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EXPERIMENTAL STUDY OF MODEL PILED RAFT FOUNDATION EMBEDDED WITHIN PARTIALLY SATURATED COHESIONLESS SOILS

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Abstract: This paper presents an experimental study conducted on model piled rafts in partially saturated sandy soil. The aim of the experimental program is to study the effect of matric suction on the load carrying capacity of piled rafts embedded within partially saturated sandy soil .The influence of number of piles are presented and discussed in this study. The piled raft is arranged in different configurations of piles (single, double and triple piled raft with spacing 3.5D c/c) with the same area ratio (raft area to the cross section area of piles) to avoid different contact pressure area and to show the effect of different piles number and its group action. The influence of matric suction (i.e., capillary stresses) in partially saturated zone is typically not taken into account in the conventional design of both shallow and deep foundations so that the present research study the determination and contribution of matric suction towards the load carrying capacity of piled raft. The experimental work consist of 3 models of footing "single piled raft (8.3 x 5) cm, double piled (16.6 x 5) cm and triple piled raft (25 x 5) cm". All these models are loaded and tested under both of fully saturated condition (i.e., matric suction equals to 0kPa) and unsaturated conditions (i.e., matric suction value equals to 6kPa , 8kPa and 10kPa), which are achieved by predetermined lowering of water table. The relationship between matric suction and depth of ground water table was measured in suction profile set by using three Tensiometers (IRROMETER). The soil, water characteristic curve (SWCC) estimated by applying fitting methods through the program (SoilVision). The results of experimental work demonstrate that the load carrying capacity of piled raft increases with increasing all values of matric suction as the number of piles supporting the raft increases. And the matric suction has a significant influence on the load carrying capacity of all tested models. The increasing value of the ultimate bearing capacity for single, double and triple piled raft under unsaturated conditions is approximately (2.1-4.47), (2-4.44) and (1.5-3.54) times higher than that at saturated condition respectively

Keywords: *Partially saturated soil, SWCC, soil suction, Piled Raft Foundation, sand.*

دراسة عمليه و تحليليه لنماذج اسس حصيريه مدعمه بالركائز مغروزه في تربه حبيبيه مشبعه جزئياً

الخلاصة: هذه الاطروحه تمثل دراسه تجريبيه على اسس حصيريه في تربه رمليه مشبعه جزئيا.الهدف من هذا البحث هو دراسة تاثير ضغط الماء السالب على قابلية التحمل للاساس الحصيري المدعم بالركائز عندما يكون مغروزا في تربه رمليه مشبعه جزئيا وكذلك تاثير عدد الركائز تم دراسته ومناقشته في هذا البحث. الاساس الحصيري المدعم بالركائز تم ترتيبه بتشكيلات مختلفه من الركائز (اساس حصيري منفرد ، مزدوج و ثلاثي) والمسافه بين الركائز مساويه الى 3.5 بقدر قطر الركيزه ، وبنسبه ثابته بين مساحه الحصيره الى مساحه المقطع العرضي للركائز وذلك لتجنب اختلاف مساحه ضغط التلامس وكذلك لبحث تاثير اختلاف عدد الركائز وفعل المجموعه للركائز . تاثير ضغط الماء السالب (اجهاد الخاصيه الشعريه) في جزء التربه المشبعه جزئيا عادة لايؤخذ في الحسابات التصميميه

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الاعتياديه لكل من الاساسات الضحله والعميقه لذلك هذا البحث يدرس وبشكل مباشر تاثير ضغط الماء السالب على قابليه التحمل للاساس الحصيري المدعم بالركائز.الجانب العملي يتالف من 3 نماذج من الاساسات :" اساس حصيري بابعاد (5×8.3) سم مدعم بركيزه واحده، اساس حصيري بابعاد (5×16.3) سم مدعم بركيزتين، اساس حصيري بابعاد (5×25) سم مدعم بثلاث ركائز". جميع هذه النماذج من الاسس تم تحميلها وفحصها تحت ظروف تربه مشبعه كليا (الضغط السالب للماء يساوي صفر كيلو باسكال) وتحت ظروف تربه مشبعه كليا (الضغط السالب للماء يساوي 6,8 و10 كيلو باسكال)، هذه القيم تم تحقيقها من خلال تخفيض منسوب المياه في التربه . تخفيض منسوب الماء من سطح التربه تم تغييره الى اعماق مختلفه للوصول الى قيم مختلفه من ضغظ الماء السالب وكذلك العلاقه بين ضغظ الماء السالب وعمق الماء في التربه تم قياسها بواسطة ثلاث اجهزة (Tensiometer). منحني خصائص الرطوبه (SWCC) تم قياسه من خلال تطبيق معادلات رياضيه باستخدام برنامج (Soil Vision). نتائج العمل المختبري اثبتت ان قابليه التحمل للاساس الحصيري "لكل قيم الضغط السالب للماء" تزداد مع زيادة عدد الركائز التي تدعم الحصيره . وكذلك بينت النتائج ان الضغط السالب للماء له تاثير واضح على قابليه التحمل لجميع النماذج المفحوصه. قيمه الزياده في قابليه التحمل لاساس حصيري مفرد ،مزدوج وثلاثي الدعم بالركائز مفحوص في ظروف تربه مشبعه جزئياً تكون تقريبا (4.47-2.1)، (4.44-2) و(3.54-1.5) مرات اكبر من قابليه التحمل المفحوصه تحت ظروف تربه مشبعه كلياً.

