saturation for soil above water table were analyzed.

Table (5) Results of analysis of the capacity of piles in saturated soils.

Soil type	Pu according to Equation (13) (kN)	Pu corresponding to settlement of 10% of pile diameter (kN)
Rasafa 1	1565	2100
Rasafa 2	1246	1100
Rasafa 3	765	1300

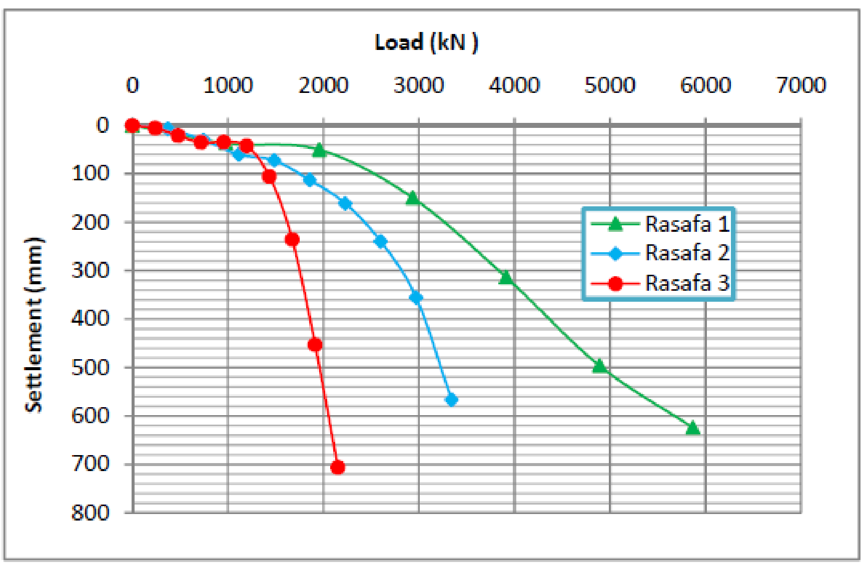


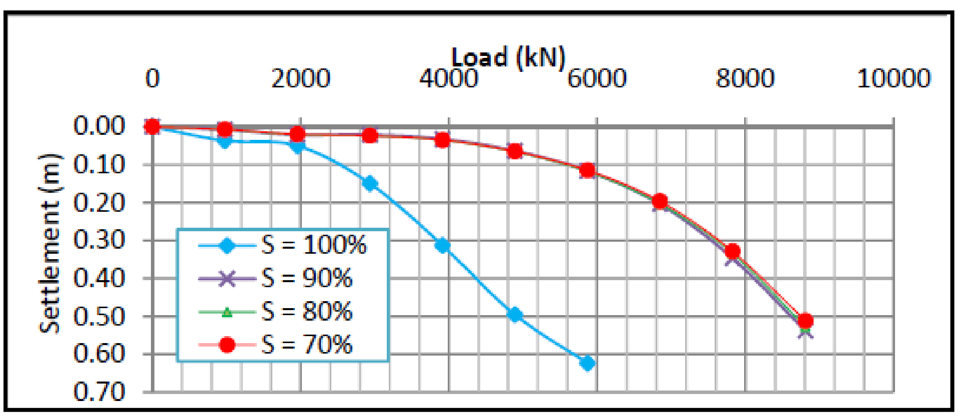
Figure (14) Load settlement curves of (0.6m) diameter pile in different types of fully saturated soils.

1. Effect of degree of saturation

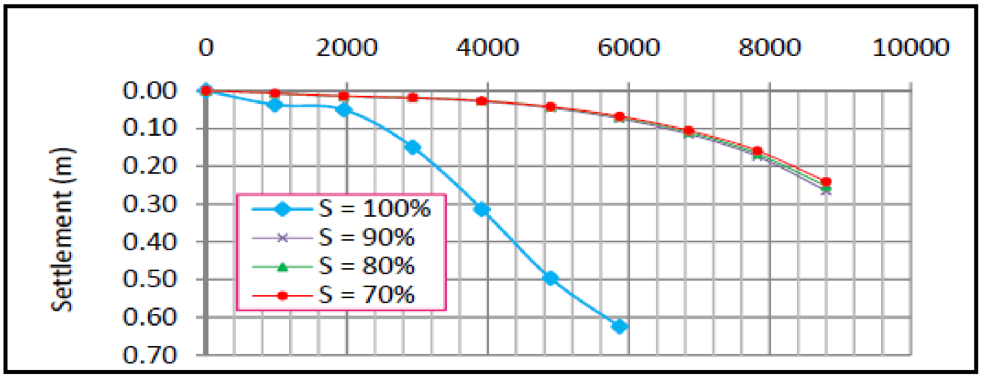
Figures (15) to (17) show the load settlement curves of (0.6 m) diameter and 12 m length pile constructed in soils with different degrees of saturation and different water table levels.

