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Behavior of Piled Raft Foundation Model Embedded within a Gypseous Soil Before and after Soaking

Abstract: *The paper explain an experimental study to show piled raft system behavior when embedded within gypseous soil in three different stats (dry, socking for 1 day and placing a bearing layer of dense sand below the gypseous soil when socking for 1 day). A small-scale "prototype" model of steel box with dimension of (60cm length x 60cm width x 75cm heights) was used for carried out the model tests. Two different lengths of reinforced concrete pile models (40cm and 45cm) of 2.0cm dia. were used to keep the same imbedded length ratio during testing piled raft and piles only. Three different configurations of pile groups (single, three and six piles) were tested in the laboratory in two ways, first; the raft does not contact with the soil and the second; the raft is in contact with the soil. In dry state, the gypseous soil showed a very high carrying capacity with reduction in settlement. Piled raft foundations show an efficient in dry state, where the load carrying capacity increased and the settlement decreased. The improvement ratios in the load carrying capacity were about 16% for single piled raft and 39% for group of three-piled raft, while settlement reduction ratios were about 18% for single piled raft and 45% for group of six-piled raft. When the gypseous soil socked with water for 1 day, the ultimate bearing capacity of foundations is generally reduced by about (69%-83%) compared with dry state for all model configurations. The improvement ratios in ultimate bearing capacity due to using piled raft in soaking state was about (11% -50%) whilst the reduction settlement ratios was about (16% -44%).*

Keywords- *Gypseous soil, Socking, Piled raft foundation, Bearing layer.*

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1. Introduction

The pile raft foundation is such a combination of a deep pile group and a shallow raft foundation, which has gained increasing recognition in very recent years. The main objective is not only the load sharing between these two components but also to restrict the total and differential settlement within acceptable limit. The concept of piled raft foundation proposed by Davis and Poulos, [1] and is now used extensively in Europe, particularly for supporting the load of high buildings or towers.

Randolph [2] has clearly characterized three diverse design philosophies with respect to piled rafts: Conventional approach, creep piling and differential settlement control. Reul et al. [3] performed the 3-D finite element analysis of three piled raft foundation on over-consolidated clay and compared the results with the measured values in terms of load sharing, total and differential settlement. Prakoso et al. [4] 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. Sanctis et al. [5] pointed out the limitations of this 2-D plain strain analysis and remarked "only 3-D finite element analysis is suitable for the development of optimum design methodology". Maharaj [6] studied the behavior of piled raft foundation by 3-D nonlinear finite element analysis. The elastic raft, subjected to uniformly distributed load and supported by elastic pile in stiff clay, was modeled by hexahedron 8-noded brick elements. Katzenbach et al. [7] 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 the significant role in the design of a pile raft foundation system. Novac et al. [8] performed a

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linear elastic three dimensional finite element analysis to study the 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. Hassen and Buhan [9] developed an elasto-plastic multiphase model in order to simulate the load settlement behavior of piled raft foundation subjected to combine (vertical and horizontal) loading. Sanctis et al. [10] 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. This analysis concluded that the bearing capacity of piled raft is the summation of the capacity of an un-piled raft and a pile group, "which can be simply evaluated in the conventional way". However, this is a controversial conclusion to the other researchers and practical measured values of the foundation behavior.

Hussein et al. [11] studied the bearing loads ratio between the pile and pile cap (raft) by developing a piled raft foundation model using computer program (Plaxis 3D Foundation V1.1). Verification with laboratory experimental work was done with the same problem of different soil layers. The effect of spacing between piles on the load-settlement behavior is studied also. The result shows that the bearing ratio carried by piles to the total applied load of the numerical model for the model of sixteen piles with raft is around 42%. Sinha [12] developed an analytical model capable to predict the settlement of each individual pile in the group under the raft. Accordingly, the differential settlement within the piled raft can be estimated. In this investigation, three independent models were developed to simulate the load-sharing model that estimates the load components of the raft and the pile group in the system.

Mahmood et al. [13] performed laboratory experimental models of piled raft foundation with two different scales of the same L/D_p ratio (Embedment length to pile diameter) and L/B_r ratio (Embedded length to raft width), to study the scale effect of plane stress condition for the large scale model and plane strain condition for the small scale model. The bearing ratio of the piles and raft have been found individually and presented as load-settlement curves. A comparison study was done between the two models of laboratory experimental test; it was found that the percentage of the bearing ratio for raft to the total applied load for the case of the four piles with raft model is ranged between (60.6-64.8) percent.

Khairalla [14] carried out laboratory experimental testing to investigate the bearing ratio of piled raft embedded within partially saturated sandy soil and investigate the effect of matric suction on the load carrying capacity. The experimental work consists of 3 models of footing "single pile model, raft model only and single piled raft model". All these models are loaded and tested under both fully saturated condition and unsaturated conditions. The results of experimental tests demonstrate that increasing values of the ultimate bearing capacities for raft foundation, single pile and single piled raft under unsaturated conditions by approximately (2.3-3.7) , (2.0-3.0) and (2.3-3.8) times higher than that of fully saturated condition respectively.

