

Bearing Capacity of Pile Group and Piled Raft Foundations on Sandy Soil

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Abstract:

This paper presents an experimental study to investigate the behavior of piled raft system in different types of sandy soil. A small scale “prototype” model was tested in a sand box with load applied to the foundation through a compression jack and measured by means of a load cell. The settlement was measured at the raft by means of dial gauges, three strain gauges were attached on piles to measure the strains and to calculate the load carried by each pile in the group by the strain indicator. Nine configurations of pile groups (1x2, 1x3, 1x4, 2x2, 2x3, 2x4, 3x3, 3x4 and 4x4) were tested in the laboratory as a free standing pile group (the raft is not in contact with the soil) and as a piled raft (the raft is in contact with the soil), in addition to tests for a raft (unpiled) with different sizes. Three different densities of sand were used for some tests.

It is found that the piles work as settlement reducers effectively when the number of piles is greater than (6) than when the number of piles is less than (6). The settlement can be increased by about 8 times in (1x2) free standing pile group compared to the piled raft of the same size. The effect of piled raft in reducing the settlement vanishes when the number of piles exceeds (6). For piled rafts (3x3) and (4x4) embedded in loose, medium and dense sand; an increase in the ultimate capacity by about 93%, 96% and 98% is obtained when the group is enlarged from (3x3) to (4x4). This is attributed to increase in footing size (cap) and the increase of the number of piles in the group.

Keywords: Piled raft, bearing capacity, group, sand density.

قابلية تحمل مجاميع الركائز و الأساس الحصييرية المدعمة بركائز على ترب رملية

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الخلاصة:

يمثل هذا البحث دراسة عملية للتحري عن تصرف منظومة الأساس الحصييري المدعم بالركائز في ترب رملية مختلفة. تم فحص نموذج مختبري مصغر في صندوق من الرمل مع حمل مسلط على الأساس من خلال مرفاع ضغط هيدروليكي و مقاسا بواسطة خلية حمل. و قد قيس الهبوط في الأساس بواسطة مقاييس ازاحة و ربطت مقاييس انفعال بالركائز لقياس الانفعالات و من ثم حساب الحمل الذي تحمله كل ركيزة في المجموعة بواسطة قاريء انفعالات. و قد فحصت تسعة أشكال من مجاميع الركائز ($1x2, 1x3, 1x4, 2x2, 2x3, 2x4, 3x3, 3x4, 4x4$) باعتبار أن الركائز حرة النهايات و أن قبعة الركائز ليست في تماس مع التربة، ثم فحصت المجاميع بجعل قبعة الركائز بتماس مع التربة بالإضافة الى فحص أساس حصييري (بدون ركائز) بأحجام مختلفة. و قد أستعمل رمل بكثافات مختلفة في بعض الفحوص. و قد وجد أن الركائز تعمل كمقلات هبوط بكفاءة عندما يكون عدد الركائز أكبر من (٦) عن حالة عدد الركائز أقل من (٦). ان الهبوط يمكن أن يزداد بحدود (٨) مرات في مجموعة الركائز ($٢x١$) مقارنة مع أساس حصييري مستند على ركائز بنفس الحجم. ان دور الأساس الحصييري المستند على ركائز في تقليل الهبوط يتلاشى عندما يتجاوز عدد الركائز (٦). و للأساس الحصييري المستند على ركائز بحجم ($3x3$) و ($4x4$) المستند على تربة رملية مفككة و متوسطة و كثيفة، لوحظ حصول زيادة في قابلية التحمل بحدود ٩٣% و ٩٦% و ٩٨% على التوالي عند زيادة حجم المجموعة من ($3x3$) الى ($4x4$) بسبب الزيادة في حجم الأساس (القبعة) و زيادة عدد الركائز في المجموعة.

Introduction:

The use of piled raft foundations has become more popular in the recent years, as the combined action of the raft and the piles can increase the bearing capacity, reduce settlement, and the piles can be arranged so as to reduce differential deflection in the raft.

The piled raft foundation is a geotechnical composite construction consisting of three elements: piles, raft and soil. In situations where a raft foundation alone doesn't satisfy the design requirements, it may be possible to enhance the performance of the raft by the addition of piles. The use of a limited number of piles may improve the ultimate load capacity, the settlement and differential settlement performance of the raft and the required thickness of the raft (Poulos 2001).

As with any foundation system, design of a piled raft foundation requires the consideration of a number of issues, including:

1. Ultimate load capacity for vertical, lateral and moment loadings,
2. Maximum settlement,
3. Differential settlement,
4. Raft moments and shears for the structural design of the raft, and
5. Pile loads and moments for the structural design of the piles.

The Concept of Piled Raft Foundation

Piled raft foundations are composite structures unlike classical foundation where the building load is either transferred by the raft or the piles alone. In a piled raft foundation, the contribution of the piles as well as the raft is taken into account.

The piles transfer a part of the building loads into deeper and stiffer layers of soil and thereby allow the reduction of settlement and differential settlement in a very economic way. Piles are used up to a load level which can be of the same order of magnitude as the bearing capacity of a comparable single pile or even greater (Hartmann and Jahn, 2001).

The conventional pile design philosophy is based on that piles carry all the load and they are accepted as a group, no contribution is made by the raft to the ultimate load capacity. The new trend in the foundation engineering is combining raft foundations and pile foundations. The combined system can be based on different design philosophies which can be classified as follows (Yilmaz, 2010):

1. ***Settlement reducing pile concept:*** In this philosophy, piles are only located to reduce the total settlement and they are designed to work at limiting equilibrium, in other words, for the piles, factor of safety values against bearing capacity is taken as unity.
2. ***Piled raft concept:*** This philosophy is one of the newly adopted concepts in which a significant portion of total load is carried by the raft contrarily to the conventional design. Piles are designed to work at 70-80% of the ultimate load capacity.

3. **Differential settlement control:** Placing piles under the raft strategically and of course in a limited number will enhance the ultimate load capacity of the foundation and decrease both the settlement and the differential settlement.

Apparatus, Materials, and Testing Techniques

The main purpose of the experimental work implemented in this paper is to study the load sharing mechanism between raft and piles, as well as the load settlement behavior of piled raft with different configurations. The following sections describe the test setup used to perform the model tests, the configuration of model piled rafts, material properties, the testing program and procedures.

Test setup

All model tests were conducted using the setup shown in **Figure (1)**, which consists of frame, soil tank, model piled raft and loading machine. The vertical load was applied to the model piles by means of 10 ton hydraulic compression handle jack. During all the experimental tests, the loading rate is kept approximately constant at 3 mm/min. The applied load is measured using a “Sewha, Korea” load cell 5 ton capacity. A digital weighing indicator “Sewha, Korea” is used to read and display the load value. Two deformation dial gauges with 0.01 mm sensitivity have been used for measuring displacements of the piled raft model. Three strain gauges were adhered to the piles and connected to a strain indicator with three channels so as to measure the strains in the piles, and the strain indicator is connected to a computer through an interface device to read the strain value. **Figure (2)** shows the setup in three-dimensional view.

Soil tank

The soil tank has 0.45 m length, 0.45 m width, and 0.5 m height. It is supported by the frame. The dimensions of the tank were chosen so that the tank can be put inside the testing frame and there will be no interference between the walls of the soil tank and the failure zone around the piled raft system.

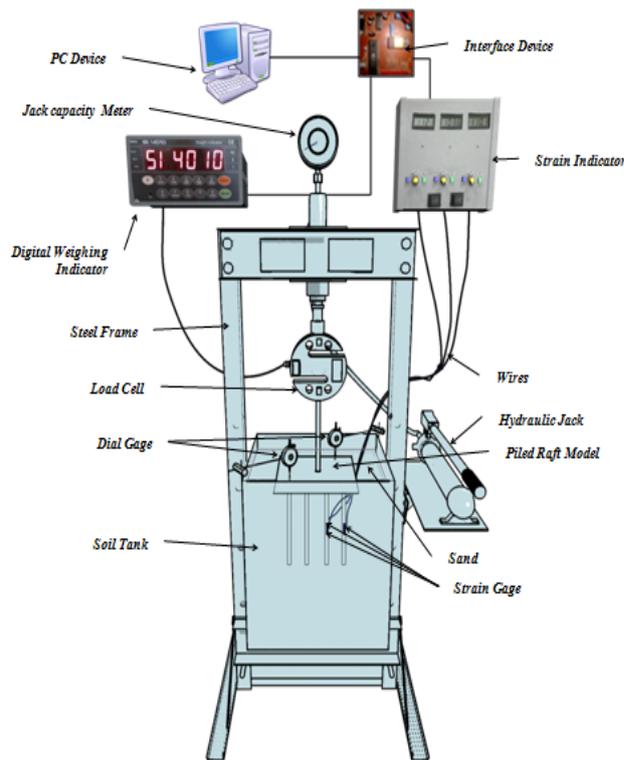


Fig. (1) Setup of the laboratory apparatus.



Fig. (2) Three-dimensional view of the setup.