1. Introduction

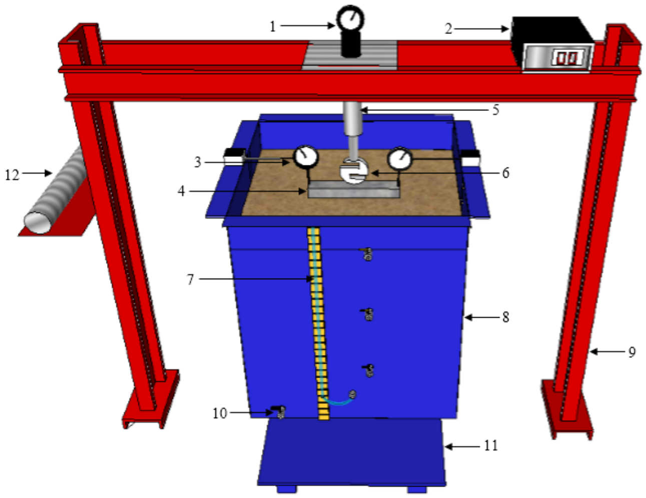
The piled raft foundation system has recently been widely used for many countries to support different types of structures like bridges, buildings and industrial plants in different types of soil. The Piles in combination with raft plays an important role in settlement reduction and thus can lead to economical design without compromising the safety of the structure.

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

To get high bearing capacity for shallow and deep foundations that are used to carry the loads from super structures its prefer to place it above the ground water table , where the soils are in a state of unsaturated condition. The influence of matric suction (i.e., capillary stresses) in this zone is typically not taken into account in the conventional design of both the shallow and deep foundations. Steensen-Bach et al. [1] comment that ignoring the influence of capillary stresses in the bearing capacity of unsaturated soils would be equivalent to disregarding the influence of reinforcement in the design of reinforced concrete. Several studies undertaken during last 50 years highlighted the contribution of matric suction towards the bearing capacity of unsaturated soils [1,2, and 3]. There are some studies reported in the literature taking into account the influence of matric suction in the design of footings [4,5, and 6].

2. Test setup

All the model tests were conducted using the setup shown in Plate (1), which consists of steel frame, steel soil tank, reinforcement model piles and pile cap model of piled raft and the vertical load is applied on the model piles by means of 10 ton capacity hydraulic compression handle jack. During all the experimental tests, the loading rate is kept approximately the same. The applied load is measured using a load cell with 0.5 ton capacity. A digital weighing indicator is used to read and display the load value. Two deformation dial gages with 0.01 mm sensitivity have been used for measuring the displacements of the piled raft model and three tenseometer were used to measure the matric suction in the soil.



1- Pressure gauge
2- Digital Weighing Indicator.
3- Dial gauge.
4- Piled raft model.
5- Axial loading system.
6- Load cell
7- Piezometer.
8- Soil container.
9- Steel frame.
10- Drainage valve.
11- Steel base.
12- Hydraulic Jack.

Plate (1): Setup of the experimental model

3. Soil Material

The soil used in this study is dry sand obtained from Baghdad city (Abu Nawas) site. The grain size distribution of the sand used is shown in Figure (1). The standard tests are performed to determine the physical properties of the soil as follows:

1. Specific gravity.
2. Grain size distribution.
3. Maximum and minimum dry unit weight, and
4. Direct shear test.

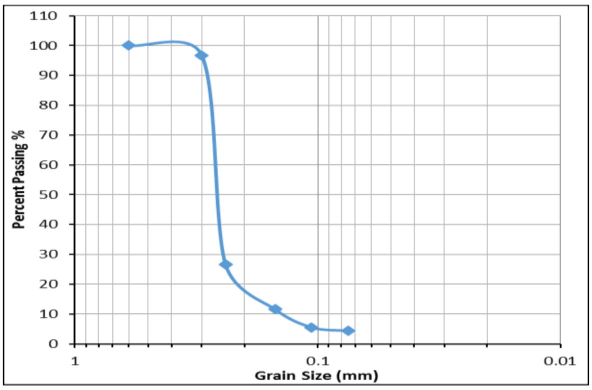


Figure (1) Grain size distribution.

The results are shown in Table (1). The bed of soil is prepared by adopting raining full technique with a dry unit weight of 14.91 kN/m^3 at height of drop 80 cm with void ratio of (0.76) and a relative density of (60.4%).

Table (1): Physical properties of the sand used in present tests.

