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Experimental and Numerical Analysis of Piled Raft Foundation Embedded within Partially Saturated Soil

Abstract*-This paper presents an experimental and numerical study to investigate the load carrying capacity of piled raft foundation embedded within partially saturated sandy soil. The effect of matric suction on the bearing capacity of the foundation system was investigated. The experimental work consists of two models of foundation, circular raft foundation and circular piled raft foundation. The circular raft foundation has dimensions of 10cm in diameter, and 2.5cm thickness, while the piled raft foundation has the same dimensions of the circular raft model but with a single pile of 2.0cm in diameter and 40.0cm in length fixed at the center of the raft. Both models are loaded and tested under both fully saturated condition and unsaturated conditions, which are achieved by, predetermined lowering of water table. The lowering of water table below the soil surface was achieved in to two different depths to get different values of matric suction and 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 software (SoilVision). A validation process then was carried out for the case of circular piled raft foundation with lowering the water table 45cm bellow soil surface in the aid of a sufficient finite element computer program ABAQUS 6.12. An eight-node axisymmetric quadrilateral element CAX8RP and CAX8R were used to simulate the soil continuum and piled raft respectively. The interaction method used to simulate the intersect surfaces of the system (pile-raft-soil) is a surface-to-surface discretization method under the concept of master and slave theory. The behavior of piled raft material is simulated by using a linear elastic model while the behavior of soil is simulated by an elasto-plastic model by the use of the Mohr-Coulomb failure criterion. The results of the experimental work demonstrate that the matric suction has a significant role on the bearing capacity of all tested models. It shows that the ultimate bearing capacity of circular raft foundation under a partially saturated condition is increases by about (7.0-8.0) times than the ultimate bearing capacity of fully saturated condition when lowering the water table 45 cm below the soil surface. While the ultimate bearing of circular piled raft foundation under partially saturated condition increases by about (8.0-9.0) times than the ultimate bearing capacity of fully saturated condition when lowering the water table 45 cm below the soil surface. The results of the ultimate bearing capacity of piled raft foundation that obtained from the experimental model and from the numerical modelling for the same soil condition and same matric suction indicate that a successful validation is achieved for the simulation process.*

Keywords*- Partially saturated soil, SWCC, soil suction, Piled Raft Foundation, Finite Element Method, ABAQUS, sand*

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1. Introduction

Piled raft foundations provide an economical foundation option for circumstances where the performance of the raft alone does not satisfy the design requirements. Under these situations, the addition of a limited number of piles may improve the ultimate load capacity and reduce the settlement [1]. Katzenbach *et al.* [2] termed piled raft foundation as a Combined Piled Raft Foundations (CPRF), which is consists of three bearing elements, piles, raft and subsoil. The stiffness of raft and pile, the soil properties, the dimension and strategy of pile location play a significant role in the design of a pile raft foundation system. Among the various structures, storage tanks are more suitable for using circular piled-raft foundation system. The behavior of a circular piled-raft foundation is carried out in this study, which enhanced by the most common soil condition, partially saturated soil to make a full imitation to projects using that type of foundation system such as oil and water tanks in refineries and depots. To increase the performance of piled raft foundation of unsaturated soils where encountered due to soil suction. Soil suction, generally, consists of two components: matric

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component and osmotic component [3]. The sum of these two components is called total suction. The matric component of soil suction comes from the hydration forces and capillary component effect [4]. Therefore, the matric suction is the sum of the hydration forces and the capillary forces.

Numerical Method where used also as an alternative analysis approach. In this method, the foundation behavior is investigated of modeling the piled raft foundation in the form of plate-loaded spring. This method reduces the rigorous numerical analysis by including analytical solution with some approximation. It requires fewer equations to solve than the finite element method, and "the time consuming numerical integration of the boundary element method are not necessary" [5]. Therefore, a great saving in computer memory utilization makes the foundation analysis more convenient and less expensive.

Davis and Poulos [6], performed an elastic analysis of pile-raft interaction, considering soil as semi-infinite elastic medium. The analysis is based on the interaction between two units, where each unit consists of a rigid floating pile connected with a rigid circular cap, which is subjected to a point load. Randolph [7], developed the simplest analysis method for a single pile cap unit and showed its applicability for a 3x3-pile group raft foundation. The analysis was on a unit of rigid floating pile, which is attached to a rigid circular cap and the soil was considered as elastic semi-infinite mass.