Soil Properties

The soil used for the model tests is clean, oven-dried, uniform quartz (Kerbela) sand. The maximum and minimum dry unit weights of the sand were determined according to the ASTM (D4253-2000) and ASTM (D4254-2000) specifications, respectively, the specific gravity test is performed according to ASTM (D854-2005), the grain size distribution is analyzed according to ASTM (D422-2001) specifications and direct shear test according to the ASTM (D 3080-1998). **Figure (3)** shows the grain size distribution of the sand and **Tables (1)** and **(2)** summarize the physical properties of the tested sand. The angle of internal friction is determined using the direct shear test which was carried out for the three types of sand.

The sand deposit was prepared using the sand raining technique. A special raining device similar to that recommended by Bieganousky and Marcuson (1976) was designed to obtain a uniform deposit with the desired density.

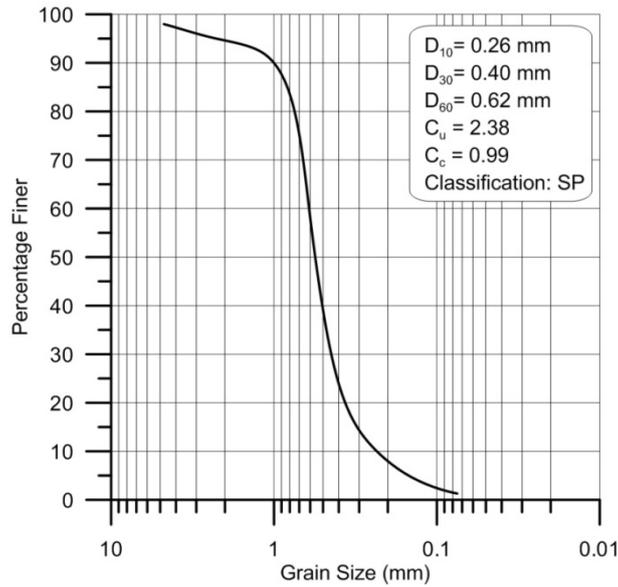


Fig. (3) Grain size distribution of the sand.

Table (1) Physical properties for the tested sand.

Property	Value
Grain size analysis	
Effective size, D_{10}	0.26 mm
Coefficient of uniformity, C_u	2.38
Coefficient of curvature, C_c	0.99
Classification (USCS)*	SP
Specific gravity, G_s	2.62
Dry unit weights	
Maximum unit weight, $\gamma_{d(max)}$	17.8 kN/m ³
Minimum unit weight, $\gamma_{d(min)}$	14.8 kN/ m ³
Test unit weight, $\gamma_{d(test)}$	16.5 kN/ m ³
Relative density, D_r	62%
Void ratio	
Maximum void ratio, e_{max}	0.73
Minimum void ratio, e_{min}	0.44
Test void ratio, e_{test}	0.56

* USCS refers to Unified Soil Classification System

The unit weight of the sand deposit in the raining method depends primarily on the drop height and the discharge rate of the sand (Turner and Kulhawy, 1987). The height of the

free fall of the sand can be controlled by adjusting the elevation of the raining device with respect to the sand tank while the discharge rate of the sand was kept constant. Sand deposits were prepared with the sand tank resting on the loading platen of the testing frame so that the sand deposit was not disturbed and hence the desired unit weight of the sand is not altered. The height of drop was chosen to be (8, 50, 90) cm which corresponds to a placing unit weight of (15.2, 16.5, 17) kN/m³, void ratio of (0.68, 0.55, 0.51) and a relative density of (15, 60, 77) %, respectively.

Table (2) Properties of different types of sand used in the tests.

Type of sand	Dry unit weight (γ_d)	Angle of friction (ϕ)	Relative density (Dr%)	Void ratio (e)
Loose	15.2 kN/ m ³	36°	15	0.68
Medium	16.5 kN/ m ³	42°	60	0.55
Dense	17 kN/ m ³	44°	77	0.51

Model Piled Rafts

The model piles used in this study are smooth aluminum pipes. The diameter of piles is 12 mm, while the length of piles is kept at 200 mm. The embedment (depth to diameter) ratio $l/d = 17$, where l represents the pile length and d is the outside diameter of the pipe pile. The spacing between piles is kept constant ($S = 36$ mm) in all tests. The model raft used in the test was also made of aluminum plate with smooth surface having a thickness of 4 mm. Both piles and rafts were composed of ALUPCO alloy, which is supplied locally by ALUPCO Alloys Company.

Strain Measurement

Three-channel strain indicator was used to read the strain initiated in the piles, specifically designed for use with strain gauges. The strain indicator, which was manufactured locally, can be used to obtain extremely accurate, high resolution strain measurements in a variety of circumstances. Accuracy of $\pm 10 \mu\epsilon$ (micro strain) can be obtained, with a sampling range max. $\pm 19990 \mu\epsilon$. It consists of quarter bridge (tension / compression) with 120 Ω resistance of strain. The strain indicator is connected to a computer to display and record the results of the strain that is measured through three channels by using interface device.

Load Measurement

A compression/tension load cell “SEWHA, Korea” model S-beam type: SS300 is used to measure the load. It is made of stainless steel – LS300, with a maximum capacity 5 ton, rated output (R.O.) is 2.0 ± 0.005 mV/V, combined error is 0.03%, excitation 10-15V (10 recommended) as shown in **Figure (4)**.

Digital weighing indicator

A digital weighing indicator is used for displaying the load amount “SEWHA, Korea” model SI 4010 with an input sensitivity of $0.2 \mu\text{N}/\text{Digit}$, load cell excitation DC 10V $\pm 5\text{V}$, maximum and signal input voltage 32mV as shown in **Figure (5)**.

Testing Procedure

The procedure followed in testing the piled raft model can be described in the following steps:

I. Building the piled raft model:

Aluminum pipe piles with constant diameters and lengths, forming nine configurations of piles (1x2, 1x3, 1x4, 2x2, 2x3, 2x4, 3x3, 3x4 and 4x4), were prepared to fulfill the testing program of the experimental study. The piles were fixed to approximately rigid rafts using super glue. Glue was used as a substitute for welding the piles to the raft since the aluminum may melt in the extremely high temperature of welding. The glue simulates a semi-fixed connection of piles to the raft.



Fig. (4) Load cell.



Fig. (5) Digital weighing indicator.

II. Attachment of strain gauge:

A strain gauge was placed in the middle of the pile shaft. The strain gauge was covered with a thin layer of sponge to protect it from damage, at the same time; sponge does not bear any load, and it is covered with tape to prevent the gauge from any moisture, as shown in **Figure (6)**.

III. Preparation of sand deposit and placing of piled raft model:

The sand was placed in the tank according to the raining technique, i.e. maintaining a dropping height constant for each density. After each test, the sand box should be emptied to a depth below the zone of influence (which was considered as $2l$ below the raft, where l is the pile length). During the process of sand raining, the piled raft model was placed at the center of the tank and under the load cell 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.

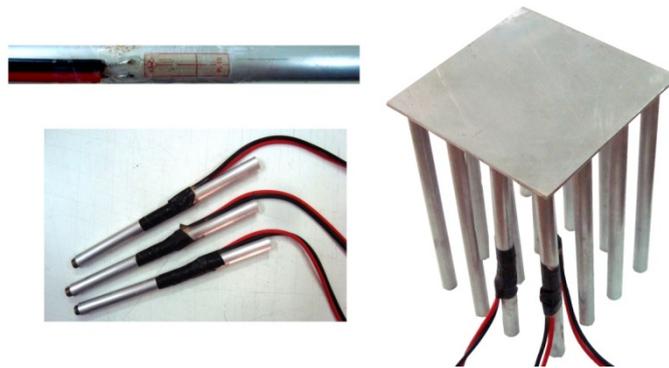


Fig. (6) Attachment of strain gauges.

IV. Connection of wires to the strain indicator:

A quarter bridge connections was performed through the use of strain indicator, a gauge factor of 2.03, excitation voltage of 10V and shunt calibration resistor of 120Ω were used to compensate for the lead wire resistant. Before starting the test, a reading of 0.00 was set in the strain indicator and waiting for 10 minutes to allow the system to be stable, then if the reading is still around 0.00, the test can be started successfully.

V. Application of vertical load:

A vertical load is applied through a 5 ton load cell; a constant loading rate has been adopted in the entire testing program. The test is continued until recoding a continuous displacement of the piled raft under constant load. The load will be read from a digital weighing indicator connected to the load cell. The central displacement of the raft is read

by two dial gauges of 0.01 mm sensitivity, and the strain in the pile is read from the strain indicator.

Some photos describing the loading process are shown in **Figure (7)**. The loading and measuring system assembly is shown in **Figure (8)**.



Fig. (7) Testing process.



Fig. (8) Testing system assembly.

Presentation and Discussion of Results

The load applied to the center of the model raft is transmitted partly to the soil and another part is transmitted to the piles. The percent of load carried by piles to the total applied load can be determined in the laboratory through instrumentation of the piles with strain gauges to measure the strain initiated in each pile. Strain can be measured in three piles in the group.

Rigid rafts have been used to distribute the load equally to the piles, and by knowing the load in three piles, the total load carried by other piles can be obtained due to symmetry. By knowing the strain in a pile, one can calculate the load in that pile if the cross sectional area and the modulus of elasticity are known.

