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Effect of pile group geometry on bearing capacity of piled raft foundations

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Abstract. This is an experimental study to investigate the behaviour 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 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 calculate the load carried by each pile in the group. Nine configurations of group (1×2, 1×3, 1×4, 2×2, 2×3, 2×4, 3×3, 3×4 and 4×4) were tested in the laboratory as a free standing pile group (the raft not in contact with the soil) and as a piled raft (the raft in contact with the soil), in addition to tests for raft (unpiled) with different sizes.

It is found that 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 approximately 100% greater than free standing pile group containing the same number of piles. This difference increases to about 4 times for 16 pile group. 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 (1×2) 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.

Keywords: piled raft; bearing capacity; group; geometry

1. Introduction

Raft and pile groups are the two alternative foundation options to support structures with heavy column loads. Raft is normally designed as rigid in order to withstand high moment and differential settlement, which is a function of intensity of load and relative stiffness of raft and soil. In the case of pile groups, more piles are provided than required to cater the column load and to practically eliminate the settlement, which makes the foundation expensive. The concept of pile raft was conceived and introduced about three decades back to overcome the difficulties stated above as well as for the effective utilization of the pile group. The piled raft is a geotechnical

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composite construction consisting of the three elements, piles, rafts and soil. The design of piled rafts differs from that in traditional foundation design, where the loads are assumed to be carried either by the raft or by the piles, considering the safety factors in each case. Key questions that arise in the design of piled rafts concern the relative proportion of load carried by raft and piles, and the effect of additional pile support on absolute and differential settlements (Randolph 1994).

2. 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 adoption of piled raft foundations concept in the design of pile groups is by no means new, and has been described by several authors, including Zeevaert (1957), Davis and Poulos (1972), Hooper (1973), Burland *et al*. (1977), Katzenbach and Reul (1997), Prakoso and Kulhawy (2001), and Reul and Randolph (2003), among many others. In the early years, because of the limited availability of computers memory and processing speed, the use of numerical methods was confined to simple problems. Due to the rapid development in computer technologies, numerical methods such as full three- dimensional methods are now used to solve complex problems.

Generally, predictions are made of settlements and pile loads at the end of construction. However, there are many case studies reported in the literature where the piled raft foundation has continued to settle for several years after the supported structure has reached its full height and weight. These time-dependent settlements of piled raft foundations can be due to two factors; (i) primary consolidation of the foundation due to dissipation of pore pressures (ii) creep of the soil (Mandolini *et al*. 2005, Small and Liu 2008).

The conventional pile design philosophy is based on piles that 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.

Based on a numerical study by means of three-dimensional finite-element analysis, Reul (2004) discussed investigations of the bearing behaviour of piled rafts in overconsolidated clay. It was shown that the interaction between piles and rafts is a major influence. The potential savings of an optimized foundation design were demonstrated for a simple example. As a result of pile– raft interaction, the skin friction was shown to increase with an increase in load or increase in settlement. It was also shown that under practically relevant loads, the piles of a piled raft do not reach their ultimate bearing capacity.

An analytical method has been proposed by Shelke and Patra (2008) to predict the net ultimate uplift capacity of pile groups embedded in sand considering the arching effect. This method takes into consideration the embedded length (L), diameter of the pile (d), surface characteristics of pile, group configuration, spacing of the pile group (3d to 6d), and the soil properties. Arching develops due to relative compressibility of sand relative to pile which activates the soil-pile friction. As piles/pile groups move up, the active state of soil is initiated. The modified value of active earth pressure coefficient considering arching effect has been derived. Typical charts for evaluation of net ultimate uplift capacity for pile groups were presented through the figures. The predicted values of ultimate uplift capacity of pile groups with different configuration and slenderness ratios were compared with the available experimental results. The predicted values considering arching effect were found to be in good agreement with the data available from the literature.