Katzenbach *et al*. [8] simulated the soil-structure interaction of piled raft foundation by means of an axi-symmetric 3-D finite element analysis. Kim et al. [9] developed "an optimization scheme" to minimize differential settlements by modeling raft, soil and pile as Midline's plate, Winkler spring and coupled spring respectively. Prakoso *et al*. [10] proposed a general design methodology for the optimum pile raft design. This design methodology was developed based on a two-dimensional plain strain analysis of a vertically loaded pile raft. The geotechnical finite element code PLAXIS were used with six nodded triangular elements. The main problem of this simplified finite element analysis is that, only regular loading pattern can be analyzed, and like plate on spring approach, it cannot give the torsional moment in the raft. All the analyses are performed considering soil as a single-phase medium.

Kitiyodem et al. [11] performed an approximate numerical analysis by modeling raft as thin plate, piles as elastic beam and soil as spring. Novac *et al*. [12] performed a linear elastic three-dimensional finite element analysis for the load settlement behavior of piled raft foundation and found good agreement for the measured value of two case studies (Westend I of Frankfurt, Germany and Urawa of Japan) on over consolidated stiff clay. Sanctis *et al.* [13] performed a 3-D FEM analysis by ABAQUS to evaluate the bearing capacity of a vertically loaded piled raft on Italian soft clay. This axi-symmetric, displacement-controlled analysis considered smooth contact between rigid raft and elasto-plastic soil.

The main objectives of this search are:

1) To investigating and studying the influence of lowering the water table and the matric suction on the bearing capacity of circular raft and circular piled raft foundation through laboratory models.
2) Determining the unsaturated soil parameters required for estimating the soil water characteristic curve. This will be done by measuring the soil suction by direct method using Tesiometer, (IRROMETER) [14] in the laboratory model and by using Soil Vision software for determination of soil matric suction [15].
3) Incorporating finite element analysis for piled-raft foundation in partially saturated soil to investigate the effect of the above parameters on load-settlement relationship through numerical analysis of an axisymmetric model analyzed by the computer program software ABAQUS.
4) A validation process between the results of the experimental model and the results of the numerical analysis.

2. Experimental Work

I. Properties of the Soil Used

Figure 1 shows the grain size distribution of the sand used. Table 1 shows the result of soil properties**.**

II. Sand Deposit Preparation

The soil bed is prepared by adopting a raining full technique, which is designed to obtain a uniform deposit of sand. The desired density of 14.9 kN/m^3 was achieved by height of drop of 0.8m with avoid ratio of (0.76). The soil was placed in the tank through special device V-shaped hopper to rain the sand through narrow slots in form of thin curtain by opening the gate of this hopper. A piece of steel mesh with a diameter of the aperture 4mm is placed at the end of hopper to reduce the impact of the particles.

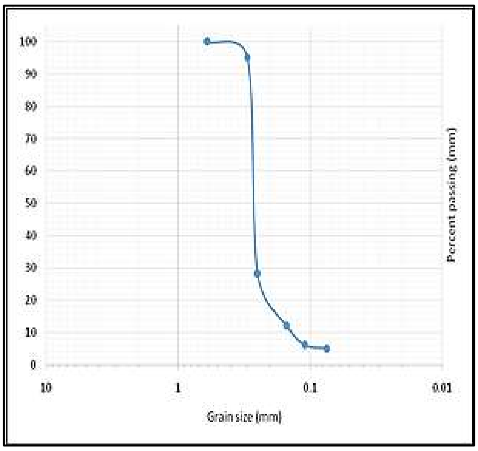

Figure 1: Grain size distribution of the soil used

Table 1: Physical properties of the soil

Property	Value	Specification
Dry unit weights		
Maximum unit weight, $\gamma_{d\,(max)}$	17.12kN/m^3	ASTM D-4253-00
Minimum unit weight, $\gamma_{d\,(min)}$	14.58kN/m^3	ASTM D-4254-00
Void ratio		
Maximum void ratio, e_{max}	0.82	
Minimum void ratio, e_{min}	0.54	
Soil Classification according to USCS	SP	
Specific gravity	2.68	ASTM D-854-00
Permeability	$2.45x10^{-4}$m/sec	ASTM D-2434-00

3. Piled Raft Models

A reinforced concrete of pile raft model was used in this study with a pile diameter of 20mm and 400mm length, see Plate 1. Embedment length to diameter ratio L/D=20. The reinforcement of pile consists of three bars of 3mm diameter connected with stirrups. A circular raft model used in this study was also made of reinforced concrete of 100mm diameter and 25mm thickness as shown in Plate 2. Two types of circular raft were caste, with a circular groove of 22 mm diameter and 5mm depth in order to fix the model pile for piled raft tests. A Single piled-raft model used in this study (Experimental and Numerical Analysis), consists of circular raft and single pile placed at the center of the raft fixed at the groove within the bottom surface of the raft. During the process of sand raining, the pile was fixed at the center of the container by using steel guides, and then the raining was continued to a level of the lower surface of the raft. The final layer of the sand is leveled by a sharp edge ruler then the raft model is fixed carefully above the piles to be in touch with the soil and piles at the same time.