From these figures, it can be stated that when the soil becomes partially saturated, the ultimate bearing capacity of Rasafa1 soil increases from (2100 kN) when it is fully saturated (S=100%) to (4800 kN) when it is partially saturated at (S=90%). These results are due to contribution of matric suction and the increase of cohesion in the case of partial saturation.

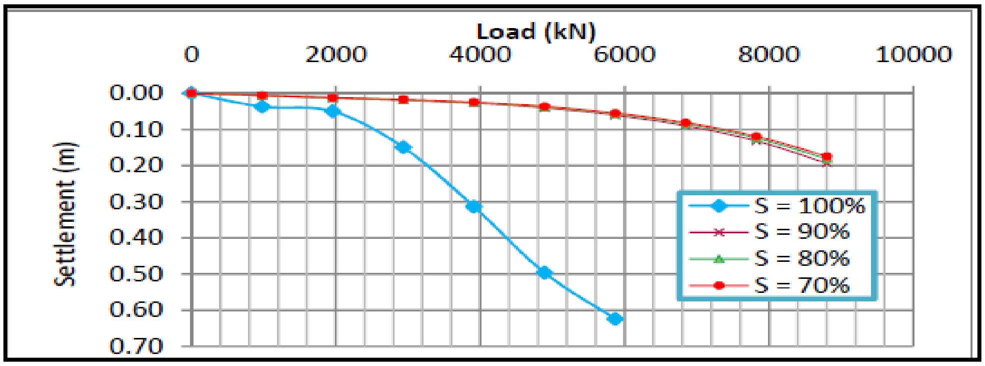
The values of the ultimate bearing capacity which are obtained from these figures according to the criterion of a load corresponding to a settlement equals to (10%) of the pile diameter are summarized in Table (6) from which it can be noticed that the ultimate bearing capacity of partially saturated soil is higher than for fully saturated by about (3 to 5) times. This increase is mainly due to the increase of the shaft resistance; the influence of partial soil saturation is insignificant for small depths of the G.W.T. but becomes more important at larger depths of G.W.T. The amount of increase in the bearing capacity due to dropping of water table is consistent with the amount of increase obtained by Georgiadis (2003) who investigated the influence of partial soil saturation on the behavior of footings and piles in unsaturated soil, and found that the bearing capacity increases with the increase of the depth of ground water table, and the influence of partial soil saturation increases with the increase in the G.W.T and becomes more important at larger depths of G.W.T.



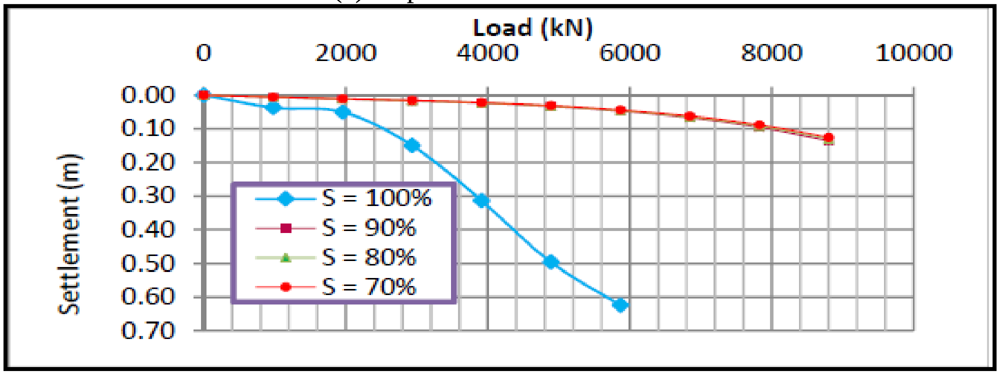
(a) Depth of water table = 2 m.



(b) Depth of water table = 4 m.



(c) Depth of water table = 6 m.