Gypseous soils are very dependable for foundation bearing stress when they are dry, but upon wetting these soils will suffers immediate settlement (called collapse) which eventually take place even if there was little or no load at all. If a structure is exist over these soils immediate will occur upon wetting of soil. Al-Saoudi et al. [15] has been reported that many major projects suffered from several problems related to construction on or by gypseous soils such as cracks, tilting, collapse and leaching the soil. Zakaria [16] studied the collapse behavior of a small prototype model of steel pile founded into gypsifereous sand. It is intended to study, in precise, the settlement - time relationship for such piles founded into a gypsum-sand soil mixture when subjected to socking and then to leaching periods. Thereafter, the gypsum-sand soil is changed in the sense of the gypsum content. Al-Busoda and Al-Rubaye [17] performed an experimental pile models embedded within gypseous soil of 42% gypsum content. Several criteria have been used to calculate the bearing capacity of the model bored pile through the results of the pile load tests. It was found that Shen's method gave almost an acceptable result for all model pile load tests. Large draw down in bearing capacity was observed when model pile has been loaded after it was subjected to soaking for (24) hours because of the losses of cementing action of gypsum.

2. The Material Used

I. Soil used

The soil used was from "Ayn-Tamor in a holly Kerbella city", the soil sample is collected from a depth of 0.5m below the soil surface. It is subjected to routine laboratory tests to determine physical, chemical and its engineering properties as shown in Table 1. Figure 1 shows soil grain size distribution by three methods (Dry Sieve, Wet sieving with water, polar solvent and wet sieving with kerosene, nonpolar solvent).

Table 1 : Results of physical properties of the soil used

Properties	Values	Specification
Grain size analysis		
Effective size, D_{10} mm	0.17	
Coefficient of uniformity, Cu	5.29	
Coefficient of curvature , Cc	0.99	
Classification (USCS)	SP	ASTM D 422-02 [20]
Specific gravity, Gs	2.45	ASTM D 854-05 [21]
Dry unit weights		
Maximum unit weight (kN/m^3) ($\gamma_{d\,(max)}$)	17.5	ASTM D 4253-00 [22]
Minimum unit weight (kN/m^3), $\gamma_{d\,(min)}$	14.1	ASTM D 4254-00 [23]
Test unit weight (kN/m^3), $\gamma_{d(test)}$	15.62 (Dr 50%) 16.13 (Dr 65%)	
Relative density, Dr%	50%, 65%	
Void ratio		
Maximum void ratio ,e_{max}	0.73	
Minimum void ratio,e_{min}	0.40	
Testing void ratio, e_{test}	0.569 (Dr 50%) 0.519 (Dr 65%)	
Angle of internal friction Ø at Dr. 50%	40°	ASTM D 3080-00 [24]
Angle of internal friction Ø at Dr. 65%	42°	ASTM D 3080-00 [24]
Cohesion, Due to Gypsum at Dr. 50% (kPa)	12	ASTM D 3080-00 [24]
Cohesion, Due to Gypsum at Dr. 65% (kPa)	13	ASTM D 3080-00 [24]

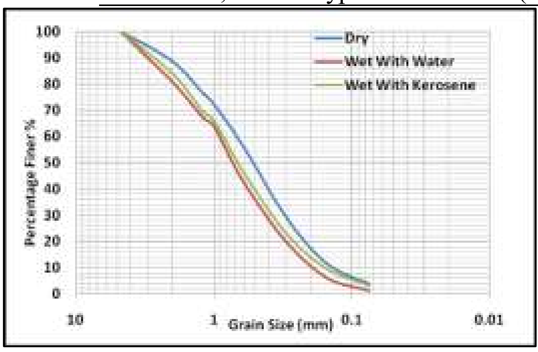


Figure 1: The grain size distribution of the soil used

II. Chemical tests

Chemical tests were performed according to British Standard (BS 1377: 1990) [18] to find the chemical properties of the soil used. Tests results shows in Table 2.

III. Engineering tests

Collapsible tests were carried out according to ASTM D 5333–03 [19] to assess the collapsibility of gypseous soil sample and the results shows in Table 3.

Table 2: Results of chemical properties of used soil

Properties	Values	Specification
Gypsum Content (%)	59.1	B.S. 1377 test no. (9) and hydration method [18]
Total Sulphate Content SO_3 (%)	27.36	B.S. 1377 test no.(9) [18]
Total Soluble Salts T.S.S %	45.53	Earth manual (1998) [25]
pH Value	7.8	BS 1377 test no. (11) [18]
X-Ray Diffraction		Gypsum, Quartz, Calcite, Feldspar
Organic content %	Nil	BS 1377 test no.(8) [18]

Table 3: Results of collapse potential test

ASTM D 5333 - 03		
Type of test	**Single Collapse**	**Double Collapse**
$\Delta e^* = (e_1 - e_2)$	0.055	0.077
Collapse Index, Ie % $= [\Delta e/(1+eo)]*100$	3.62	5.04
Degree of Specimen Collapse	Moderate	Moderate

* Δe is the difference between the void ratio before socking e_1 and void ratio after socking e_2 under same applied pressure.