Property	Value	Specification
Grain size analysis		ASTM D422-63
Effective size, D_{10}	0.14	
Coefficient of uniformity, C_u	1.98	
Coefficient of curvature, C_c	1.60	
Classification (USCS)	SP	
Specific gravity, G_s	2.685	ASTM D854- 00
Dry unit weights		ASTM D4253-93
Maximum unit weight, $\gamma_{d\,(max)}$	16.16 kN/m^3	
Minimum unit weight, $\gamma_{d\,(min)}$	13.34 kN/m^3	
Void ratio		
Maximum void ratio, e_{max}	0.97	
Minimum void ratio, e_{min}	0.63	

4. Piled Rafts Models

The piled raft models used in this study are made from reinforcement concrete, the diameter of piles is 20 mm, while the length of models piles is kept at 400 mm. The embedment (depth to diameter) ratio L/D = 20, where L represents the pile length and D is the outside diameter of the concrete pile. To construct model piles ،the reinforcement of each pile consists of three bars of 3mm diameter and 500 mm length. The yield strength of the reinforcement (fy) is 290 MPa.

The raft model used in this study was also made from reinforcement concrete having a thickness of 25 mm, the reinforcement of the raft is placed in two directions (mesh), diameter of each bar is 2 mm, the yield strength of the reinforcement (fy) is 175MPa.The space between the reinforcement c/c is 24 mm in addition, the end of each bar is twisted in the vertical direction with length of 15 mm. Wood parts are used to construct a form, this form used to cast the raft. In order to make hole inside raft for fixing model pile, circle woods were used to make hole with in the raft of 2 mm diameter larger than diameter of pile.

5. Direct Measurement of Soil Suction (Tensiometer Method)

This method is used for measuring the negative pore water pressure. The principle of this method is that the water pressure in the high air entry material will come to equilibrium to the water pressure of the soil making it possible to measure the pore water pressure. Since a true of semi permeable membrane is not available, only the matric suction will be measured by this technique not the osmotic suction [7].

In this method, a small ceramic cup is attached to a narrow very stiff plastic tube where de-aired water or the tensiometer solution in the tube is connected to a pressure measuring device, as shown in plate (2). The ceramic tip will be saturated by filling the tube with water then allowing it to drain from the tip in 24 hours. Submerging the tip in distilled water not less than 24 hours to ensure a full saturated condition in the ceramic tip. Then applying vacuum pressure to reduce the water pressure by drying up the cup, and removing any air bubbles that may be trapped in the high entry ceramic tip. Any entrapped air within the cavitations of the filter element will be forced to dissolve in the water under the application of the high pressure thus, increasing the accuracy of the measurable suction by the system. The limitation of this device is the possibility of air presence in the sensor which may come from the water as the pressure is reduced or from the soil diffusion through the ceramic disc. Removal of the diffused air and the refilling the water on a regular basis is the method to reduce such a problem (IRROMETER Manual Book, IRROMETER company, Inc.)

Plate (2): Three tenseometers used with its accessories

6. Results of the Suction Profile Set

Suction profile of soil was measured using the suction profile set described below. The results obtained from suction profile set (i.e., variation of suction above the water table measured) are used to determine the depth of water table to achieve a pre-decided matric suction profile below the model footings prior to conduct bearing capacity tests. The suction values of the soil for the suction profile set are determined using three Tensiometers. The first Tensiometer was installed at 7.5 cm below the soil surface, the second was installed at 22.5 cm below the soil surface and the third was installed at 37.5 cm below the soil surface.

The soil was initially saturated by raising the water level in the container from bottom to ensure fully saturation and escape air from soil .The water table was then lowered to 15cm below the soil surface (i.e. first stage) for a period of 24 hours to let capillary suctions reached the equilibrium conditions . This procedure was repeated by varying depth of water table below the soil surface to another different levels (30 cm and 45 cm) (i.e. second stage and third stage) respectively. Then the matric suction is measured after 24 hours as described below. Figure (2) summarizes the measured suction values above the water table for the three stages. The suction profile of the soil used shows that the matric suction increases with the lowering of water table .The soil suction near soil surface (7.5 cm below the soil surface) increases steeply as the depth of water table increases. The rapid increase of matric suction values at the soil surface of sand may be attributed to evaporation of water from soil surface [8,9]. Figure (3) show the variation of matric suction (i.e., measured and hydrostatic matric suction profiles) with respect to depth of the water table in the first, second and third stage of the suction profile test respectively. Table (2) summarized the corresponding average matric suction for lowering water table to achieve equilibrium conditions.

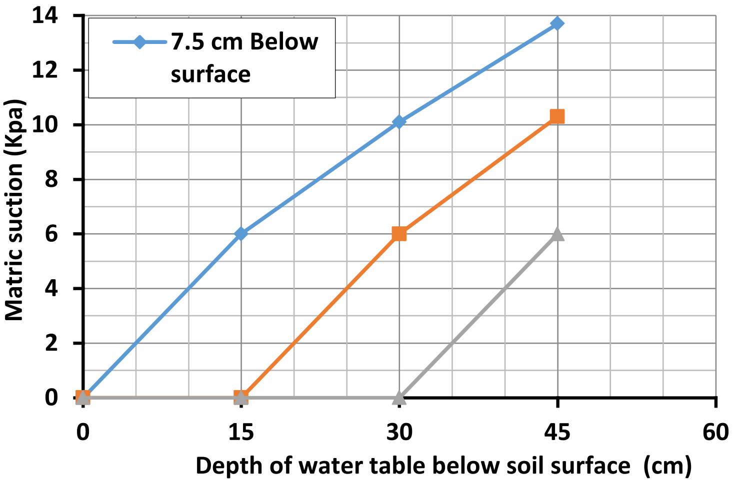


Figure (2): Matric suction values for three stages of water table below soil surface.