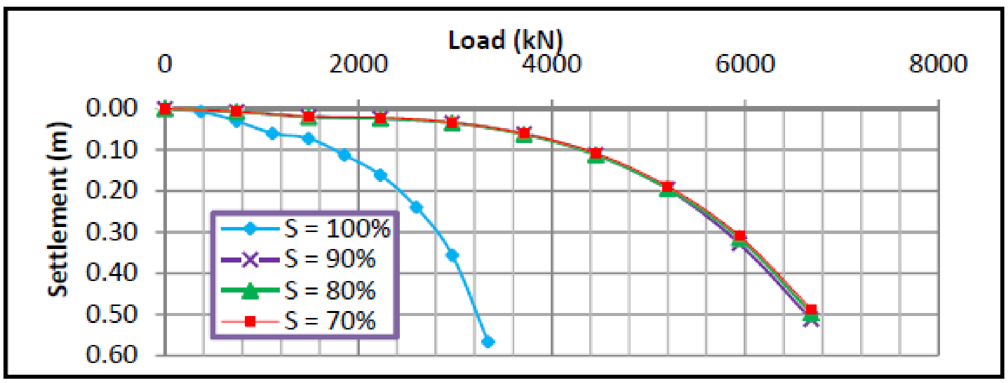


(d) Depth of water table = 12 m.

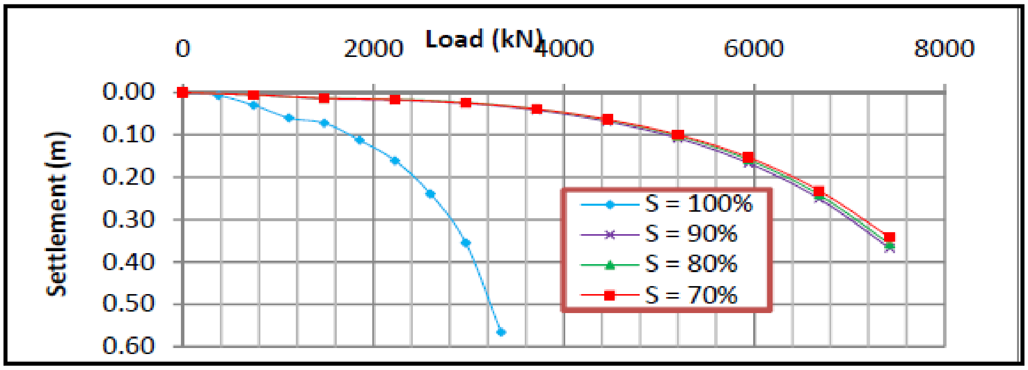
Figure (15) Load settlement curve for a pile (0.6 m) diameter in Rasafa 1 soil with different degrees of saturation.

Table (6) Results of ultimate capacity (kN) for piles constructed in soils of different degrees of saturation as obtained from finite element analysis.

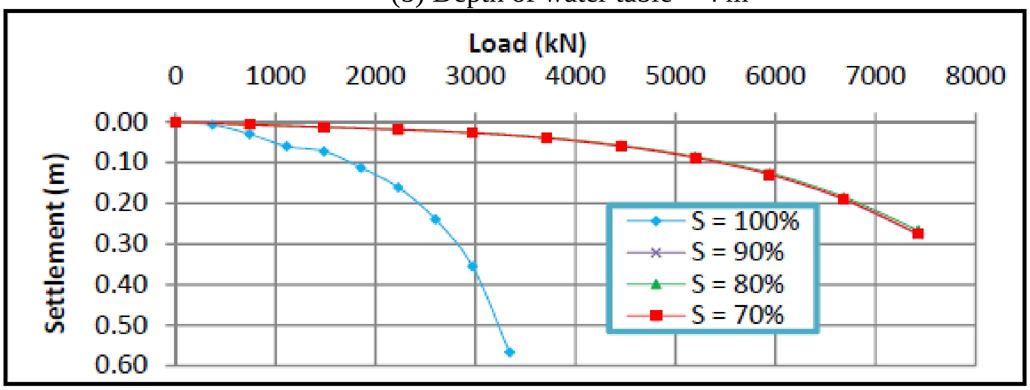
W.T depth	Degree of saturation	Rasafa 1	Rasafa 2	Rasafa 3
0 m	100 %	2100	1100	1300
2 m	90 %	4800	3600	2420
	80 %	4780	3600	2450
	70 %	4800	3600	2500
4 m	90 %	5400	4200	2820
	80 %	5520	4300	2950
	70 %	5600	4400	2950
6 m	90 %	5800	4430	3070
	80 %	6000	4500	3180
	70 %	6100	4480	3250
12m	90%	6500	5200	3600
	80%	6700	5270	3700
	70%	6800	5400	3780