The main criteria adopted for the design and some aspects of the observed behaviour of the piled foundations of a cluster of circular steel tanks were reported by de Sanctis and Russo (2008). They were designed to store sodium hydroxide, a toxic liquid with a unit weight of 15.1 kN/m^3. Shallow foundations would have been safe against a bearing capacity failure, while the predicted settlement was beyond the allowed limit. Accordingly, piles were designed to reduce the settlement and improve the overall performance of the foundations. While conventional capacity based design approach led to a total of 160 piles to support the five tanks, the settlement based design approach led to a total of 65 piles achieving significant savings on the cost of the project. The settlements of four out of the five tanks were measured and for two out of the five tanks, the load sharing among the raft and the piles was also observed. Both the analyses carried out at the design stage and the back-analyses of the observed behaviour were based on the interaction factors method as implemented in the computer code NAPRA (Russo 1998)

Xia *et al*. (2009) described the design of a partially piled raft foundation (PPRF) adopted under complex geotechnical conditions, in the City of Toronto, Canada. The design of PPRF was governed by lateral soil pressure, unevenly distributed building loads, and non-uniform bearing capacity of foundation soils. Piles were distributed in the area with excessive settlement. Most of the supporting piles were located in the northwest portion of the raft foundation, where high bearing pressure and low soil bearing capacity were encountered. A unit criterion of the proposed settlement has been applied in the design of the raft slab and the piles in order to keep the integrity of the PPRF. Global stability, including sliding and over turning of the PPRF were an integral part of the design. A state of the art computer analysis was utilized.

The interaction and load sharing mechanism, as well as its time effect should be studied primarily in order to design the piled raft structure rationally. Specific to the piled raft foundation of high speed railway, Su *et al*. (2011) adopted field tests and simplified calculations and integrated the two methods to analyzing the load sharing mechanism and its time changing law. The results showed that the construction process is the load sharing adjustment process; the main vertical load was undertaken mainly by piles and rafts, and was transferred to the substratum by piles, the soil between piles only bears a small amount of load (about 3.7%) and was suggested to considering as a safety margin in the design; the raft shares about 14~20% of the upper load, which should be considered in the structure design.

Zhang *et al*. (2014) studied the vertical bearing properties of sea-crossing bridge main pier pile

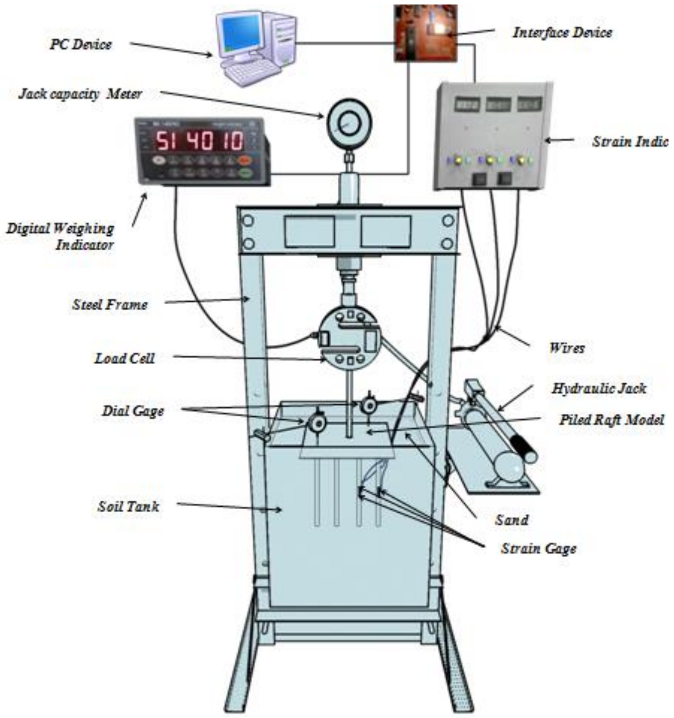

Fig. 1 Setup of the laboratory apparatus.