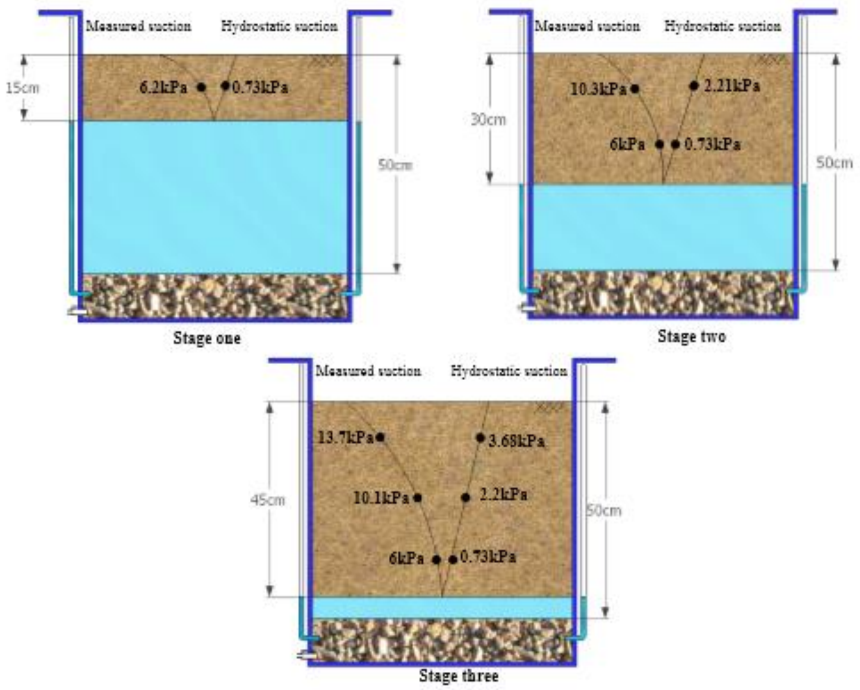


Figure (3): Variation of matric suction and Hydrostatic suction during three stages

Table (2): Summarized the results of the corresponding average matric suction for lowering water table suction profile set

Soil conditions	Lowering of Water table From soil surface in (cm)	Corresponding average Matric suction in (kPa)
Fully saturated	0	0
Partially Saturation	15	6
	30	8
	45	10

7. SWCC Estimated by Tensiometer

The wetting SWCC for this soil was measured by using tensiometers which were inserted in the suction profile model at different depth (i.e.7.5cm, 22.5 cm and 37.5 cm).

Figures (4) and (5) show the SWCC for the soil as estimated by the Fredlund and Xing and Van Genuchten equations respectively with the aid of Soil Vision program.

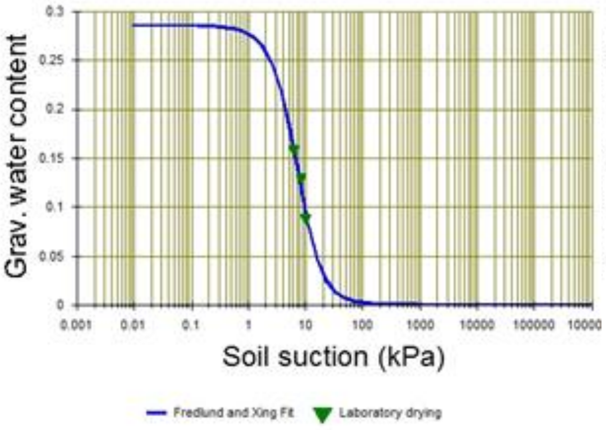


Figure (4): Relationships between the gravitational water content and the matric suction obtained by the program soil Vision.by by using Fredlund and Xing equation.

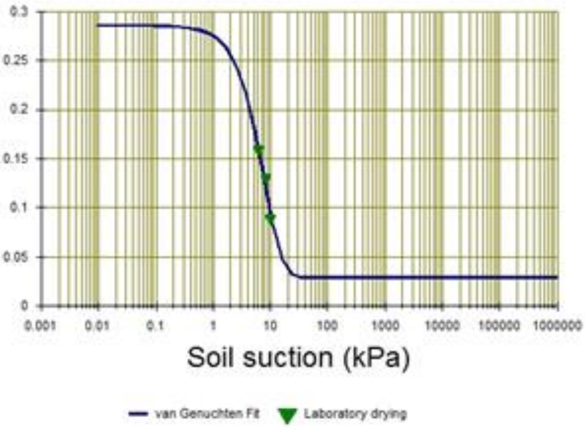


Figure (5): Relationships between the gravitational water content and the matric suction obtained by the program soil Vision.by by using Van Genuchten equation.