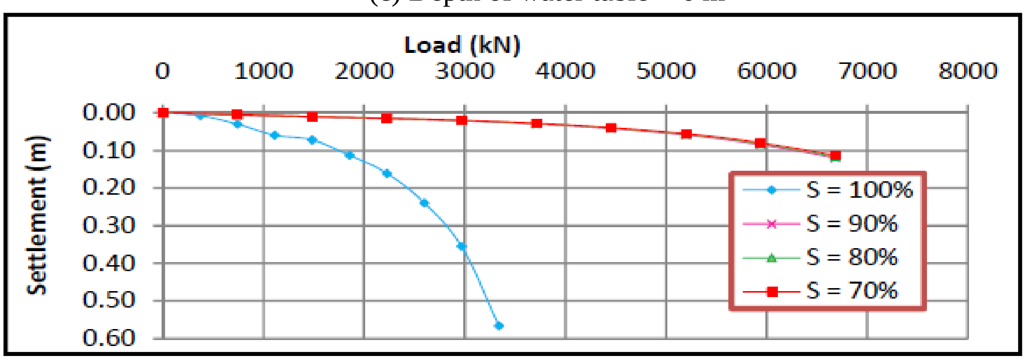
(a) Depth of water table = 2 m



(b) Depth of water table = 4 m

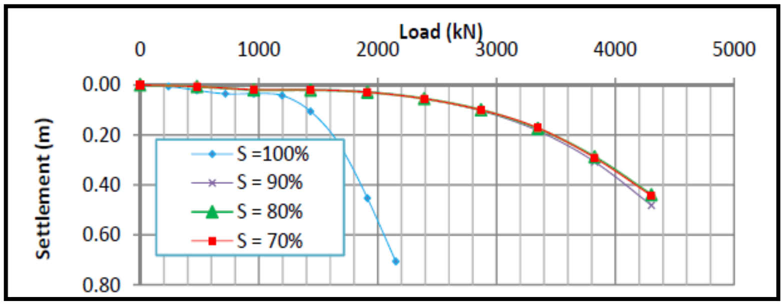


(c) Depth of water table = 6 m

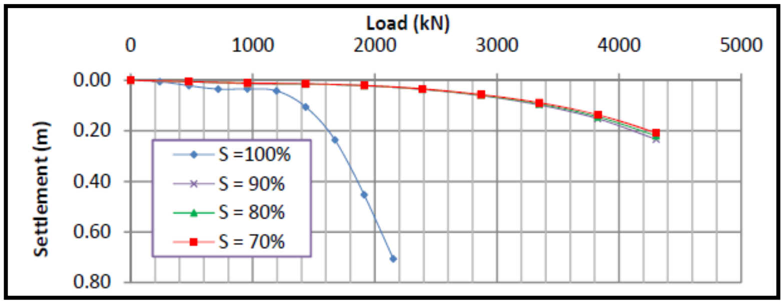


(d) Depth of water table = 12 m

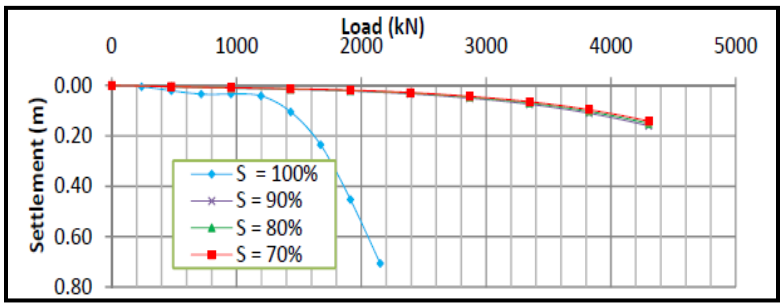
Figure (16) Load settlement curve for a pile (0.6 m) diameter in Rasafa 2 soil with different degrees of saturation.



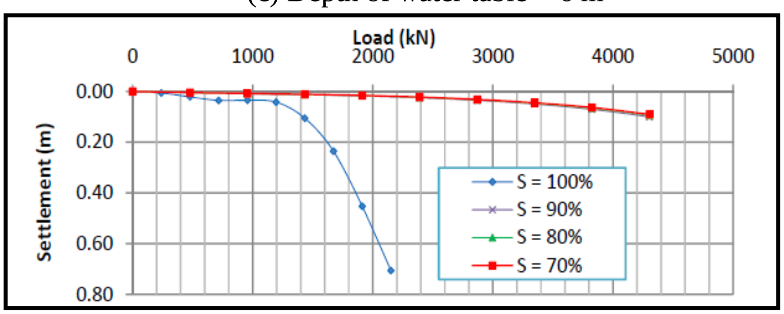
(a) Depth of water table = 2 m.



(b) Depth of water table = 4 m.