Fig. 2 Three-dimensional view of the setup

foundations through pilot load tests. Large tonnage load test of Qingdao Bay Bridge main pier pile program was designed by using per-stressed technique to optimize the design of anchor pile reaction beam system. Test results showed that the design is feasible and effective. This method can directly test bearing capacity of main pier pile foundations, and analysis bearing behaviors from test results of sensors which embedded in the pile. Through test study the vertical bearing properties of main pier pile foundation and compared with the generally short pile, author summarized the main pier pile foundations vertical bearing capacity and the main problem of design and construction which need to pay attention, and provide a reliable basis and experience for sea-crossing bridge main pier pile foundations design and construction.

3. Apparatus, materials, and testing techniques

Laboratory-scale investigations into piles behaviour remain popular because of the high cost of field testing and the possibility of achieving specific soil characteristics in a laboratory environment. The monitored behaviour of prototype structures has led to a better understanding of pile foundation and enables more reliable and economical design to be employed.

Model tests are relatively inexpensive and can be conducted under controlled laboratory conditions. This provides an efficient means of investigation. For instance, Cox *et al*. (1984) reported a study in which tests on 58 single piles and 41 pile groups were performed. Tests at laboratory scale are affected however by not realistic stiffness due to the low stress environment and also the friction between the pile and the soil may be altered by the scale ratio between the size of the particles and the size of the pile section. The geometric arrangement of piles within groups varied, in addition to the number of piles per group, and the spacing between piles.

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 behaviour 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.

4. Testing preparation

4.1 Test setup

All model tests were conducted using the setup shown in Fig. 1, which consists of frame, soil tank, model piled raft and loading machine. The vertical load is applied to the model piles by means of 10 ton hydraulic compression handle jack. During all the laboratory model tests, the loading rate is kept approximately constant at 1 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. Fig. 2 shows the setup in three-dimensional view.

4.2 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.

4.3 Soil properties

The soil used for the model tests is clean, oven-dried, uniform quartz sand from Kerbela city in Iraq. 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)**. Fig. 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.

The unit weight of the sand deposit in the raining method depends primarily on the drop height

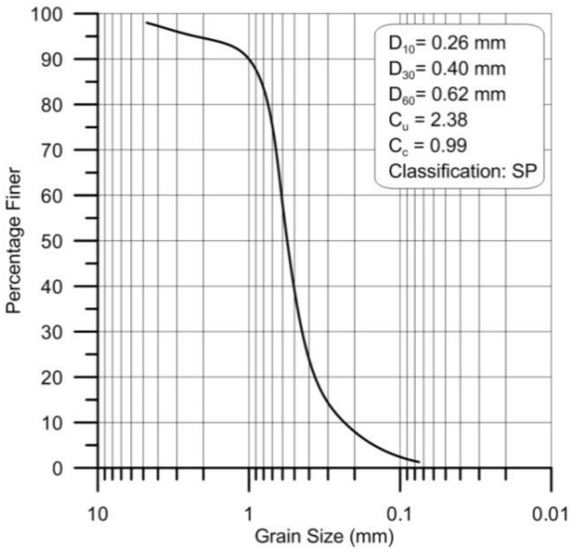

Fig. 3 Grain size distribution of the sand

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

Table 2 Properties of sand used in the tests at different densities.

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

Table 3 Mechanical properties of the used Aluminum alloy.

Property	**Value**
Minimum yield strength (MPa)	160
Minimum ultimate yield strength (MPa)	215
Minimum % of elongation	10
Poisson's ratio	0.34

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/m^3, void ratio of (0.68, 0.55, 0.51) and a relative density of (15, 60, 77) %, respectively.

5. 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, according to the technical specification and the mechanical properties of the used alloy shown in Table 3.

6. 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 can be used to obtain extremely accurate, high resolution strain measurements in a variety of circumstances. Accuracy of ±10 $\mu\varepsilon$ (micro strain) can be obtained, with a sampling range max. ±19990 $\mu\varepsilon$. 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.

If the elastic modulus of the object material is known, strain measurement enables calculation of stress. Thus, strain measurement is often performed to determine the stress initiated in the substance by an external force, rather than to know the strain quantity**.** A strain gauge produced by "Tokyo Sokki Kenkyujo", was attached to the pile shaft and connected to a strain indicator to read the strain in the pile. Since the modulus of elasticity and the cross sectional area of the piles are known, then the amount of load carried by pile can be obtained. The load sharing mechanism between piles and raft can be well studied.