From SWCC of soil its can be notice there are two distinct changes in slope along the SWCC. According to (D.G. Fredlund et al. 2001)[10] the changes in slope define two points that are pivotal to describing the SWCC. The first point is termed the ‘‘air-entry value’’ of the soil, where the largest voids start to desaturate as suction is increased. The second point is termed ‘‘residual conditions’’, and it defines the point where the removal of water from the soil becomes significantly more difficult (i.e., requires significantly more energy for water removal). The changes in slope subdivide the SWCC into three distinct zones, namely, the ‘‘boundary effect zone’’ in the lower suction range, the ‘‘transition zone’’ between the air-entry value and the residual value, and the ‘‘residual zone’’

From the soil water characteristics curve, Figures (4) and (5), and fitting curves proposed by Fredlund and Xing (1994)[11] and Van Genuchten (1980),[12] the air – entry value $(u_a - u_w)_b$ (kPa) was 2.37kPa and 2.4kPa respectively .as stated by

(E.C.Leong,1997)[13] In general, the different parameters in each equation do not vary the shape of the curves; however .the parameters show large variations in value depending on the number of data points used for the curve fit . Due to this reason there is no big different between two curves and no sharp change in the slope of the curves.

The equation suggested by Fredlund and Xing (1994) [11] gave the best fit among the equations, therefore recommended that the Fredlund and Xing be used for the soil-water characteristic curve (E.C.Leong, 1997).[13]

8. Load Carrying Capacity of Piled Raft

In these tests, the piled raft is arranged in different configurations of piles with the same area ratio (raft area to the cross section area of piles) of 13.26 to avoid different contact pressure area and to show the effect of different piles number and its group action. Table (3) shows the details of piled raft models which have been used in this study.

Table (3): The details of piled raft configuration models

Raft size(cm)	Raft Area (cm^2)	Cross section area of piles (cm^2)	Number of piles	Piles configuration
25 x 5	125	9.42	3	3 x 1
16.6 x5	83	6.28	2	2 x 1
8.3 x5	41.5	3.14	1	Single piled raft

Each model was tested for both condition of the soil; fully saturated and partially saturated with different value of matric suction (6 kPa, 8 kPa and 10 kPa) which is achieved by lowering water table level. All the models of piled-raft are constructed at the same initial conditions with the same area ratio to determine the bearing capacity of the piled-raft under the effect of matric suction. Figures (6) to (8) shows the load-settlement behavior of single piled raft, double piled raft (2 x 1) and triple piled raft (3 x 1) models.

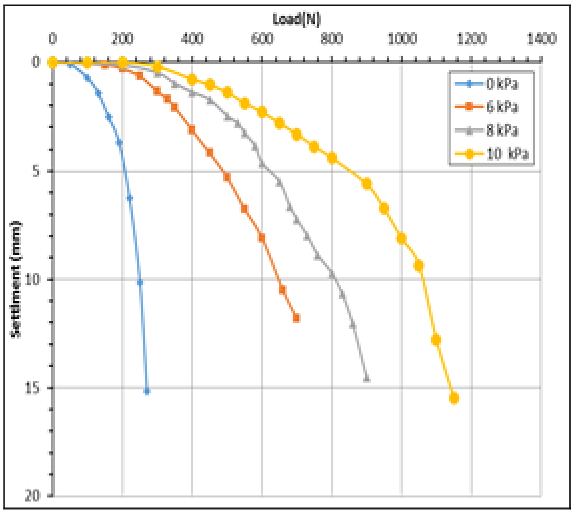


Figure (6): Single piled raft models under different average matric suction values.

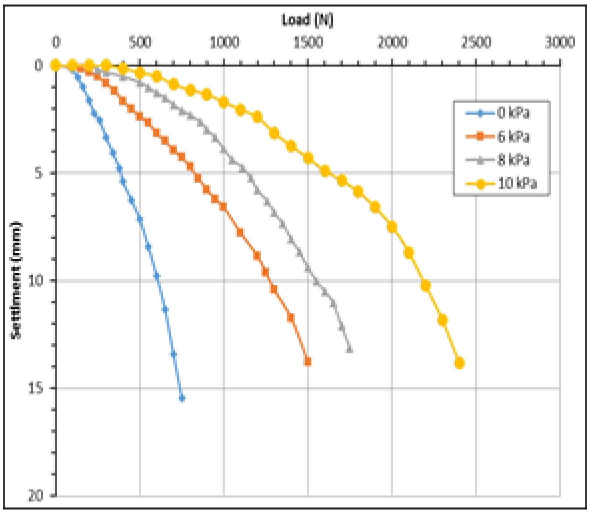


Figure (7): Double piled raft models (2 x 1) under different average matric suction values.