3. Test Setup

All the models were tested by using the setup, which consist of:

1. Steel soil tank.
2. Steel frame and hydraulic compression handle jack.
3. Load cell.
4. Digital weighting indicator.
5. Reinforcement model concrete piles and steel pile cap model of piled raft.

I. Steel soil tank

The soil tank has dimensions of (0.6m) length, (0.6m) width and (0.75m) height with steel plate of (6mm) thickness as indicated in Plate 1. These dimensions were chosen large enough to eliminate the effect of interface between the walls of the tank and the failure zone around the piled-raft system. The container has enough rigidity to prevent lateral deformation during the preparation of the soil bed and during the test.

II. Steel frame and hydraulic compression handle jack

The steel loading frame was manufactured to support the piston of hydraulic jack of 10-ton capacity as clarified in Plate 2 for applying the testing loads.

III. Load cell

A compression load cell (model: SM 600E) was used to measure the applied load, with maximum capacity of 2 tons, rated output (R.O) is 2 ± 0.005 mV/V, combined error is 0.15% , excitation 10-15V (10 recommended) .

IV. Digital weighting indicator

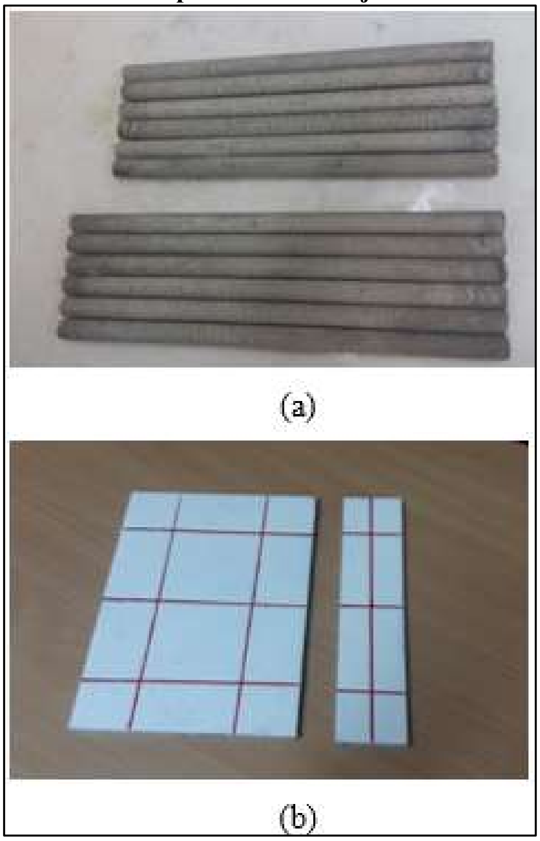
A digital weighting indicator was used to show the amount of the applied load (model SI 4010) input sensitivity 0.2 μN/Digit, load cell excitation DC 10V ±5V, max. signal input voltage 32mV.

V. Reinforcement concrete pile models and pile cap model of piled raft

The piled raft models consist of piles and raft, the raft model was used as steel plate having 10mm thickness as shown in Plate 3.a.The piles model were reinforced and casted as a reinforced concrete as shown in Plate 3.b with two different lengths, 450mm length were used to carry out pile group test only and 400mm length were used to carry out the piled raft tests, both models of 20mm diameter. The spacing (*S*) between piles is kept constant as 80mm c/c with *(S/d* = 4), in all tests.

Plate 1: The steel soil continer

Plate 2: The steel frame with hydraulic compression handle jack



(a)

(b)

Plate 3: Piled raft models, (a) Concrete pile models, (b) Steel plates

4. Configurations of Piled Rafts

Three different configurations of piled raft were used to investigate the effect of pile numbers and group action. These models consist of single piled raft, group of (1x3) piled raft and group of (2x3) piled raft. These types of piled raft considered as small piled raft where (B/L<1) (width of the raft to pile length). A schematic diagram for the three configurations are shown in Figure 2.