Hansen's Bearing Capacity Equation

The bearing capacity of model rafts on sandy soil is calculated using **equation (1)**, where:

$$q_f = 0.5 \gamma B N_\gamma S_\gamma \dots\dots\dots (1)$$

Where N_γ and S_γ are the bearing capacity factor and shape factor, respectively. **Table (4)** shows the results of bearing capacity calculated by Hansen's equation.

Configurations of Piled Rafts

Piled raft configurations used maintain symmetrical shapes, especially where the differential settlement is expected to be of no major concern. Nine different configurations of piles are used in the piled raft prototypes. The groups consist of (1x2), (1x3), (1x4), (2x2), (2x3), (2x4), (3x3), (3x4) and (4x4) piles. A schematic diagram for the configuration models is shown in **Figure (9)**.

Table (4) Bearing capacity of rafts by Hansen's equation.

Raft Size (m)	γ (kN/m ³)	ϕ	N_γ	s_γ	Bearing Capacity (kN/m ²)	Bearing Load (kN)
0.025 x 0.06	16.5	42 ⁰	127.8	1.17	30.75	0.05
0.025 x 0.09	16.5	42 ⁰	127.8	1.11	29.29	0.07
0.025 x 0.133	16.5	42 ⁰	127.8	1.08	28.34	0.09
0.06 x 0.06	16.5	42 ⁰	127.8	1.4	88.57	0.32
0.06 x 0.09	16.5	42 ⁰	127.8	1.27	80.13	0.43
0.06 x 0.133	16.5	42 ⁰	127.8	1.18	74.68	0.60
0.09 x 0.09	16.5	42 ⁰	127.8	1.4	132.85	1.08
0.09 x 0.133	16.5	42 ⁰	127.8	1.27	120.58	1.44
0.133 x 0.133	16.5	42 ⁰	127.8	1.4	196.32	3.47

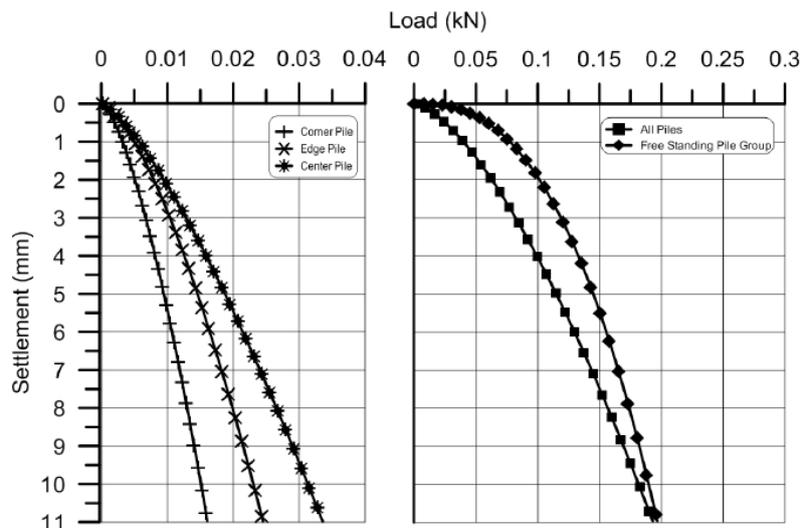


Fig. (10) Load-settlement curve for (3x3) free standing pile group in loose sand.

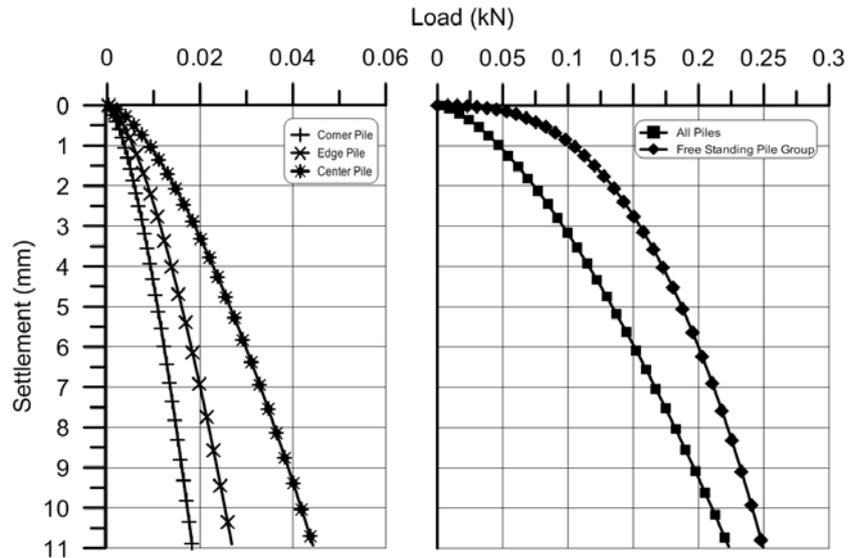


Fig. (11) Load-settlement curve for (3x3) free standing pile group in medium sand.

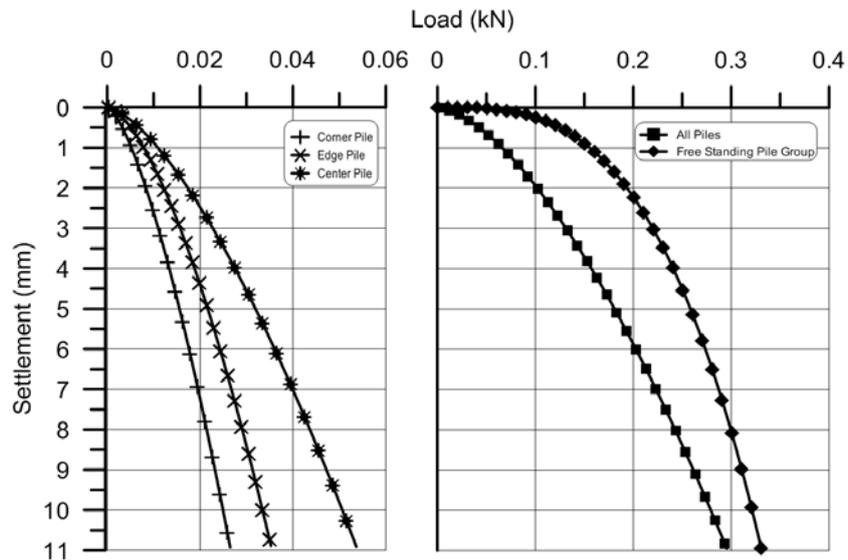


Fig. (12) Load-settlement curve for (3x3) free standing pile group in dense sand.

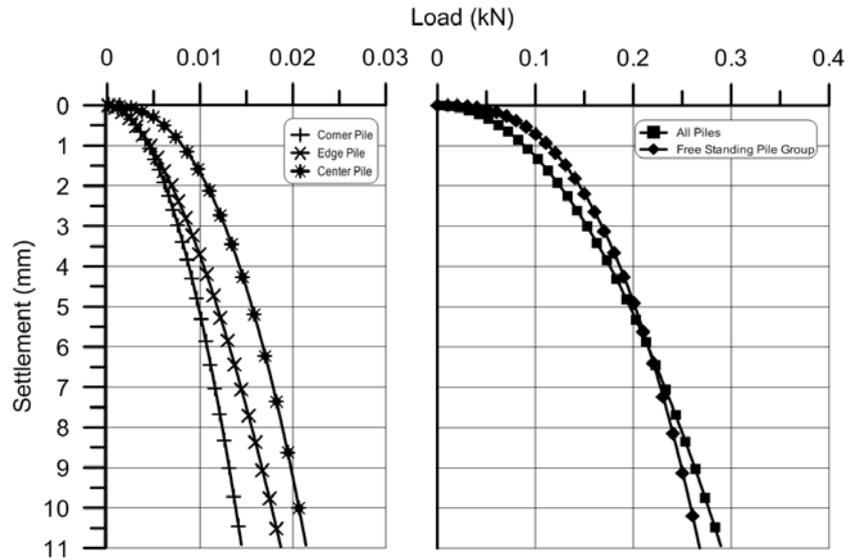


Fig. (13) Load-settlement curve for (4x4) free standing pile group in loose sand.

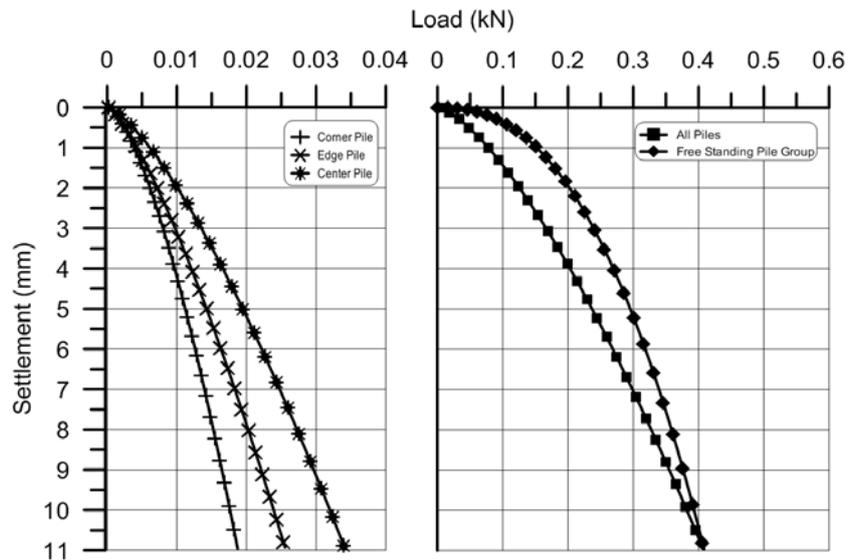


Fig. (14) Load-settlement curve for (4x4) free standing pile group in medium sand.