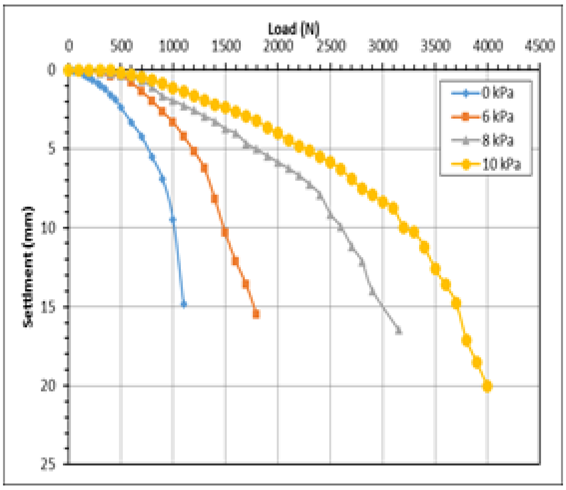


Figure (7): Double piled raft models (2 x 1) under different average matric suction values.

Figures (6) to (8), it can be stated that the shape of load-settlement curves indicate that the local shear failure is governed. The values of the ultimate bearing capacity of the piled-raft models are summarized in Table (4).From Table (4) it can be noticed that the results of the piled-raft load tests a significant increase in ultimate bearing capacity values under unsaturated conditions in comparison with saturated condition. As the matric suction value increased from 0 kPa (i.e., saturated condition) to 6 kPa , 8 kPa and 10 kPa (i.e., unsaturated condition), the ultimate bearing capacity increased significantly. The results demonstrate that, the matric suction plays an important role in the contribution of increasing the bearing capacity and reducing settlement. This trend of result agreed with many recent research studies which demonstrated that there is a significant contribution of matric suction towards the bearing capacity of both shallow and deep foundations in both unsaturated fine and coarse-grained soils [4,5,14,15].

Figure (7): Double piled raft models (2 x 1) under different average matric suction values.

Piled raft Model	Dimension (cm)	Lowering of Water table (cm)	Average matric Suction (kPa)	Ultimate bearing Capacity (N)
Single piled Raft	8.3 x5	0	0	190
		15	3.03	400
		30	6.2	640
		45	9.6	850
Double piled Raft(2 x 1)	16.6 x5	0	0	360
		15	3.03	720
		30	6.2	990
		45	9.6	1600
Triple piled Raft(3 x 1)	25 x 5	0	0	720
		15	3.03	1080
		30	6.2	1760
		45	9.6	2550

The increasing value of the ultimate bearing capacity for piled raft under unsaturated conditions is approximately (3.5 to 4.4) times higher than that for saturated condition. This increase is mainly because of the increase in the shaft resistance along pile shaft subjected to the effect of matric suction. The increase in matric suction causes pulling the particles together effectively and offering more resistance to the applied load on the raft. Due to this combination effect of matric suction on both deep foundation (pile)and shallow foundation(raft), the load carrying capacity of the piled-raft relatively increases with the lowering of water table level i.e. increase matric suction.

9. Effect of Number of Piles

In this section, the effect of piled raft size on the ultimate carrying capacity is investigated at different average matric suction values. Figures from (9) to (12) show load-settlement curves for single piled raft, double piled raft and triple piled.

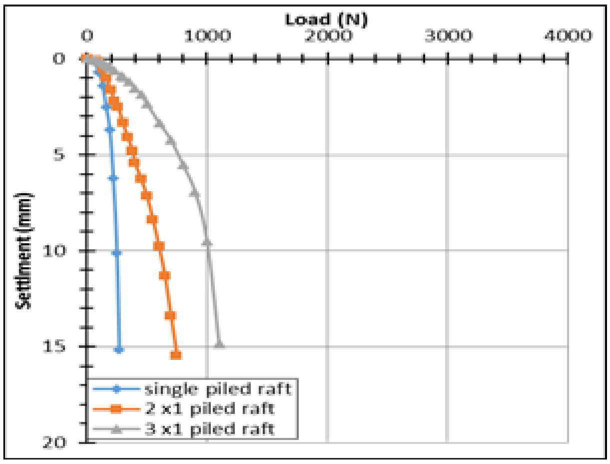


Figure (6): Single piled raft models under different average matric suction values.

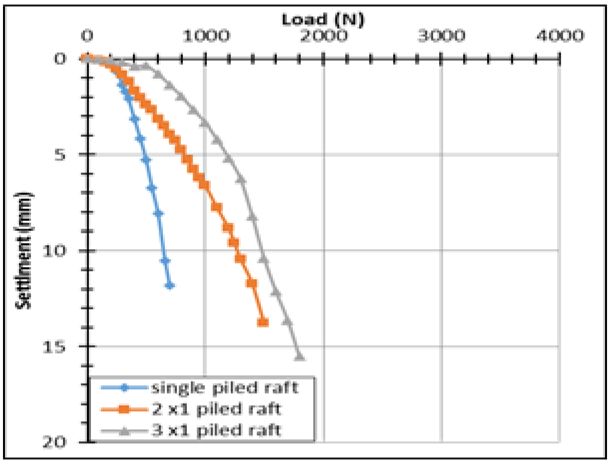


Figure (6): Single piled raft models under different average matric suction values.