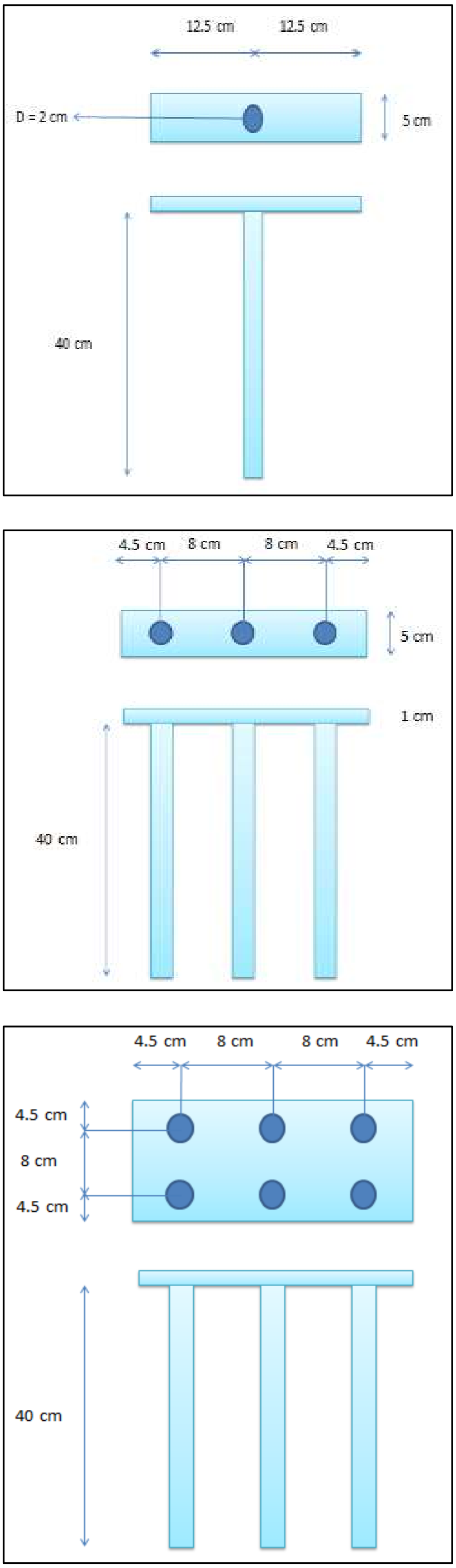


Figure 2: Piled rafts configurations

5. Preparation the Tested Model

The testing procedure can be describe in the following steps:

1) Drying and cleaning the soil tank model.

2) Place the filter at the bottom of the soil tank with 10cm height and density of 18.9 kN/m^3 (Dr 50%), then compacted by a hammer to the required height. Then, Geotextile mesh was placed over the filter to prevent the mixing with the tested soil.

3) A bearing layer of 25cm thickness of cohesion less soil was placed in layers above the filter layer and compacted to a relative density of 80% to get a bearing layer state. After that, gypsums soil was placed in the container in layers as mentioned earlier then compacted with a hammer to the required relative density of (Dr 50%). The model piles were fixing by steel guides to keep its verticality and to prevent the horizontal movement during preparation the soil bed, as shown in Plate 4.

4) After the soil bed preparation, if the test for the piles only it should be used piles model of 45cm length (40cm inserted within the soil bed and 5cm free left above the soil surface to insure there is no any attachment of the raft with the soil). If the test for piled raft, pile models of 40cm length were used to get full insertion within the soil bed and to keep the pile head level with the soil surface.

5) In the case of dry state testing the model will be tested after placing the raft on the soil surface directly. While when the test performed in a socking state for 1 day, the model will saturate after placing the raft immediately and the test carried out in the next day. The raft and piled raft footing models tested and loaded by hydraulic jack according to specification ASTM D1194-07 [26] (for the raft only) ,while pile group models tested and loaded according to specification ASTM D1143/D 1143M-07 [27] as shown in Plate 5.The settlement was measured by mean of two dial gages of 0.01mm precise.

Plate 4: Fixed piles by steel plates

Plate 5: Test in both dry and socking for 1-day cases

6. Bearing Layer Properties

The bearing layer was used in this study as base layer for supported pile models, its effect on ultimate bearing capacity.

The bearing layer of cohesion less soil has been placed above the filer with a thickness of (25cm) in the form of three layers with density of 17.99 KN/m^3. The physical properties of the bearing layer show in Table 4.

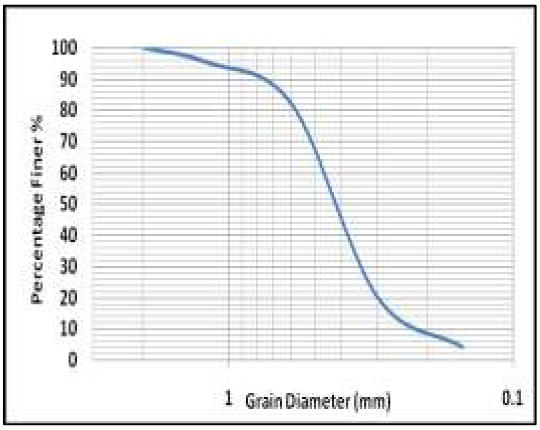


Figure 3: Grain size distribution of the bearing layer

Table 4: Physical properties of the bearing layer

Properties	Values	Specification
Grain size analysis		
Effective size, D_{10}	0.24mm	
Coefficient of uniformity, Cu	1.9	
Coefficient of curvature, Cc	1.1	
Classification (USCS)	SP	ASTM D 422-02 [20]
Specific gravity, Gs	2.67	ASTM D 854-05 [21]
Dry unit weights		
Maximum unit weight (kN/m^3) ,$\gamma_{d\ (max)}$	18.60	ASTM D 4253-00 [22]
Minimum unit weight (kN/m^3), $\gamma_{d\ (min)}$	15.92	ASTM D 4254-00 [23]
Test unit weight (kN/m^3), $\gamma_{d(test)}$	17.99	
Relative density, Dr %	80	
Void ratio		
Maximum void ratio, e_{max}	0.67	
Minimum void ratio, e_{min}	0.43	
Test void ratio, e_{test}	0.48	
Angle of internal friction, Ø	36°	ASTM D 3080-00 [24]