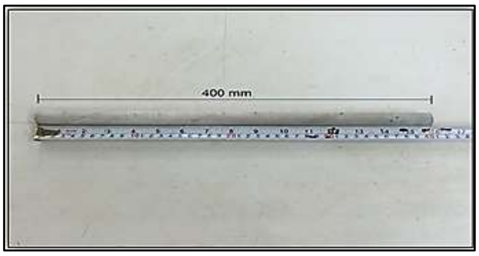

Plate 1: Concrete Pile model

Plate 2: Raft model

3. Measuring the Soil Suction

Several techniques were used to measure and controlling suction in unsaturated soils. In this study, direct measurement method of soil suction by Tensiometer was used.

I. Tensiometer

The commercial Tensiometer or “IRROMETER” used in the present research program were manufactured by the IRROMETER Company in California, United States of America. It consists of the features shown in Plate 3.

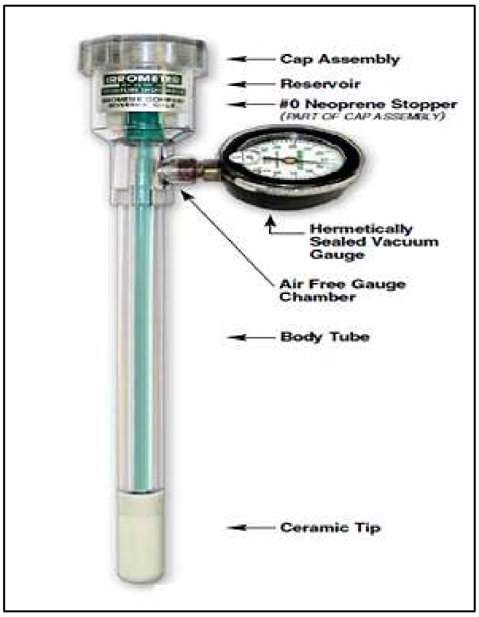

Plate 3: IRROMETER (Moisture Indicator Reference Book, IRROMETER company, Inc

II. Suction Profile

The first Tensiometer was inserted at a depth of 7.5cm, the second was inserted at 22.5 cm and the third Tensiometer was inserted at 37.5cm below soil surface. After 24 hours, equilibrium condition achieved, so the readings of the three Tensiometers were recorded and water content at the same depth of Tensiometers were measured. Figure 2 illustrates the suction profile set.

III. Results of Suction Profile Set

The values of matric suction illustrate in Table 2 shows clearly the inversely relationship of the negative pore water pressure which is measured by IRROMETER with the elevation of water table.

4. Estimation of Soil-Water Characteristic Curve (SWCC)

A combined laboratory measurement for pore water pressure and knowledge-based approach capability of the SoilVision program was used to improve the perfect prediction of the SWCC. Figure 3 illustrates the SWCC for the used soil in this study depends on Fredlund and Xing [16] fitting equation which gives the best fit among the equations, therefore recommended that the Fredlund and Xing be used for the soil-water characteristic curve [17]. From the curve the air-entry value or the bubbling pressure is 1.3kPa also, a lot of information was estimated from this curve in order to achieve a perfect numerical simulation of the partial saturated soil.