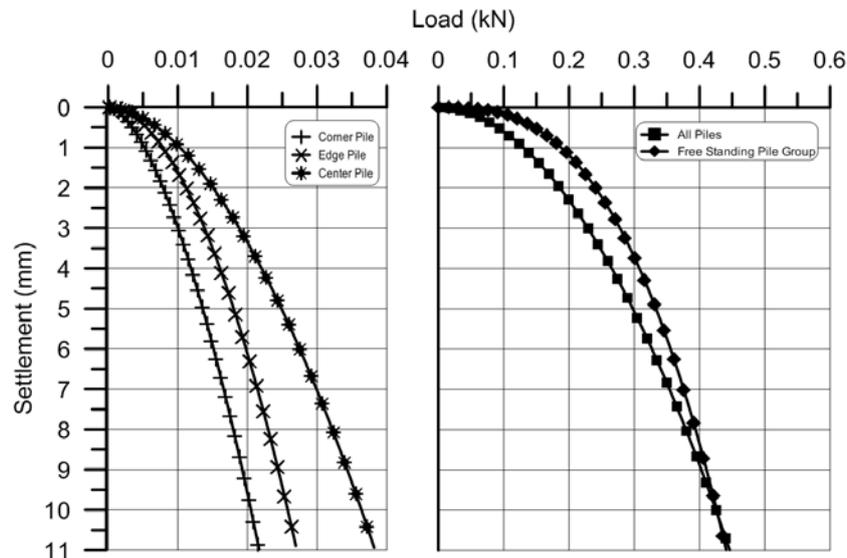


Fig. (15) Load-settlement curve for (4x4) free standing pile group in dense sand.

The effect of density on free standing pile group is clear; the load capacity increases by increasing the sand density, and the effect of density on (4x4) pile group is greater than the effect on (3x3) pile group.

The comparison of load-settlement curves for piles embedded in sands of different densities is also presented in **Figures (16)** and **(17)** for (3x3) and (4x4) group, respectively. In **Figure (16)**, the increasing of ultimate load from loose to medium is about 25% and from medium to dense is about 32%, while in **Figure (17)** the increasing of load from loose to medium is about 55% and from medium to dense is about 10%.

It is shown that for comparison between (3x3) and (4x4) group, the ultimate load is increased by 35%, 64% and 33% when the group is changed from (3x3) to (4x4) in loose, medium, and dense sand, respectively. These results lead to the conclusion that the bearing capacity factors are not linearly varying with the increase in the angle of internal friction but they might be affected by the shape of the group.

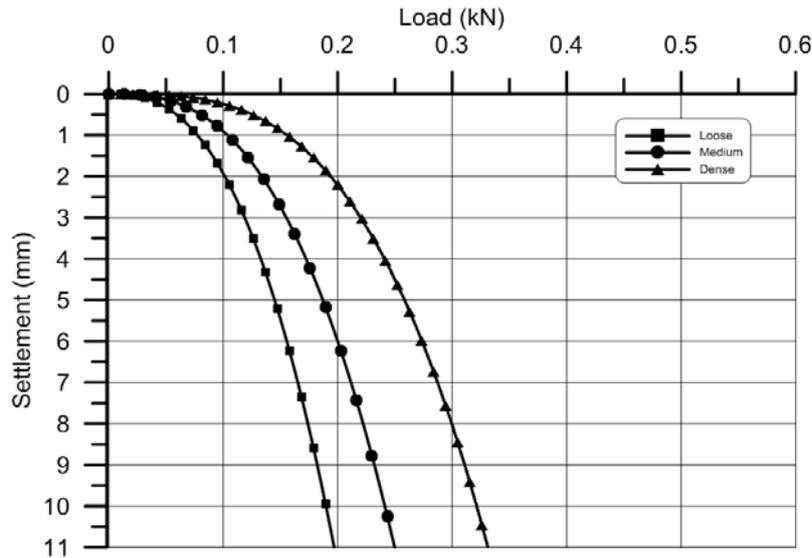


Fig. (16) Load-settlement curve for (3x3) different sand densities free standing pile group.

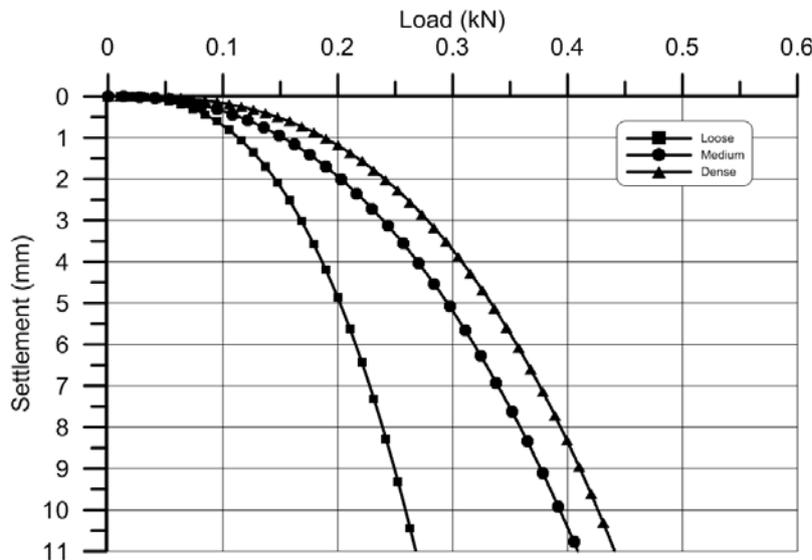


Fig. (17) Load-settlement curve for (4x4) different sand densities free standing pile group.

Selection of Failure Criterion

Several criteria have been proposed for defining the failure load of the foundations and piles. Some of these criteria are described by Fellenius (2009) as follows:

- **Terzaghi (1947) proposal;** where failure is defined as the load corresponding to displacement of 10% of the model footing width (or pile diameter).
- **De Beer (1968) proposal (as reported by Winterkorn and Fang, 1975).** The bearing capacity is taken at break point of two interesting straight lines of different

slopes after plotting the load-settlement relationship in log-log plot. This break point represents failure.

- **Tangent proposal;** in which definition of failure is based on the intersection of the two tangents of load-settlement curve, the first one is the upper flatter portion tangent of the curve while the second is tangent to the lower flatter portion of the curve.
- **Chin-Kondner (1970) proposal;** this method assumes that the load-settlement curve is hyperbolic in shape when the failure load is approached. Each load value is divided by its corresponding settlement value and the resulting value is plotted against the settlement, the plotted value fall on a straight line, so the inverse of the slope of this line is the Chin failure load.
- **Davisson (1972) proposal;** the failure load is corresponding to the movement which exceeds the elastic compression of the pile by a value of 0.15 inch (4 mm) plus a factor equal to the diameter of the pile divided by 120.
- **Decourt (1999) proposal;** a method by which each load is divided by its corresponding settlement and the resulting value against the applied load. A linear regression over the apparent line determines the line. Decourt identified the ultimate load as intersection of this line with load axis.

The bearing capacities for rafts of different sizes are calculated using the previous criteria and compared with those calculated by Hansen's equation. The results are listed in **Table (6)**.

After examining the previous methods and by making a comparison of these methods with Hansen equation for calculating the bearing capacity of the raft, it was found that Decourt proposal can be adopted in specifying the ultimate capacity.

Table (6) Different methods used for definition of failure of raft.

Raft Size (m)	Davisson (kN)	Terzaghi (kN)	Tangent (kN)	Chin-Kondner (kN)	De Beer (kN)	Decourt (kN)	Bearing capacity by Hansen Equation (kN)
0.025 x 0.06	0.038	0.028	0.032	0.052	0.028	0.055	0.05
0.025 x 0.09	0.047	0.038	0.042	0.060	0.037	0.070	0.07
0.025 x 0.133	0.062	0.045	0.051	0.093	0.042	0.100	0.09
0.06 x 0.06	0.077	0.075	0.055	0.132	0.055	0.135	0.32
0.06 x 0.09	0.080	0.080	0.060	0.144	0.064	0.260	0.43
0.06 x 0.133	0.110	0.105	0.065	0.190	0.066	0.270	0.60
0.09 x 0.09	0.140	0.160	0.085	0.256	0.095	0.360	1.08
0.09 x 0.133	0.170	0.190	0.100	0.417	0.105	0.500	1.44
0.133 x 0.133	0.380	0.420	0.260	0.625	0.247	0.680	3.47

Load Carrying Capacity of Single Pile

In order to make a basic value for comparison, loading test was carried out on a single pile.