7. Failure Criterion

There are too many criteria can be used to determine the failure load of the foundations and piles; some of these criterion are described by Fellenius [28].

One of these criteria is Terzaghi's proposal which has been adopted for definition failure criteria for raft and piled raft system (at which the failure is defined as the load corresponding to dispalcment of 10% of footing width) ,which is almost used for esy difinition of failure crateria for shallow footings. While the failure criteria for piles without raft found adopted according to ASTM D1143/D 1143M-07[27] is 15% of the pile diameter.

8. Test Results

I. Ultimate bearing capacity at dry state

Figures 4 to 7 shows the load-settlement behavior for two unpiled-rafts only, single pile only and single piled raft, groups of three piles only, groups of three piles three piled raft and group of six piles only and six piled raft in dry state.

The improvement ratio in ultimate bearing capacity for single piled raft is 16%, for group of three piled raft is 39% and for group if six piled raft is 31% than the ultimate bearing capacity of the raft only. The settlement reduction ratio due to piled raft to the raft only for single piled raft is 18%, for group of three piled raft is 34% and for group of six piled raft is 45%. The figures show that the ultimate bearing capacity of single piled raft is greater than the ultimate bearing capacities of (raft plus single pile) individually. The same conclusion can be obtained for three piled raft and six piled raft that the ultimate bearing capacities which are higher than the ultimate bearing capacities individually for (raft 5x25cm plus 3 piles) and (raft17x25cm plus 6 piles) respectively. This is show that the piled raft system works efficiently. These results are agreed with the results of Hakam [29], Al-Tameemi [30], Hameedi [31], Al-Showely [32] and Abdul-Aziz [33] who found that the efficiency of piled raft system is greater than the summation of piles and raft capacities individually.

II. Ultimate bearing capacity after soaking

The second stat of the experimental work is socking for a 1day and then doing the test. Socking for 1 day causing a change in most of the soil characteristics, this change in soil properties has a significant effect on the ultimate bearing capacity values and the magnitudes of settlement as clarifies in Table 5.

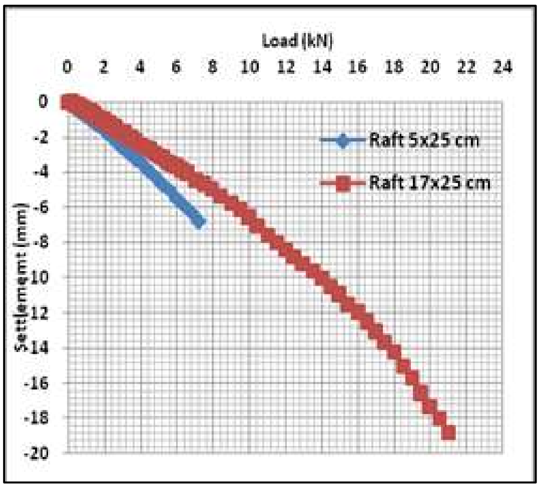


Figure 4: Load-settlement curve for un-piled rafts in dry state

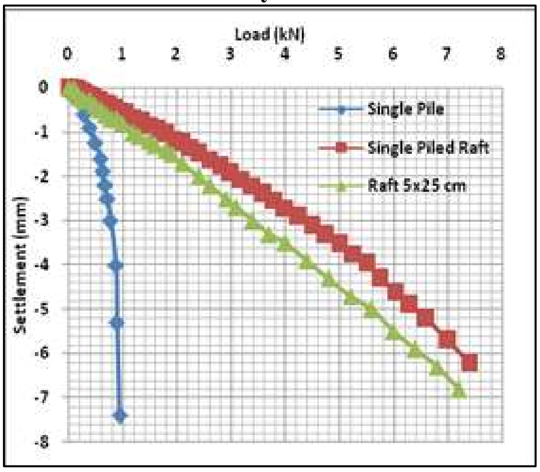


Figure 5: Load-settlement curve for raft, single pile and single piled raft in dry state