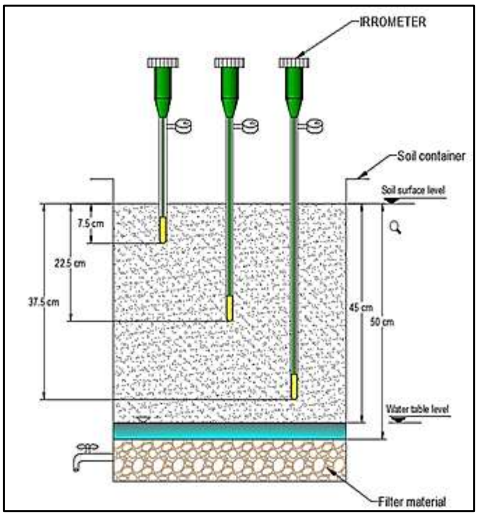

Figure 2: Suction profile set

Table 2: The matric suction values (achieved by lowering the water table 45 cm from soil surface)

Depth of Tensiometer (cm)	water content%	Matric suction (kPa)
7.5	9.3	13.7
22.5	12.7	10.0
37.5	15.1	6.0

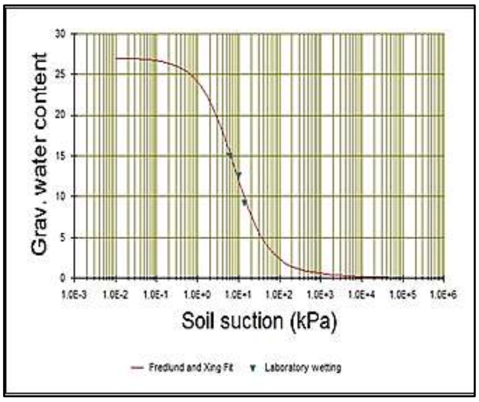

Figure 3: Relationships between the gravitational water content and the matric suction

5. Apparatus Setup

All the model tests were conducted using the setup shown in Plate 5, which consists of steel frame, steel soil tank and the vertical load is applied on the model piles by means of 10ton capacity hydraulic compression manual jack. During all the experimental tests, the loading rate is kept approximately the same.

6. Testing Procedure

I. Testing under Fully Saturated Condition

The adjustments of the water level were inspected periodically in the Piezometers. The supplier valve was closed once the water level reached the soil surface in the tank. Then all the testing models were conducting at a fully saturated soil under zero suction value.

1. Steel Frame 2. Pressure age 3. Hydraulic Jack
4. Soil Container 5. Axial Loading System
6. Piezometer 7. Drainage Valve 8. Weight Indicator

Plate 5: Test Setup

II. Testing under Partially Saturated Condition

The water table was then lowered down (using drainage valves) to a different level below the soil surface (i.e., 300mm and 450mm) to achieve different suction values. Equilibrium conditions with respect to suction value in the soil were typically achieved at a period of 24 hours. Then bearing capacity of the unsaturated soil was measured by loading test under different average suction values.

7. Results of the Experimental Models

I. Selection of Failure Criterion

Several criterions have been proposed for defining the failure load of the foundations and piles. In this study, the Tangent intersection proposal was adopted, at which the definition of failure is based on the intersection of the two tangents of load-settelment curve, the first one is tangent to the upper flatter portion tangent of the curve while the second is the tangent to the steeper flatter portion of the curve. This proposal is effective because of its' simplisity and suficiently in estimating the ultimate bearing capacity of the foundation system.

II. Selection of Testing Specification

The models of raft foundation was tested under the standerd specification ASTM-D1194-07 [18], "Bearing Capacity of Soil for Static Load and Spread Footings" while the models of piled-raft foundation was tested according to the ASTM-D1143-07, [19] "Standard Test Method for Piles Under Static Axial Compressive Load", Procedure A: Quick Test.

III. Bearing Capacity Results

The model of circular raft footing subjected to loading tests under three different matric suction values which is a chivied by lowering water table from the soil surface. Figure 4 and Table 3 shows the load settlement curves for raft footing model rested on soils with different values of matric suction.

Lowering of water table (cm)	Average matric suction (kPa)	Ultimate raft bearing capacity (N)
0	0	175
30	8	1175
45	10	1450

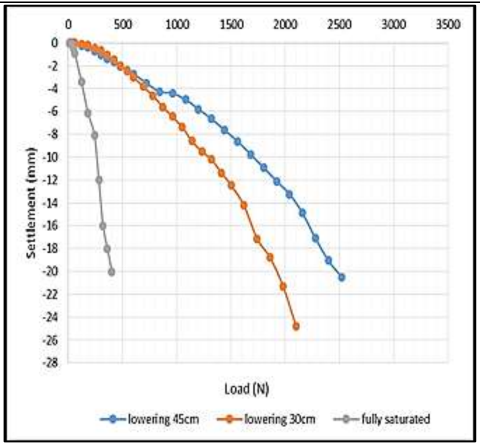

Figure 4: Load settlement curve for circular raft foundation under different matric suction values

Table 3: Results of ultimate bearing capacity of raft foundation under different average matric suction values