The load-settlement curve is presented in **Figure (18)**.

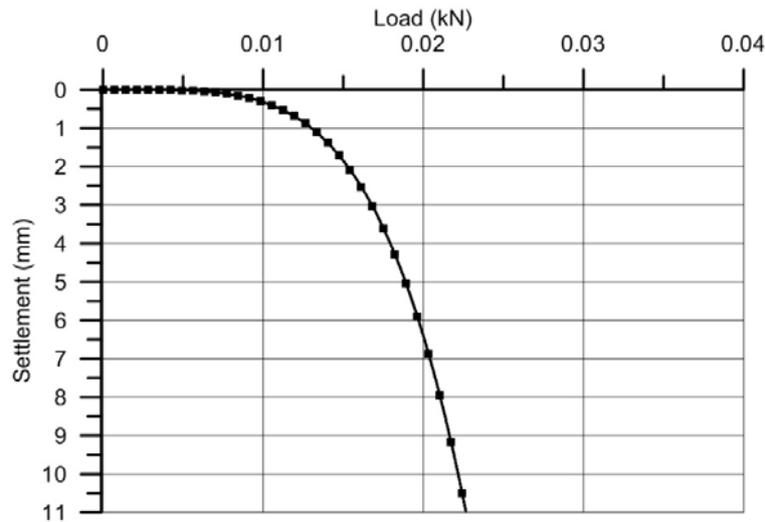


Fig. (18) Load-settlement curve for single pile.

Load Carrying Capacity of Free Standing Pile Groups

In order to make a comparison between the load carried by each pile and the summation of loads carried by piles and the total load carried by the group, **Figures (19) to (24)** are drawn for (1x2), (1x3), (1x4), (2x2), (2x3) and (2x4) group, respectively. It can be seen that the load taken by the edge pile is approximately equal to (0.4-0.6) the load taken by the corner or center pile, and the load carried by all piles approximately equals the external load (free standing pile group load).

Figures (25) to (27) make a comparison between the load-settlement curves for the center, edge and corner pile and the summation of loads carried by all these piles and actual load carried by the free standing pile group for the cases of (3x3), (3x4) and (4x4) group, respectively.

From these figures, it can be noticed that the load which goes to the center pile approximately equals (2-2.25) the corner pile load, the load which goes to the edge pile approximately equals (1.5-1.75) the corner pile load, and the summation of loads that all piles carry is little bit less than the external load (free standing pile group load). This means that the group works efficiently. In **Figure (26)** which deals with (3x4) group, it can be seen that the load carried by the edge pile from short side is little greater than the load carried by edge pile from long side.

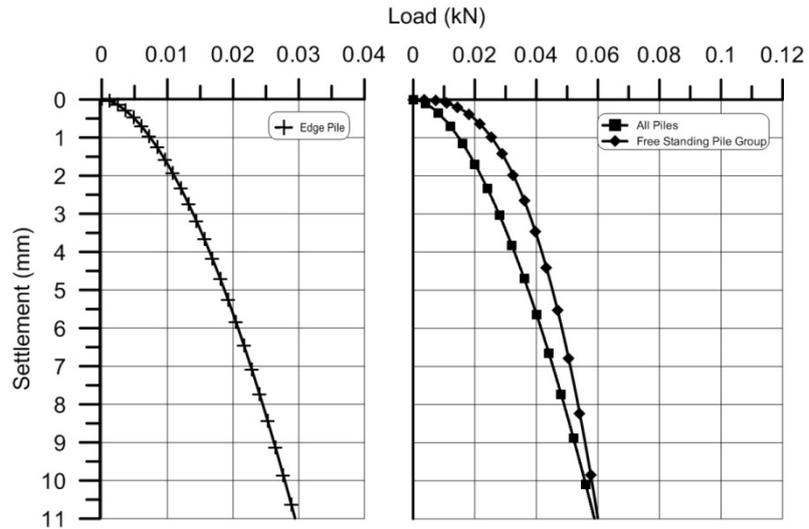


Fig. (19) Load-settlement curve for (1x2) free standing pile group.

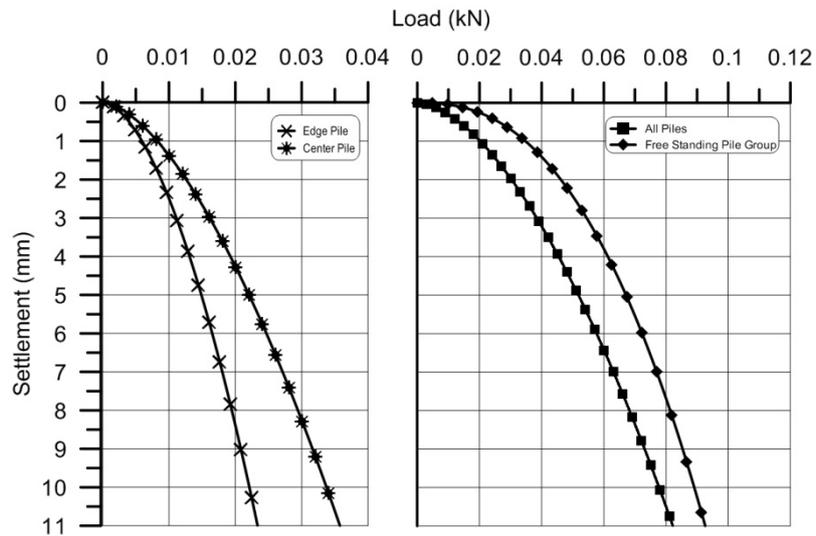


Fig. (20) Load-settlement curve for (1x3) free standing pile group.

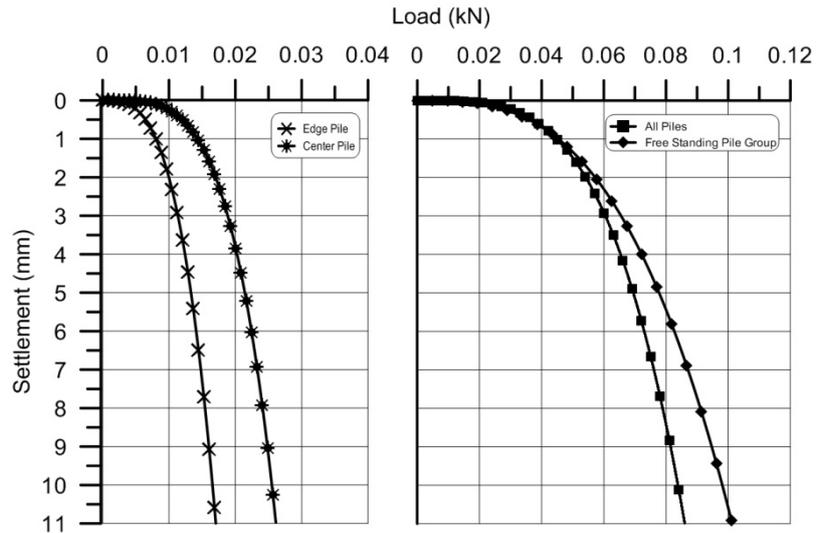


Fig. (21) Load-settlement curve for (1x4) free standing pile group.

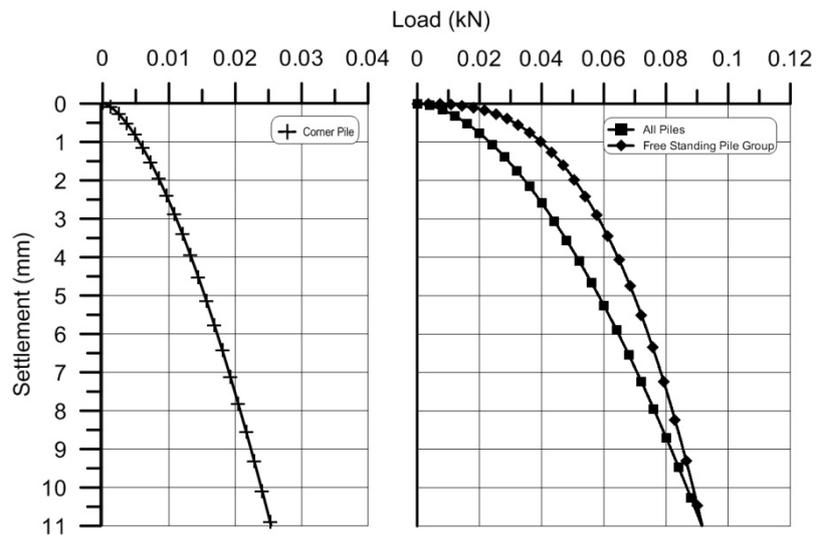


Fig. (22) Load-settlement curve for (2x2) free standing pile group.