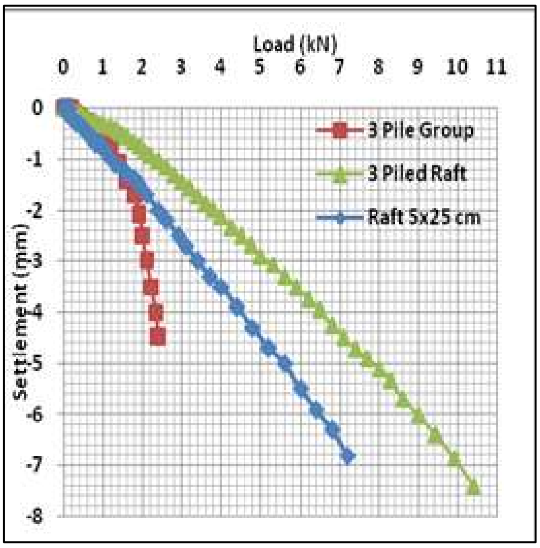


Figure 6: Load-settlement curves for raft, 3-pile group and 3 piled raft in dry state

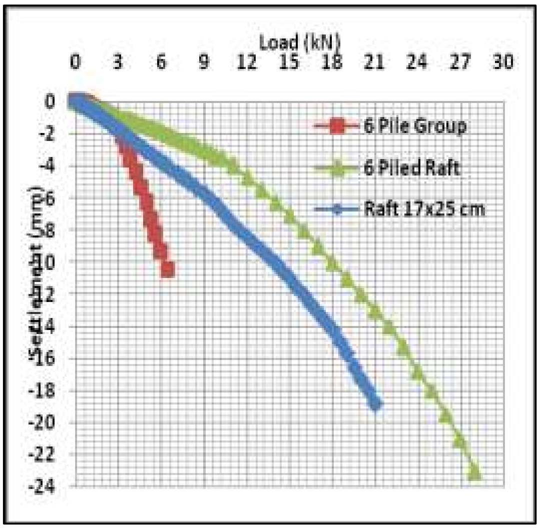


Figure 7: Load-settlement curves for raft,6 pile group and 6 piled raft in dry state

Table 5: Soil properties at dry and socking for 1-day conditions

properties	At dry state	At socking for 1 day state
Gypsum Content (%)	59.1	44.46
Total Sulphate Content SO_3 (%)	27.36	20.58
T.S.S %	45.53	34.13
Angle of internal friction Ø	44^o	39^o

Figures 8 to 11 shows that the ultimate bearing capacity after soaking reduced by 83% and 75% for small and large raft respectively compared with dry state. While the ultimate bearing capacities of single pile, group of three piles only and group of six piles only, reduced by about 69.2%, 69.0% and 69.4% respectively. Whereas, the ultimate bearing capacities of single piled raft, three piled raft group and six piled raft group, reduced by about 83.1 %, 81.5%, and 79.6 % respectively compared with dry state. This sharp lost in ultimate bearing capacity values due to combined effect of loosening bond between soil particles and some dissolution of gypsum [16, 34, 35].

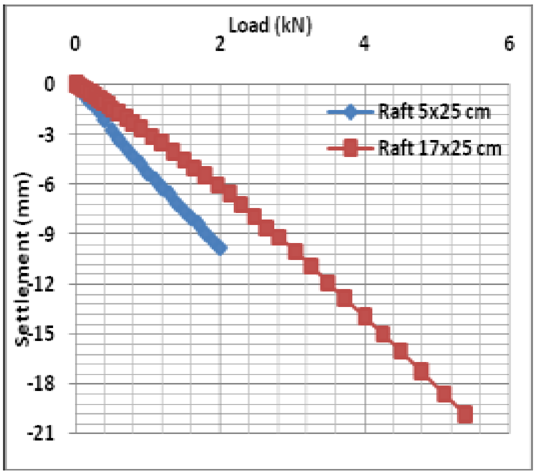


Figure 8: Load-settlement curves for un-piled rafts in socking for 1-day state

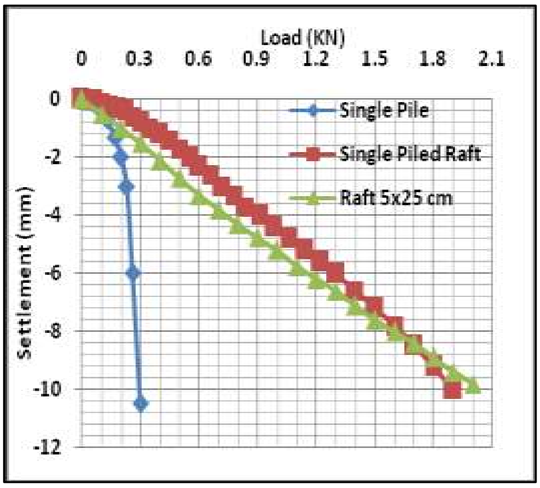


Figure 9: Load-settlement curves for raft, single pile and single piled raft in socking state