Fig. 4 Photos showing the test procedure

7. 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). A digital weighing indicator is used for displaying the load amount “SEWHA, Korea” model SI 4010 with an input sensitivity of 0.2 μN/Digit, load cell excitation DC 10V ±5V, maximum and signal input voltage 32 mV.

8. Testing procedure

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

8.1 Building the piled raft model

Aluminum pipe piles with constant diameters and lengths, forming nine configurations of piles (1×2, 1×3, 1×4, 2×2, 2×3, 2×4, 3×3, 3×4 and 4×4), were prepared to fulfill the testing program of the experimental study. The piles were fixed to approximately rigid rafts using super glue. The glue simulates a semi-fixed connection of piles to the raft.

8.2 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.

8.3 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. 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. 5 Testing system assembly

8.4 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 is 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 Fig. 4. The loading and measuring system assembly is shown in Fig. 5.

9. 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 (1×2), (1×3), (1×4), (2×2), (2×3), (2×4), (3×3), (3×4) and (4×4) piles. A schematic diagram for the configuration models is shown in Fig. 6.

10. 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 find out the strain initiated in each pile. Strain can be measured in three piles in the group.

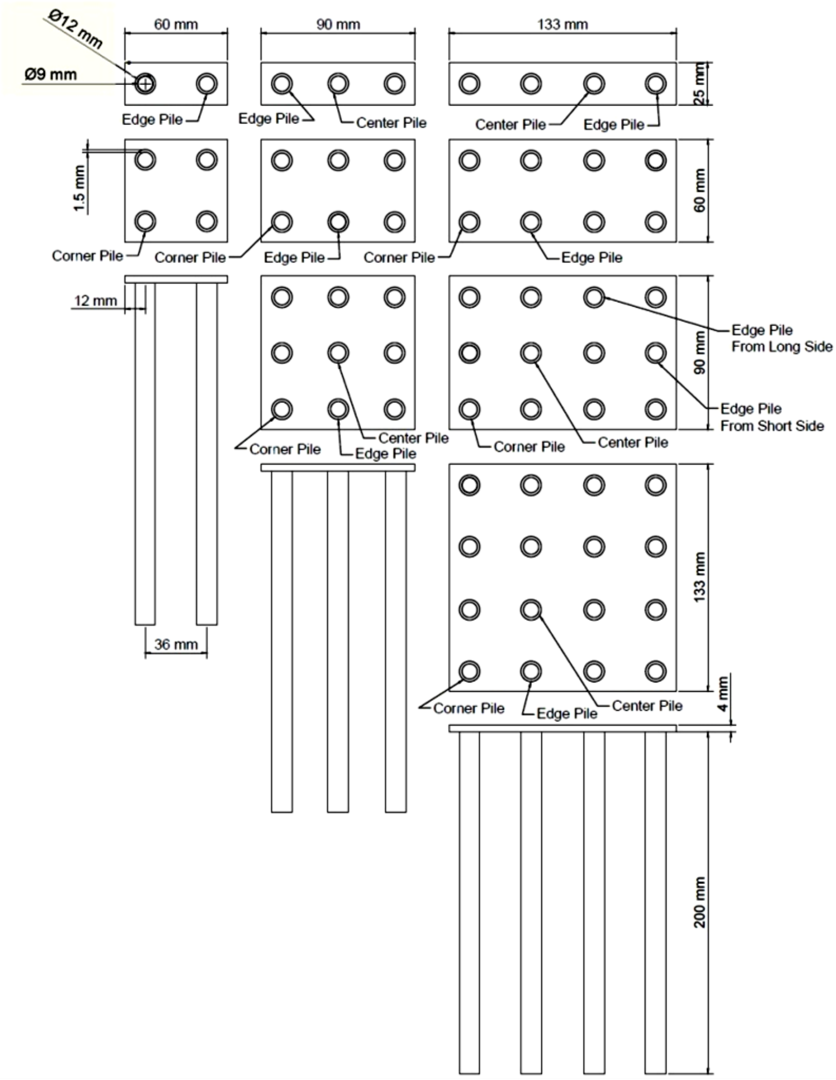

Fig. 6 Schematic diagrams for configuration models

Flexible rafts have been used 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.