The results show that the ultimate bearing capacity of circular raft foundation at lowering the water table 30cm below the soil surface increases about 5 to 6 times than the ultimate bearing capacity of the same foundation at fully saturated condition. While the lowering of water table 45cm below soil surface increases the bearing about 7 to 8 times than the ultimate bearing capacity of the same foundation at fully saturated condition. This behavior can be attributed to the increase in matric suction value due to the negative pore water pressure that generated in the unsaturated zone, which causes an increase in effective stresses. Another three loading tests consist of single pile with a circular raft foundation system (piled raft) was performed. Each model was tested under both conditions of the soil; fully saturated and partially saturated with two different values of matric suction achieved by lowering water table level. All models of piled-raft are constructed at the same initial conditions to determine the ultimate bearing capacity of the piled-raft under the effect of matric suction. Figure 5 shows load-settlement behavior of single piled raft and Table 4 illustrates the ultimate bearing capacity values.

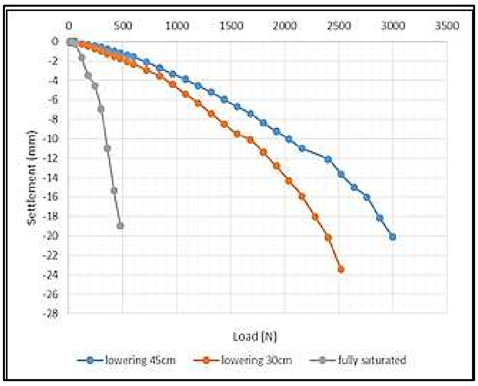

Figure 5: Load settlement curve for piled-raft foundation under different matric suction

Table 4: Results of ultimate bearing capacity of piled-raft foundation under different average matric suction values

The results show that the ultimate bearing capacity of piled raft foundation at lowering the water table 30cm bellow soil surface increases about 6 to 7 times than the ultimate bearing capacity of the same foundation at fully saturated condition. While the lowering of water table 45cm below soil surface increases the bearing about 8 to 9 times than the ultimate bearing capacity of the same foundation at fully saturated condition.

Generally the above figures shows that the bearing capacity of the raft and piled raft increases with the lowering water table level at the same density of the soil, since this lowering caused a negative pore pressure (matric suction). The increase in matric suction is effective in pulling the particles together and offering more resistance to the applied load.

IV. Comparison of Results

In order to achieve the improvement of the ultimate bearing capacity due to foundation type, a comparison between the results of piled-raft foundation and raft foundation is debated which is constructed at the same initial conditions and the same matric suction (e.g. lowering the water table 45cm), Figure 6 illustrates this comparison. The exits of pile will be affected the ultimate bearing capacity of the foundation system by increasing it 20% than the ultimate bearing capacity of the raft only which is a logical percentage occurs by a single pile only.

8. Numerical Modeling of Piled Raft Foundation using (ABAQUS)

The numerical model which is adopted to validate the experimental tests is an axisymmetric model of a single piled-raft foundation with lowering the water table 45cm from the soil surface. The same initial conditions and matric suction from the Tensiometer readings and Soil Water Characteristic Curve determinations were carried out to simulate the partial saturated condition of the soil used.

I. Geometric Modeling and Material Properties

The geometric modeling consists of simulating the soil continuum and the piled raft foundation as a separated part then ABAQUS (Student Edition 6.9) gathering the parts in the assemble module as an axisymmetric model. Figure 7 demonstrates soil and piled raft respectively while Figure 8 shows the numerical simulation as an axisymmetric model in ABAQUS/CAE. The properties of materials used in this model are summarized in Table 5.

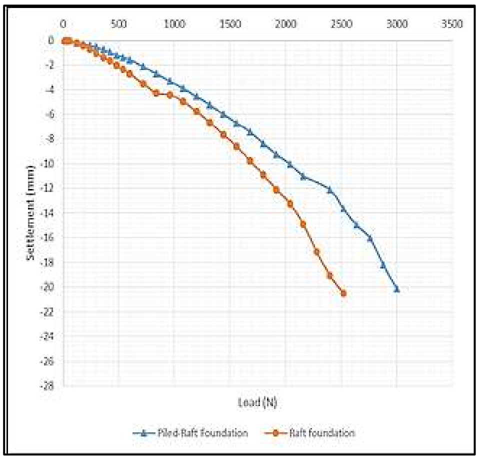

Figure 6: Load settlement curve for raft and piled-raft foundation at the matric suction of 10kPa