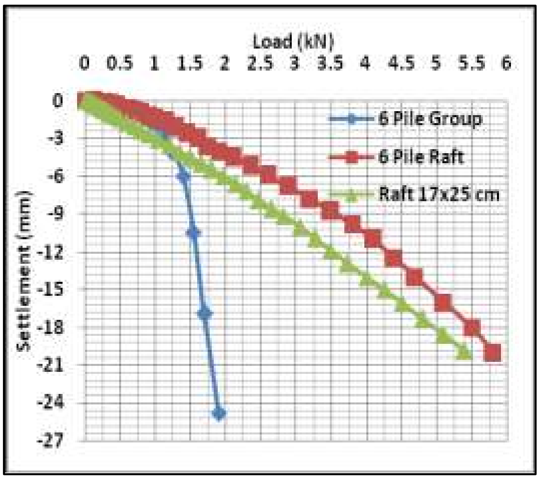


Figure 10: Load-settlement curves for raft, 3 pile group and 3 piled raft in socking

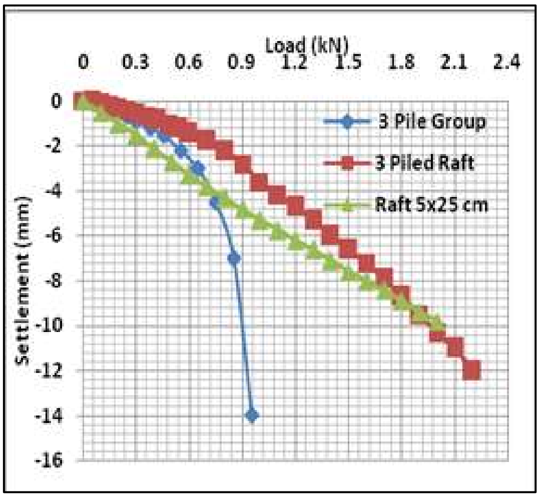


Figure 11: Load-settlement curves for raft, 6 pile group and 6 piled raft in socking

9. Effect of bearing layer with socking

The third condition of the experimental work is the socking for a 1day with using a bearing layer of cohesion less soil to investigate the effect of layered soil on soaking bearing capacity for the previous piles model configuration. Figures 12 to 15 shows the tested results of ultimate bearing capacity for testing foundations models (rafts, pile group and piled rafts) by placing a bearing layer of cohesion less soil. The testing results demonstrate that the ultimate bearing capacity of the small raft of (5x25cm) doesn't affected by bearing layer compared with the state of soaking. This is attributed to the stress of bulb pressure doesn't reach to the bearing layer (the bulb pressure for small raft extends to a depth of 2B (10 cm), while the bearing layer was at a depth equal to 30cm below the soil surface). The large raft of (17 x 25cm) affected by the bearing layer and gave a reduction of ultimate bearing capacity by about 11%. This may be due to the extent of it's bulb pressure to the bearing layer. The other results of ultimate bearing capacities for the other different configurations for pile groups only were reduced with the ranges of (20% -50%) and for piled raft with the ranges of (7% - 30%). The loss in ultimate bearing capacity of pile group individually due to presence a bearing layer was higher than that of the loss of large piled raft.

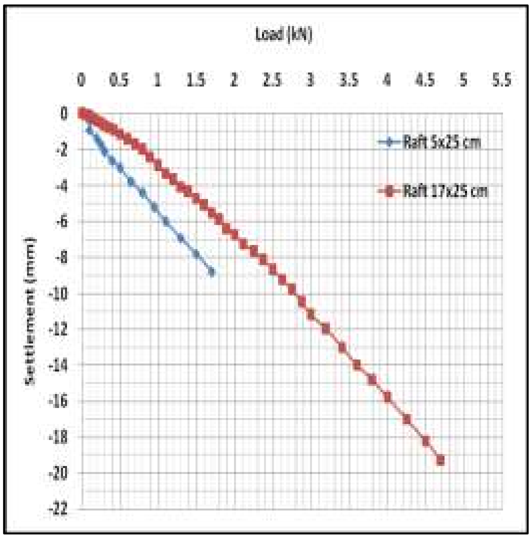


Figure 12: Load settlement curve for rafts by placing a bearing layer in socking for 1-day state

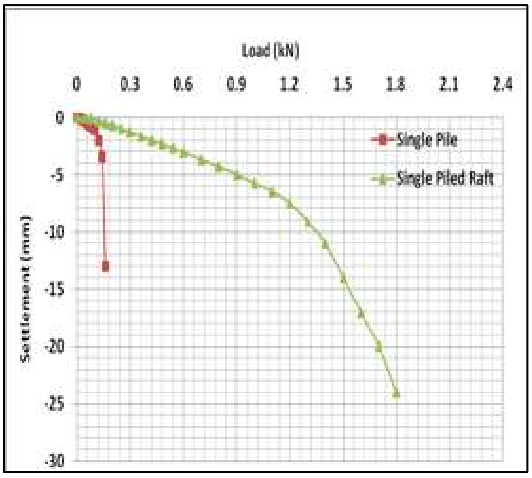


Figure 13: Load-settlement curve for single pile and single piled raft by placing a bearing layer in socking for 1-day state