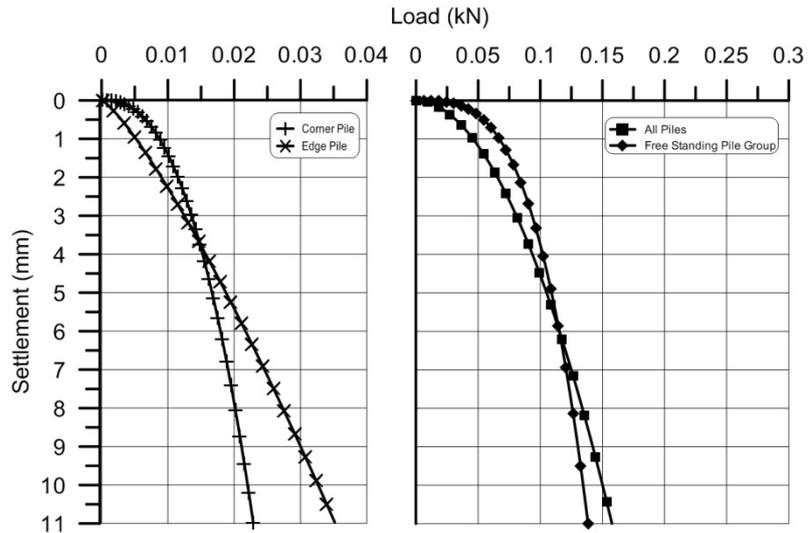


Fig. (23) Load-settlement curve for (2x3) free standing pile group.

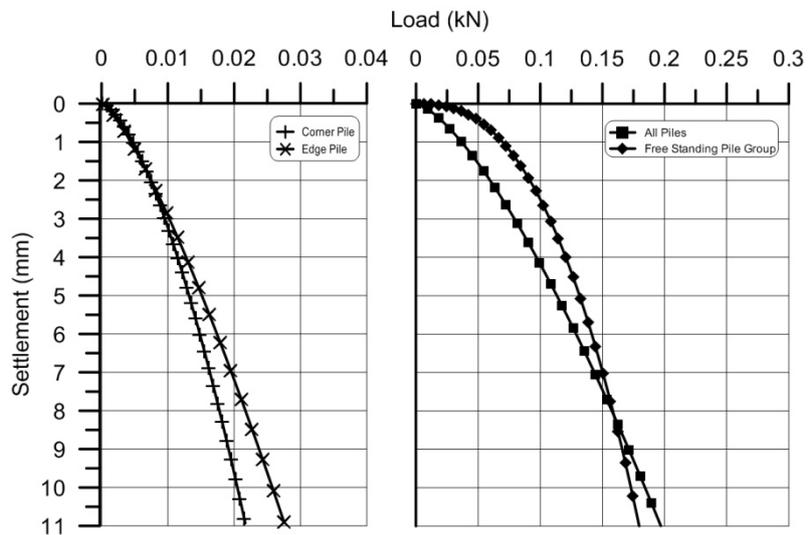


Fig. (24) Load-settlement curve for (2x4) free standing pile group.

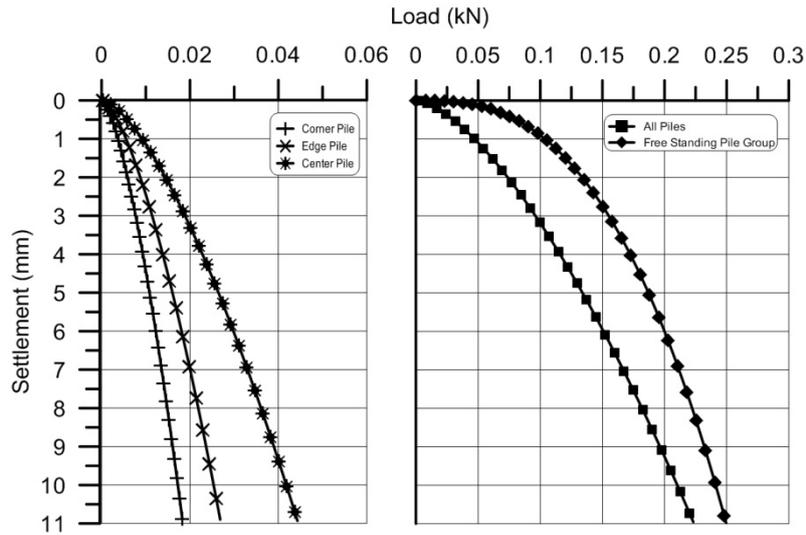


Fig. (25) Load-settlement curve for (3x3) free standing pile group.

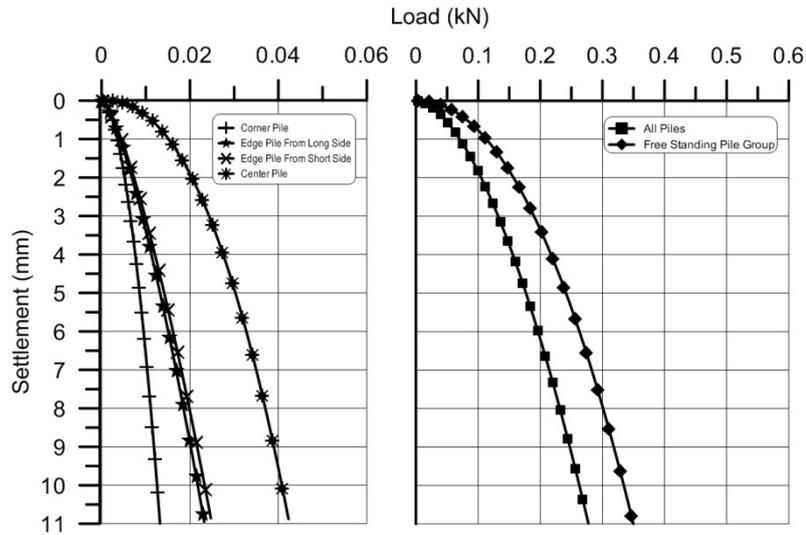


Fig. (26) Load-settlement curve for (3x4) free standing pile group.

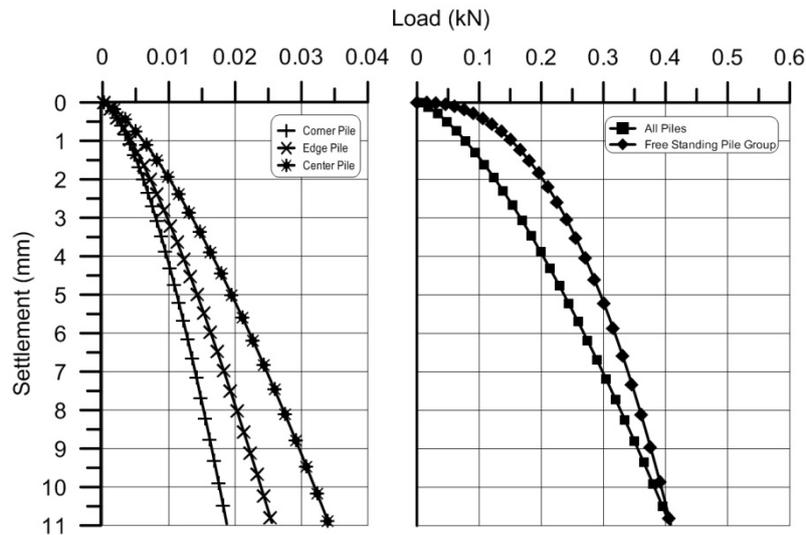


Fig. (27) Load-settlement curve for (4x4) free standing pile group.

Effect of sand density

In this section, (3x3) and (4x4) pile groups are selected to make a comparison between piles embedded in sand of different densities. **Figures (28) to (30)** show the load-settlement relationships for (3x3) group embedded in loose, medium and dense sand, respectively. It is evident that the piled raft capacity increases by about 70%, when the sand is changed from loose to dense, while the percent of load carried by raft (pile cap) is increased by about 26%. **Figures (31) to (33)** are drawn for (4x4) pile group embedded in loose, medium and dense sand, respectively. From **Figures (28), (29) and (30)**, It can be concluded that the center pile load equals 9 the corner pile load, the center pile load equals 2.8 the edge pile load. In **Figures (32) and (33)**, the center pile load equals 1.7 the corner pile load, while the center pile load equals 1.25 the edge pile load. **Figures (28) to (33)** show difference between curves representing (all piles+unpiled raft) and (piled raft) almost piled raft curve (external load) is greater, this means that the pile raft works efficiently. These results are compatible with the results of Hakam (2007) and Lutz (1993) who found that the efficiency of piled raft system is greater than the sum of piles and raft capacities. **Figures (28) to (33)** show that by increasing the sand density, the load carrying capacity is increased, and the effect of density is greater on the (4x4) piled raft than on (3x3) piled raft. This may be reasoned by the footing size (cap) which causes increase in bearing capacity.