Lowering of water table (cm)	Average matric suction (kPa)	Ultimate piled-raft bearing capacity (N)
0	0	200
30	8^*	1350
45	10	1700

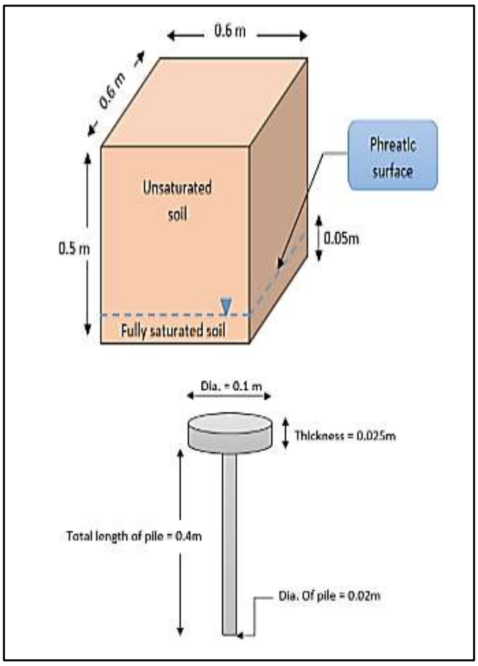

Figure 7: The model of the soil and the piled-raft foundation

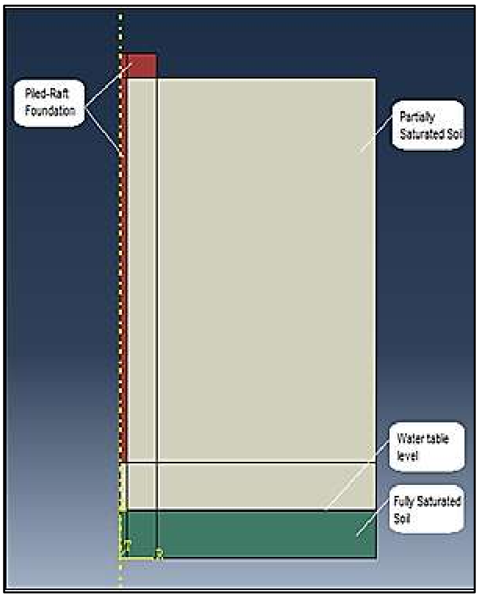

Figure 8: Parts of the Geometry in Axisymmetric Simulation

Table 5: Engineering properties of materials used

Material	γ_d kN/m^3	Modulus of Elasticity kPa	Poisson's ratio, v	e_o	Cohesion, C kPa	Angle of Internal Friction, ϕ^o	Coefficient of Permeability m/sec
Soil	14.9	18000	0.35	0.76	4	33.5	0.000245
Pile	24.0	25743000	0.25	-	-	-	-
Raft	24.0	25743000	0.25	-	-	-	-

II. Modeling the Contact Zone

The numerical treatment of contact problems involves the formulation of the geometry, statement of interface laws, variation formulation and the development of algorithms [18]. To simulate the interaction or contact behavior, specially, for the soil, pile and raft the master-slave concept developed by Wriggers [20] is used.

III. Discrimination

The element used to simulate the soil is an axisymmetric quadrilateral element named CAX8RP, which means: continuum stress/displacement (C), axisymmetric (AX), number of nodes (8), reduced integration (R) and pore pressure (P), while the piled-raft foundation system has the element CAX8R that is also an axisymmetric eight-nodded quadrilateral element. Some special partition techniques are used to make a smooth transition of element sizes from the finer to the larger one. Figure 9 shows model meshing.

IV. Boundary Conditions

Boundary conditions can be used to specify the values of all basic solution variables (displacements, rotations, warping amplitude, fluid pressures, pore pressures, temperatures, electrical potentials, normalized concentrations, acoustic pressures, or connector material flow) at nodes. The boundary conditions are assumed to be hinged at the right and bottom side of the soil to prevent horizontal and vertical lower boundary movements. The boundary condition along the left edge which is a symmetry axis is XSIMM (symmetry about plane x = constant). Figure 9 demonstrate the boundary conditions of the study. The rotational degree of freedom Ry and Rz in yz plane are not allowed. Besides the translational degree of freedom in x,y and z direction, the rotational degree of freedom were notated as Ry and Rz in the figure below.