11. Hansen's bearing capacity equation

Bearing capacity depends on many factors, Hansen and several other researchers have provided a comprehensive equation for the determination of bearing capacity called "Generalized Bearing Capacity" equation considering all factors. The Hansen's (1970) equation for ultimate bearing capacity for strip foundations is as follows from the comprehensive theory

$$q_f = cN_c s_c d_c i_c + qN_q s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma \quad (1)$$

Here, the bearing capacity factors are given by the following expressions which depend on ϕ.

$$N_c = (N_q - 1)\cot\phi$$

$$N_q = (e^{\pi\tan\phi})\tan^2(45 + \frac{\phi}{2})$$

$$N_\gamma = 1.5(N_q - 1)\tan\phi$$

Equations are available for shape factors (s_c, s_q, s_γ), depth factors (d_c, d_q, d_γ) and load inclination factors (i_c, i_q, i_γ). The effect of these factors is to reduce the bearing capacity.

The bearing capacity of model rafts on sandy soil is calculated using Eq. (1), where

$$c = 0, \quad q = 0, \quad i_\gamma = 1, \quad d_\gamma = 1, \quad S\gamma = 1 - 0.3\ B/L \quad \text{so:}$$

$$q_f = 0.5\gamma B N_\gamma s_\gamma \quad (2)$$

Table 4 shows the results of bearing capacity calculated by Hansen's equation for unpiled rafts only.

Table 4 Calculation of bearing capacity by Hansen's equation

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

Table 5 Raft dimensions.

Raft Size (m)	Area (m^2)	Ratio of perimeter of raft to perimeter of pile group.	Used for Pile Group of
0.025×0.06	0.0015	2.25	1x2
0.025×0.09	0.0023	2.03	1x3
0.025×0.133	0.0033	2.09	1x4
0.06×0.06	0.0036	1.59	2x2
0.06×0.09	0.0054	1.33	2x3
0.06×0.133	0.008	1.28	2x4
0.09×0.09	0.0081	1.06	3x3
0.09×0.133	0.012	1.09	3x4
0.133×0.133	0.0177	1.11	4x4