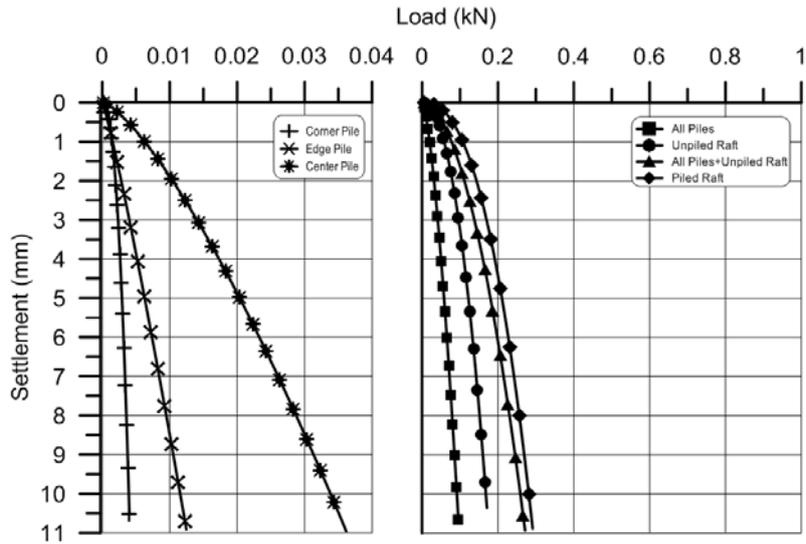


Fig. (28) Load-settlement curve for (3x3) piled raft in loose sand.

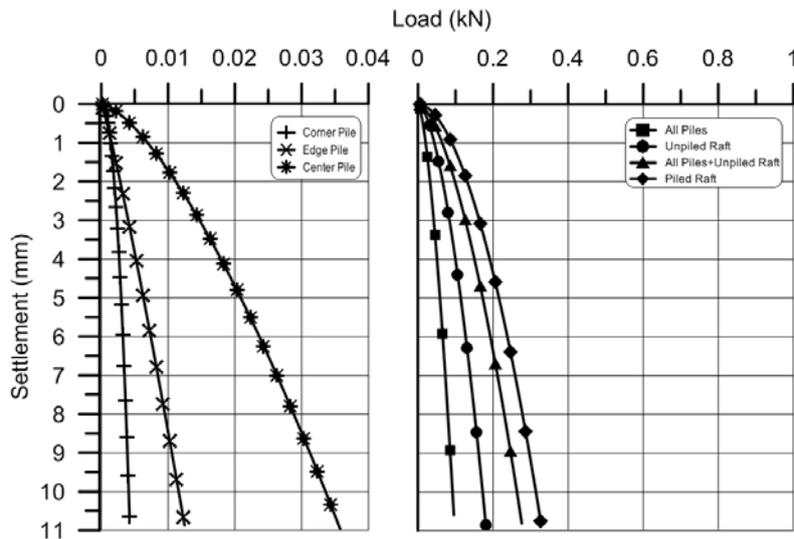


Fig. (29) Load-settlement curve for (3x3) piled raft in medium sand.

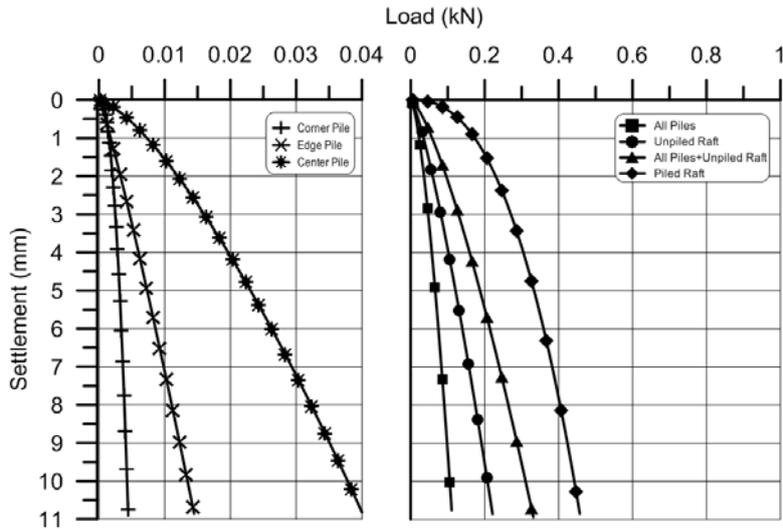


Fig. (30) Load-settlement curve for (3x3) piled raft in dense sand.

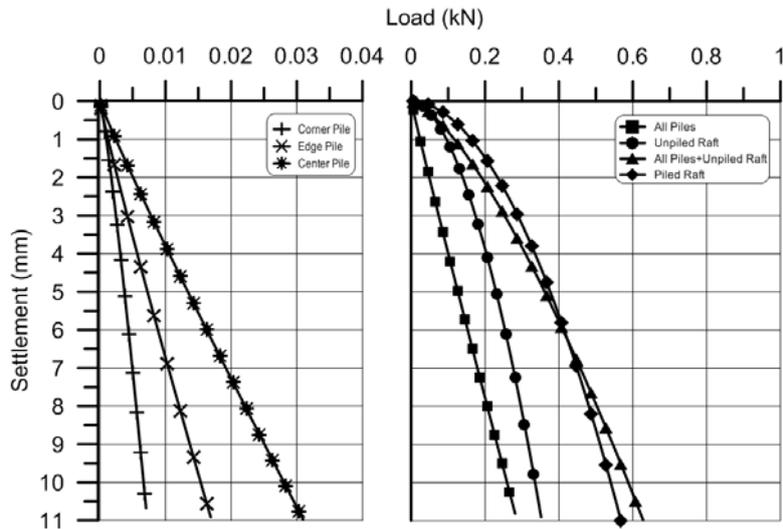


Fig. (31) Load-settlement curve for (4x4) piled raft in loose sand.

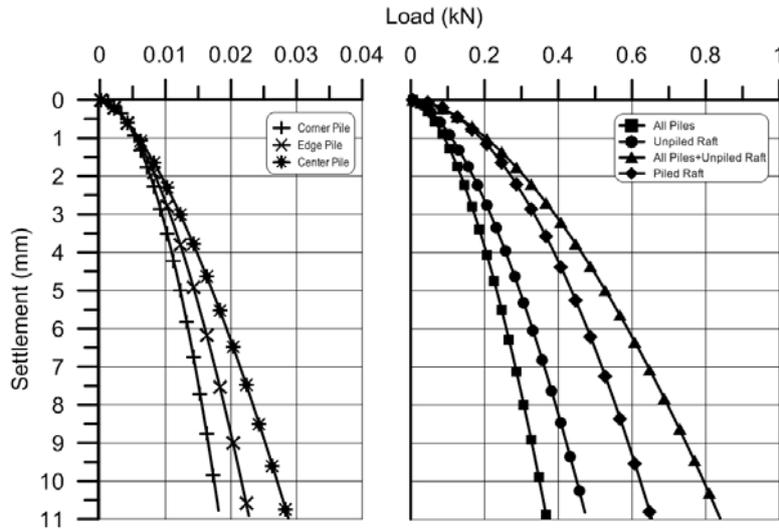


Fig. (32) Load-settlement curve for (4x4) piled raft in medium sand.

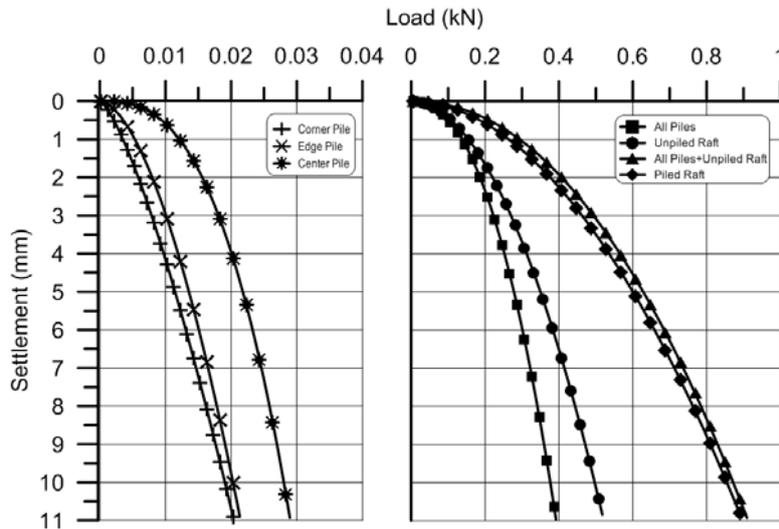


Fig. (33) Load-settlement curve for (4x4) piled raft in dense sand.

The comparison of load-settlement curves for piles embedded in sands of different densities is also presented in **Figures (34) and (35)** for (3x3) and (4x4) group, respectively. In **Figure (34)**, the ultimate load from loose to medium is increased by about 18% and from medium to dense by about 39%. In **Figure (35)**, the increasing of load from loose to medium by about 14% and from medium to dense is about 38%.

It is shown that for comparison between (3x3) and (4x4) group embedded in loose, medium and dense sand; an increase in the ultimate capacity by about 93%, 96% and 98% is obtained when the group is enlarged from (3x3) to (4x4). This is attributed to increase in footing size (cap) and the increase of the number of piles in the group.

Failure Load and Settlement

Based on the Decourt failure criterion, the failure load is calculated from the load-settlement curves for each case. Sharing loads for all foundation elements are listed in **Tables (7)** and **(8)** for free standing pile group and piled raft, respectively.