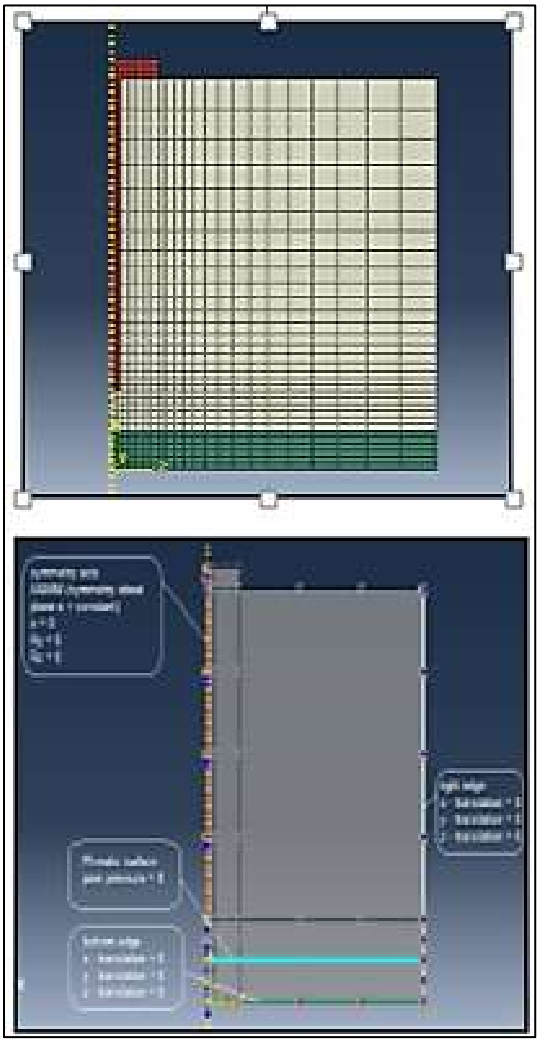

Figure 9: Meshing the Model and Boundary Conditions of the Model

9. Results of the Numerical Model

I. Validation of the Numerical Model

The load is applied incrementally with a pattern similar to the experimental applied load. The ultimate bearing capacity of the piled raft foundation from the numerical analysis is 1600 N which is obtained from the load-settlement curve using the tangent failure method. Figure 10, presents a comparison between load-settlement curves of piled-raft foundation that obtained from the experimental model and numerical analysis using finite element method. From this figure, it can be seen that, the analysis by ABAQUS program revealed a very close result with the experimental model of load settlement relationships. This is show a good agreement of the results between the experimental and numerical models are obtained.

II. Stress Result

The analysis results of the normal effective stress component (S_{22}) shows that the maximum value is in the upper third part of the pile as shown in Figure (11). The reason for concentrating stresses in that part because at the partially saturated soil having a maximum negative pore water pressure at the top of soil surface which is a propagandist of concentrating effective stresses in that part of soil. Increasing effective stress leads to increasing the friction resistance at the pile surface and constrain the movement of pile.

III. Displacement Result

The vertical movement is obtained by calculating the vertical displacement, U2 for a node located at the top surface of the raft foundation which is the same position of the dial gage in the experimental test. Figure (12 a) shows the variation in vertical displacement with depth. The red color referred to the minimum value while the blue one referred to the maximum value.

IV. Pore Water Pressure Distribution

The distribution of pore water pressure is demonstrated in Figure (12 b). The figure shows the variation of pore water pressure along the depth of the soil starting with a negative pore water pressure in the partially saturated region with a maximum negative value at the top surface equal to (-4.5) kPa. The negative pore pressure gradually decrease with the depth of soil and transverse to a positive pore water pressure in the fully saturated region with a maximum positive pore water pressure equal to (+ 0.5) kPa.

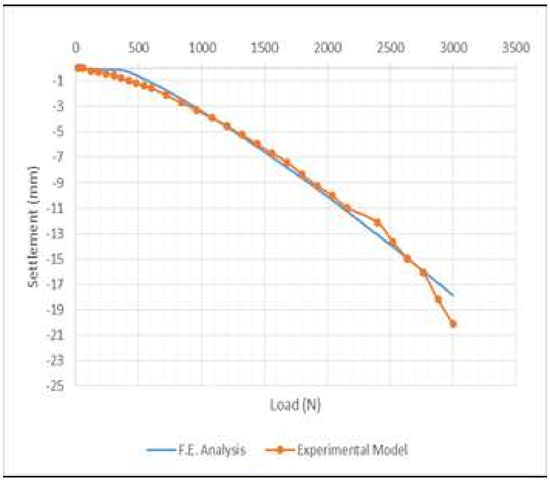

Figure 10: Load-Settlement Curve for the Numerical Simulation of a Piled-Raft Foundation (lowering 45 cm)