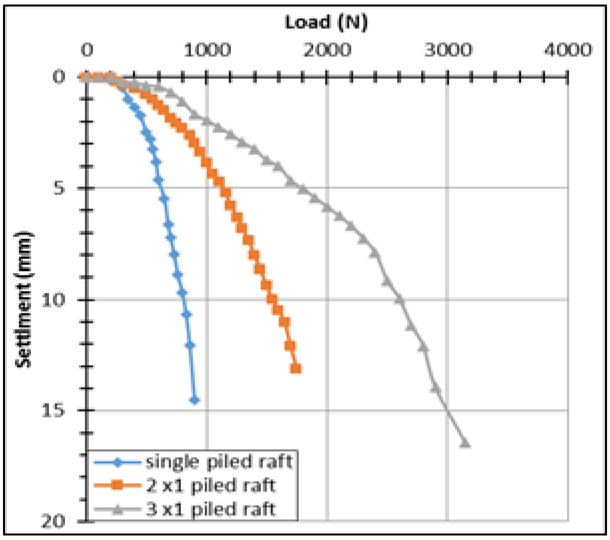


Figure (6): Single piled raft models under different average matric suction values.

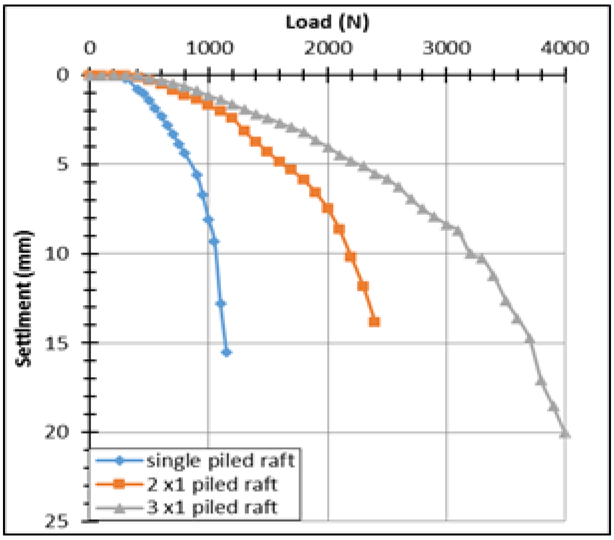


Figure (6): Single piled raft models under different average matric suction values.

By inspection these figures it can be noted that the load carrying capacity increases with the increase in number of piles for the same area ratio under the same conditions of testing (matric suction 0 kPa, 6 kPa, 8 kPa and 10 kPa). Table (5) summarized the results of ultimate load capacity for three configurations of piled raft. For example at average matric suction 6 kPa, the ultimate load has increased from 190 N for single piles raft to 720 N and 1080 N for piled raft of 2x2 and 3x3 configurations respectively and the same trend of result for all value of matric suction. From obtained result can be stated that, the load carrying capacity of piled raft increases as the number of piles supporting the raft increases. This increase is mainly due to the increase of proportion of load shared by the piles due to the increase of the number of piles.

Table (5): Ultimate load capacity for three configurations of piled raft.

Piled raft Model and number of piles	Average matric Suction (kPa)			
	0	6	8	10
Single piled Raft (1 x 1)	190	190	640	850
Double piled Raft(2 x 1)	360	720	990	1600
Triple piled Raft(3 x 1)	720	1080	1760	2550

10. Variation of Ultimate Bearing Capacity with Matric Suction

Figure (13) shows the variation of the ultimate bearing capacity with respect to the average matric suction for all the models which investigated in this study.

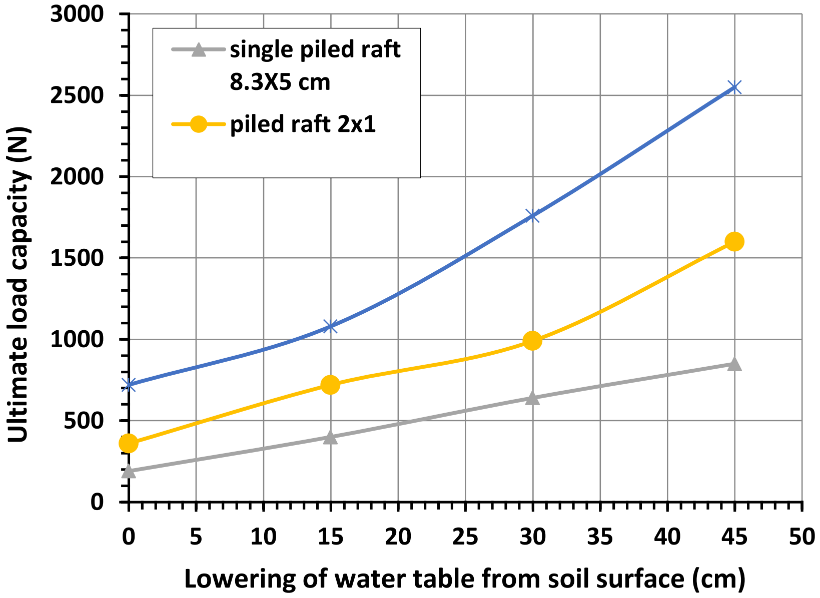


Figure (13): Variation of the ultimate bearing capacity with respect to average matric suction for all the models.