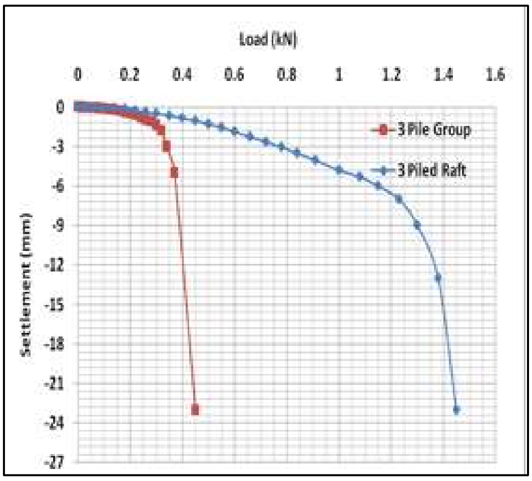


Figure 14: Load-settlement curve for 3-pile group and 3 piled raft by placing a bearing layer in socking for 1 day state

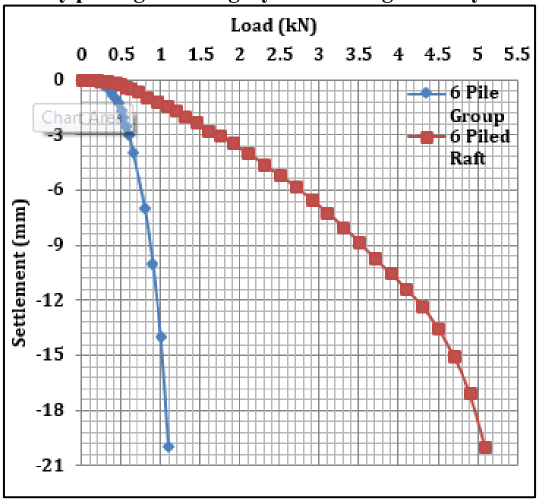


Figure 15: Load-settlement curve for 6 pile group and 6 piled raft by placing a bearing layer in socking for 1 day state

Among these three cases (dry, socking for 1 day and placing a bearing layer with socking for 1 day), the third case was the weaker case. The reason behind that was in the third case, the model consist of bearing layer and gypseous soil, the shear strength parameters, for gypseous soil in socking for 1 day were (c =5kN/m^2 and Ø = 38.5 º), while the shear strength parameters for the bearing layer were (c = 0 kN/m^2 and Ø = 35 º). When comparing the shear strength parameters for the gypseous soil and bearing layer after socking for 1 day state, it was found that gypseous soil is still have more strength than the bearing layer. That's mean that the gypseous soil needs a long time for socking to reduce its strength and become weaker than the bearing layer. So, it's concluded that the bearing layer is not efficient for a short period of socking.

10. Conclusions

1) The load carrying capacity of the raft foundations in socking state for 1 day decrease about (75% –83%) compared with the load carrying capacity in dry state.

2) The improvement ratios in the load carrying capacity for piled raft than the raft only in dry state were about 16% for single piled raft, 39% for group of three piled raft 31% for group of six piled raft. While the settlement reduction ratios were about 18% for single piled raft, 34% for group of 3 piled raft and 4٥% for group of six piled raft.

3) The improvement ratios in the load carrying capacity for piled raft than the raft only in soaking state were about 14% for single piled raft, 51% for group of three piled raft 11% for group of six piled raft. While the settlement reduction ratios were about 16% for single piled raft, 44% for group of 3 piled raft and 15% for group of six piled raft.

4) The effect of soaking reduced the load carrying capacity of single pile and pile groups of three and six pile model by 69.2%, 69.0% and 69.4% respectively compared with the load carrying capacity of dry state.

5) The effect of soaking on single piled raft and group piled raft of three and six pile model reduced the load carrying capacity by 83.1 %, 81.5%, and 79.6 % respectively compared with the load carrying capacity in dry state.

6) Settlement reduction ratios for soaking single piled raft and group piled raft of three and six pile models are 2.3%, 15% and 56% respectively compared with soaking single pile and pile groups only.

7) When using a bearing layer below the gypseous soil with socking for 1 day leads, the ultimate bearing capacity of the small raft of (5x25cm) doesn't affected by bearing layer compared with the state of soaking, While the large raft of (17 x25cm) affect by the bearing layer with a reduction of about 11% in ultimate bearing capacity.

8) The failure load of single pile, 3 pile group and 6 pile group only when using a bearing layer below the gypseous soil with socking for 1 day, leads to a decrease by 50%, 49% and 20% respectively compared with the failure load in socking state for 1 day. While the failure load of piled raft foundation decrease for single piled raft, 3 piled raft and 6 piled raft by 15%, 30% and 7.5% respectively compared with the failure load in socking for 1 day state. So, it's concluded that the bearing layer is not efficient for a short period of socking.

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