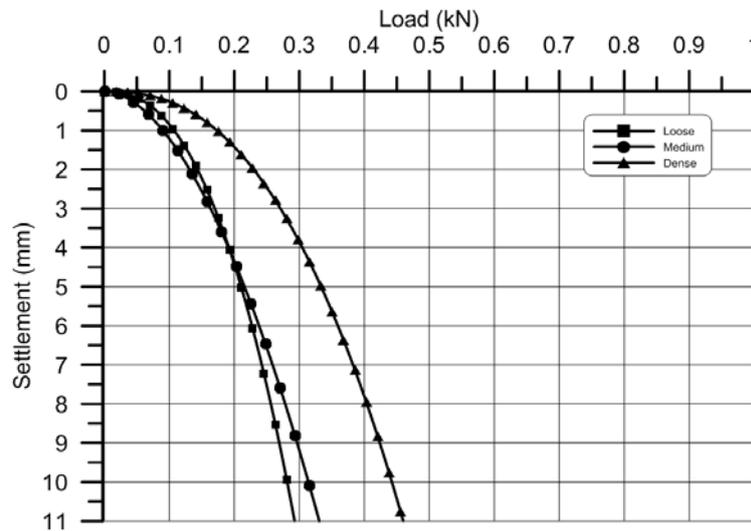


Fig. (34) Load-settlement curve for (3x3) piled raft embedded on sands of different densities.

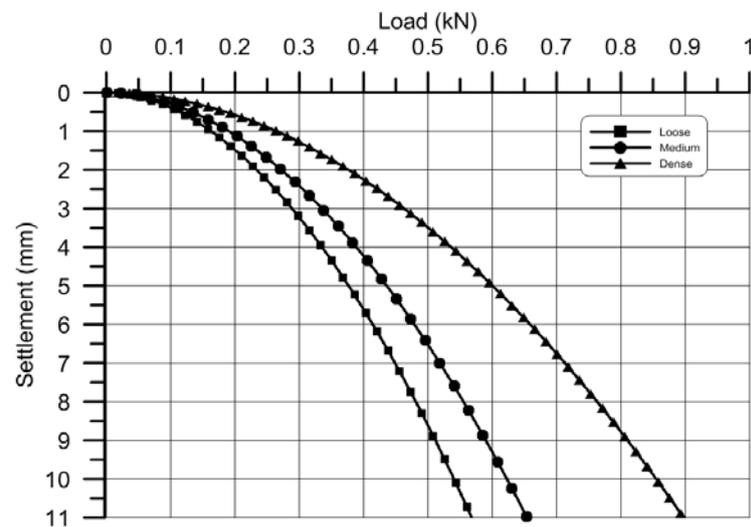


Fig. (35) Load-settlement curve for (4x4) embedded on sands of different densities.

Table (7) Failure load shared by piles in free standing pile group.

Configu ration	Corner Pile	Edge Pile	Center Pile	All Piles kN	Piles Group	Corner Pile	Edge Pile	Center Pile	All Piles %
1x2	-	0.03	-	0.05	0.08	-	37.50	-	62.50
1x3	-	0.032	0.05	0.1	0.13	-	24.62	38.46	76.92
1x4	-	0.02	0.04	0.12	0.15	-	13.33	26.67	80.00
2x2	0.035	-	-	0.14	0.16	21.88	-	-	87.50
2x3	0.038	-	0.043	0.17	0.19	20.00	-	22.63	89.47
2x4	0.045	-	0.06	0.32	0.34	13.24	-	17.65	94.12
3x3	0.035	0.045	0.09	0.38	0.4	8.75	11.25	22.50	95.00
3x4	0.025	0.05	0.07	0.48	0.5	5.00	10.10	14.00	96.00
4x4	0.034	0.04	0.06	0.56	0.58	5.86	6.90	10.34	96.55

Table (8) Failure load shared in piled rafts.

(a)

Configu ration	Corner Pile	Edge Pile	Center Pile	All Piles kN	Unpiled Raft kN	All Piles + Unpiled Raft kN	Piled Raft kN
1x2	-	0.015	-	0.03	0.061	0.095	0.11
1x3	-	0.008	0.021	0.041	0.07	0.11	0.15
1x4	-	0.016	0.032	0.08	0.12	0.2	0.21
2x2	0.022	-	-	0.1	0.12	0.21	0.22
2x3	0.015	-	0.023	0.115	0.16	0.29	0.36
2x4	0.018	-	0.02	0.15	0.24	0.4	0.56
3x3	0.02	0.03	0.06	0.28	0.26	0.67	0.81
3x4	0.01	0.04	0.053	0.51	0.47	0.86	1.15
4x4	0.02	0.04	0.06	0.88	0.78	1.88	2.56

(b)

Configuration	Corner Pile %	Edge Pile %	Center Pile %	All Piles %	Unpiled Raft %
1x2	-	13.64	-	27.27	55.45
1x3	-	5.33	14.00	27.33	46.67
1x4	-	7.62	15.24	38.10	57.14
2x2	10.00	-	-	45.45	54.55
2x3	4.17	-	6.39	31.94	44.44
2x4	3.21	-	3.57	26.79	42.86
3x3	2.47	3.70	7.41	34.57	32.10
3x4	0.87	3.48	4.61	44.35	40.87
4x4	0.78	1.56	2.34	34.38	30.47

Conclusions

1. For free standing piles in a group, the load taken by the edge pile is approximately equal to (0.4-0.6) the load carried by the corner or center pile. This percent increases for groups of greater number of piles. The load carried by the edge pile from short side is little greater than the load carried by edge pile from long side.
2. When the raft (pile cap) becomes larger, the failure load increases and the settlement decreases. This effect was found greater on the piled raft foundation than the raft or free standing pile group.
3. When the number of piles within the group is small (less than 4), there is no evident contribution of the raft to the load carrying capacity. The failure load for a piled raft consisting of (9) piles is greater by about one time than free standing pile group containing the same number of piles. This difference increases to about 4 times for (16) pile group.
4. The piles work as settlement reducers effectively when the number of piles is greater than (6) than when the number of piles is less than (6). The settlement can be increased by about 8 times in (1x2) free standing pile group compared to the piled raft of the same configuration. The effect of piled raft on reducing the settlement vanishes when the

number of piles exceeds (6). This means that as the number of piles increases further, the decrease in settlement becomes smaller and it is not economical to make use of piles as settlement reducers.

5. For piled rafts (3x3) and (4x4) embedded in loose, medium and dense sand; an increase in the ultimate capacity by about 93%, 96% and 98% is obtained when the group is enlarged from (3x3) to (4x4). This is attributed to increase in footing size (cap) and the increase of the number of piles in the group.

References

1. ASTM D3080-1998, "**Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions**", American Society of Testing and Materials.
2. ASTM D422-2001, "**Standard Test Method for Particle Size-Analysis of Soils**", American Society for Testing and Material.
3. ASTM D4253-2000, "**Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table**", American Society for Testing and Materials.
4. ASTM D4254-2000, "**Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density**", American Society for Testing and Materials.
5. ASTM D854-2005, "**Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer**", American Society for Testing and Materials.
6. Bieganousky, W. N. and Marcuson, W. F. (1976),"**Uniform Placement of Sand**", Journal of Geotechnical Engineering Div., ASCE, Vol. 102, No. GT.3, pp.229-233.
7. Fellenius, B.H., (2009), "**Basics of Foundation Design**", Book Electronic Edition www.Fellenius.net , 346p.
8. Hakam, A., (2007), "**Estimation of Bearing Capacity of Floating Raft-Pile**", TEKNIKA, No. 28 Vol.1 Thn. XIV November 2007, School of Civil Engineering - UNAND.
9. Hansen, B., (1970), "**A Revised and Extended Formula for Bearing Capacity**", Bulletin of the Danish Geotechnical Institute, Copenhagen, No. 28.
10. Hartman, F. and Jahn, P. (2001), "**Boundary Element Analysis of Raft Foundations on Piles**", Meccanica Vol. 3, pp. 351–366, Kluwer Academic Publishers. Netherlands.

11. Lutz B., (1993), "Piled-Raft-Foundations for High-Rise Buildings on Frankfurt Clay", **7th Young Geotechnical Engineers** Conference, Organised by the German Geotechnical Society.
12. Poulos, H.G., (2001), "**Methods of Analysis of Piled Raft Foundations**", a Report prepared on Behalf of Technical Committee TC18 on Piled Foundations, International Society of Soil Mechanics and Geotechnical Engineering.
13. Turner, J. P. and Kulhawy, F. H. (1987), "**Experimental Analysis of Drilled Foundations Subjected to Repeated Axial Loads Under Drained Conditions**", Report EL-5325, Electric Power Research Institute, Palo Alto, California.
14. Winterkorn, H.F., and Hsai-Yang Fang., (1975), "**Foundation Engineering Hand Book**", Van Nostrand Reinhold Company, New York.
15. Yilmaz, B., (2010), "**An Analytical and Experimental Study on Piled Raft Foundations**", MSc. Thesis, Middle East Technical University, Ankara.