(c) Depth of water table = 6 m



(d) Depth of water table = 12 m

Figure (17) Load settlement curve for a pile (0.6 m) diameter in Rasafa 3 soil at different degrees of saturation.

Conclusions

1. From the experimental work, the soil water characteristic curve was obtained by the filter paper method for Rasafa 1, Rasafa 2, and Rasafa 3 soils. Soil suction increases as the degree of saturation decreases for the three soils; Rasafa 1 has a value of matric suction more than the other soils due to its small void ratio. For each type of soil, the values of shear strength that are measured by unconfined compression test are greater for samples with smaller degrees of saturation than the higher degrees of saturation.
2. The procedure of analysis of the capacity of pile foundation in partially saturated soil by finite elements requires a proposed procedure to define the H – modulus function. The procedure followed in this work is found to be successful through the encouraging results of the problem under consideration.
3. The change in the water table level and the degree of saturation has a 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 capacity of piles in partially saturated soil is approximately (3-5) times the capacity of piles in the same soil under saturated conditions.
4. A linear increase in the capacity of piles is obtained due to lowering of water table and non linear increase due to change in matric suction for the same depth of water table. The increase in the pile capacity due to lowering of water table is greater than the increase due to matric suction. A linear increase in the capacity of piles is obtained due to lowering of water table and non linear increase due to change in matric suction for the same depth of water table. The increase in the pile capacity due to lowering of water table is greater than the increase due to matric suction.

REFERENCES

[1].ASTM – D – 2166 – 00. "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil", Annual Book of ASTM Standards,Vol. 04–08, Soil and Rock, pp.1 – 7.

[2].ASTM-D-5298-03, "Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper", Annual Book of ASTM Standards, Vol. 04.08, Soil and Rock, pp. 1 – 6.

[3].Bowles, J.E., (1996), "Foundation Analysis and Design", 5^{th} McGraw Hill Book Company. Inc. New York pp. 127.

[4].Bulut, R., Lytton, R.L., and Warren, K., (2001), "Soil Suction Measurement by Filter Paper" Geo. Special Publication Number 115, pp. 1-64.

[5].Cheong, H.K. and Alevey N.M., (2000), " Experimental Behavior Of Jacked Reinforced Concrete Beams", Journal of Structural Engineering, June, Vol. 126, No.6 pp. 692 – 699.

[6].Das, B.M., (2008), "Principle of Geotechnical Engineering".

[7].Fredlund, D.G., and Rahardjo, H. (1993), "Soil Mechanics for Unsaturated Soils". John Wiley and Sons, Inc. New York, United States of America. Curve", University of Saskatchewan, Canda.

[8].Fredlund, D.G., and Xing, A. (1994), "Equations for the Soil Water Characteristic

Curve", University of Saskatchewan, Canda.
[9].Georgiadis, K. (2003), "Development, Implementation and Application of Partially Saturated Soils Models in Finite Element Analysis". MSc. Thesis, University of London.
[10].Krahn, J., (2004), "Stress And Deformation Modeling With SIGMA/W", GEO – SLOPE International, Ltd.
[11].Lu, N., and Likos, W.J., (2004), "Unsaturated Soil Mechanics", John Wiley and Sons, New York.
[12].Mohsen, I. M., (2012), "Behavior of Single Pile in Unsaturated Clay Soils", M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Iraq.
[13].Nelson, J.D. and Miller, D.J., (1992), "Expansive Soils". John Wiley and Sons.
[14].Oh, W.T., and Vanapalli, S.K. (2008), "Modeling the Stress versus Settlement Behavior of Model Footings In Saturated And Unsaturated Sandy Soils", The 12th International Conference International Conference of International Association for Computer Methods and Advance in Geomechanics. (IACMAG), Goa, India.
[15].Poulos, H.G., and Davis, E.H., (1980), "Pile Foundation Analysis And Design". University of Sydney.
[16].Vanapalli, S.K., Oh, W.T., and Puppla, A.J. (2008), "A Simple Method for the Prediction of Modulus of Elasticity for Unsaturated Soils". Proc. 1st Int. European Conf. on Unsaturated Soils.
[17].Van Genuchent, M. T., (1980), "A Closed Form Equation for Prediction of the Hydraulic Conductivity of Unsaturated Soils", Soil Science Society America Journal, 44, pp. 892 – 898.
[18].Wong, T.T., Fredlund, D.G., and Krahn, J., (1998), "A Numerical Study of Coupled Consolidation in Unsaturated Soils", Canadian Geotechnical Journal, Vol. 35, pp. 926– 937.