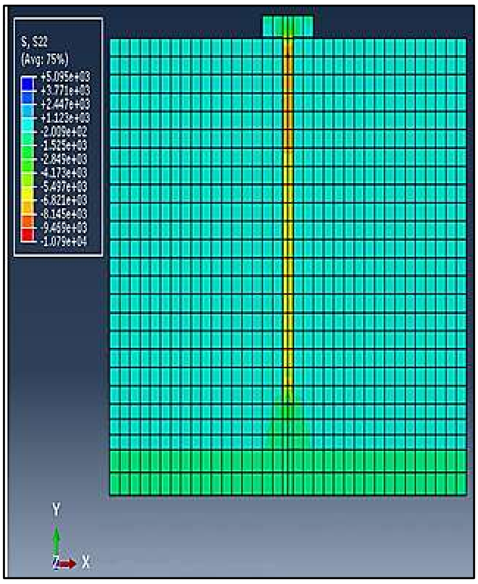

Figure 11: Distribution of Normal Effective Stress Component, S_{22}

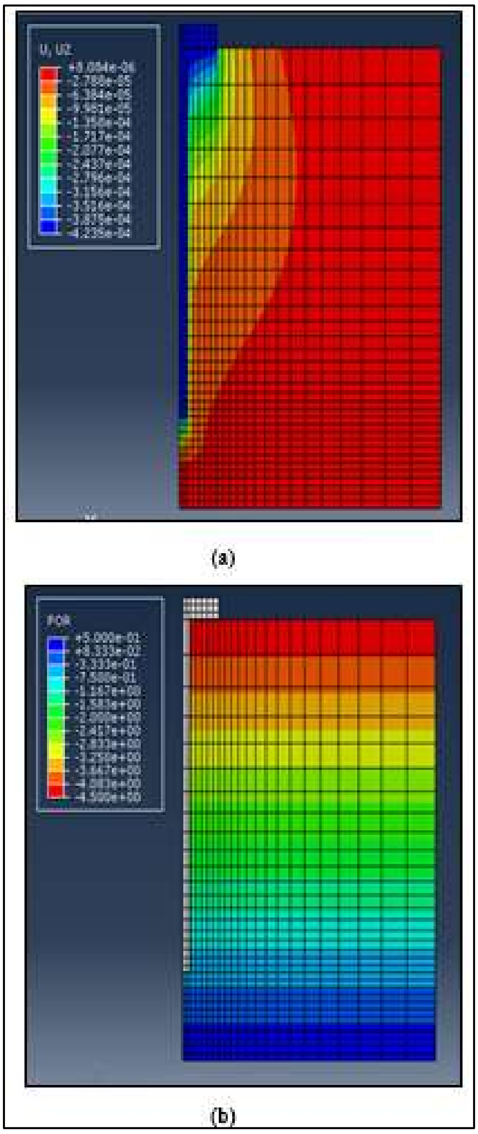

Figure 12: (a) Vertical Displacement (U2), (b) Pore Water Pressure Distribution

10. Conclusions

The following conclusions can be drawn:

1) The results of the experimental work demonstrate that the matric suction values have a significant role on the ultimate bearing capacity for all the tested models.

2) The results of experimental tests when lowering the water table 30cm below soil surface show an increase in ultimate bearing capacity by about 5.0-6.0 for circular raft foundation and 7.0-8.0 for single piled raft foundation under partially saturated condition than the ultimate bearing capacity of the same foundation at fully saturated condition.

3) The results of experimental tests when lowering the water table 45cm below soil surface show an increase in ultimate bearing capacity by about 7.0-8.0 for circular raft foundation and 8.0-9.0 for single piled raft foundation under a partially saturated condition than the ultimate bearing capacity of the same foundation at fully saturated condition.

4) A successful numerical simulation for the piled raft foundation embedded within partially saturated sand using ABAQUS software shows a good agreement with the experimental tests results of load settlement relationship.

5) Numerical analysis shows a concentrating in normal stress at the upper third part of the pile, which is a propagandist of concentrating effective stresses in that part of soil.

6) The numerical analysis provides a full profile set of positive and negative pore water pressure at the final stage of applying load and it is a logical value compared with the Tensiometer readings before applying load.

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