These relationships demonstrate that there are a significant increase in the bearing capacity of all the model of foundations due to the contribution of matric suction. The results also demonstrate that, the ultimate bearing capacity approximately increases linearly with matric suction up to the air – entry value (i.e. boundary effect zone) and there is a non – linear increase in the bearing capacity with respect to matric suction beyond the air – entry value. From the SWCC curve (see, Figure 4) which obtained from the SoilVision software by using equation of Fredlund and Xing (1994), [11] the air – entry value of soil is 2.4 kPa.

According to Vanapalli et al. (1996), [16] the trends of the results of the bearing capacity of unsaturated soil are similar to the shear strength behavior of unsaturated soils. In addition, they demonstrated the typical relationship between the shear strength and the SWCC by comparing Figure (14 a), and (14 b) shown below.

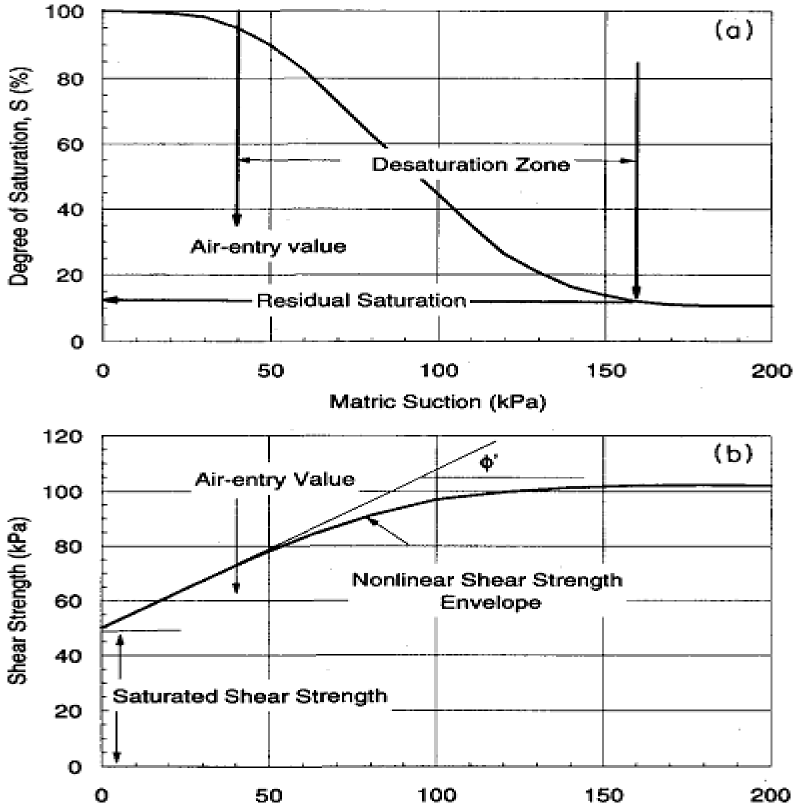


Figure (14): (a) A typical soil water characteristic curve. (b) Shear strength behavior of soil as it is related to the soil water characteristic curve, (after Vanapalli, et al., 1996).

The figure shows that 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. Escrio and Juca (1989)[17] reported that, it may be assumed that the shear strength for such soils increases up to the point where the degree of saturation approaches a zero value or an extremely high suction

11. Conclusions

In this study, an experimental program has been carried out to determine the ultimate load capacity of piled raft foundation under saturated and unsaturated conditions on sandy soil using specially designed equipment in the laboratory environment. The following conclusions can be drawn:

1. The results of experimental work demonstrate that the matric suction has a significant influence on the bearing capacity of all tested models, and these results show that there is a strong relationship between the SWCC and the ultimate load capacity.
2. The results of this experimental program suggest the conventional bearing capacity theory used in the engineering practice is highly conservative when it is applied for unsaturated soils.
3. The increasing value of the ultimate bearing capacity for single, double and triple piled raft under unsaturated conditions is approximately (2.1-4.47), (2-4.44) and (1.5-3.54) times higher than that at saturated condition respectively
4. The soil suction near soil surface increases steeply as the depth of water table increases. This rapid increase of matric suction values at the soil surface of sand attributed to evaporation of water from soil surface. The procedure of set profile suction which followed in this work is found to be good procedure through the encouraging results.
5. From the SWCC which was estimated with the aid of SoilVision program and experimental results obtained from the tensiometer method, it can be notice that the suction tends to decrease with the increase in soil initial water content because increasing the water content will increase radius of meniscus and that will decrease the soil suction.

12. References

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