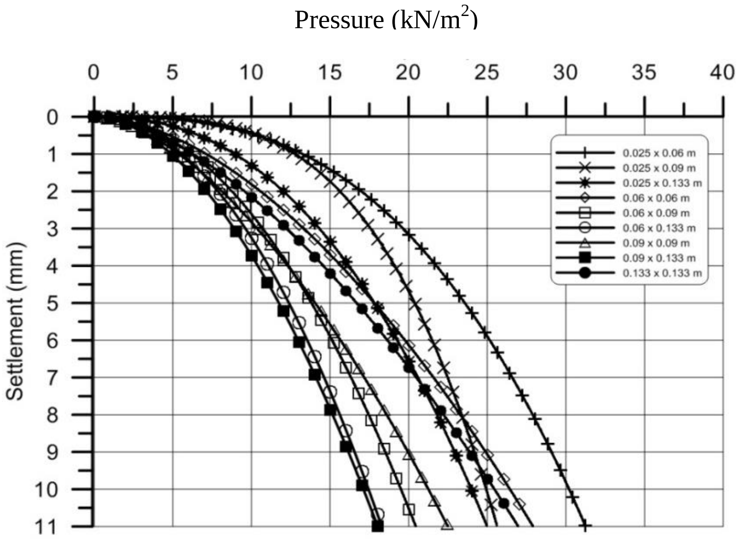

Fig. 7 Pressure-settlement curves for rafts of different sizes

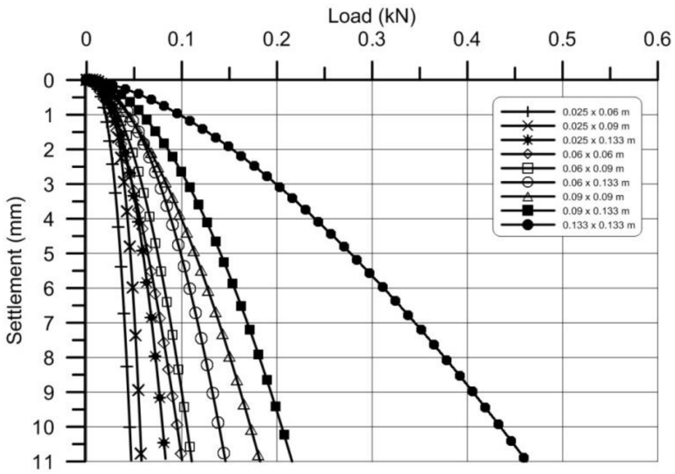

Fig. 8 Load-Settlement curves for rafts of different sizes

12. Load carrying capacity of rafts

In this section, the load-settlement relations of the rafts for each raft size are presented. The aluminum plates used for rafts have the dimensions shown in Table 5. All rafts have a thickness of 4 mm.

13. Effect of raft size

In this section, the effect of raft size on the bearing capacity is investigated and presented in Figs. 7 and 8.

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)	Failure Load by Hansen Equation (kN)
0.025×0.06	0.038	0.028	0.032	0.052	0.028	0.055	0.05
0.025×0.09	0.047	0.038	0.042	0.060	0.037	0.070	0.07
0.025×0.133	0.062	0.045	0.051	0.093	0.042	0.100	0.09
0.06×0.06	0.077	0.075	0.055	0.132	0.055	0.135	0.32
0.06×0.09	0.080	0.080	0.060	0.144	0.064	0.260	0.43
0.06×0.133	0.110	0.105	0.065	0.190	0.066	0.270	0.60
0.09×0.09	0.140	0.160	0.085	0.256	0.095	0.360	1.08
0.09×0.133	0.170	0.190	0.100	0.417	0.105	0.500	1.44
0.133×0.133	0.380	0.420	0.260	0.625	0.247	0.680	3.47

By inspection of Fig. 8, it can be noted that the load carrying capacity of rafts increases with increasing raft size, and it is obvious that when the raft becomes larger, it can carry greater load than the smaller one; for example the raft of (0.133×0.133) m size can carry double the load that is carried by the raft (0.09×0.133) m size.

14. Selection of failure criterion

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

• **Terzaghi** in 1947 proposal; where failure is defined as the load corresponding to dispalcment 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-settelment 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 (Chin 1970).

• **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 (as cited by Fellenius 2009); 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

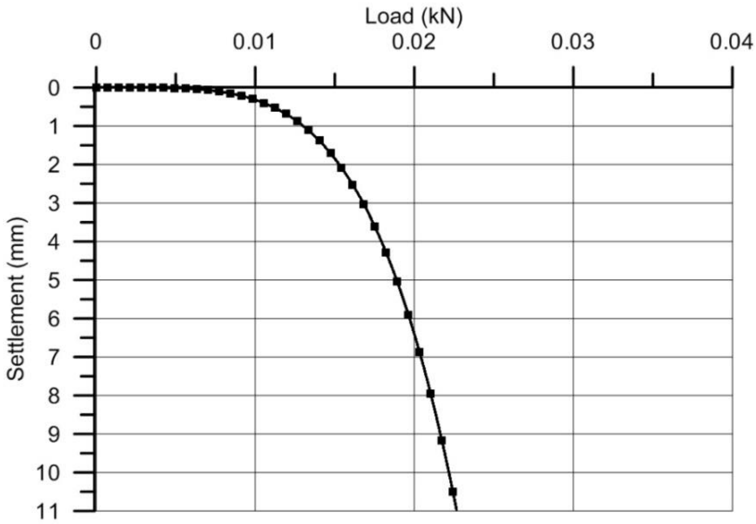

Fig. 9 Load-settlement curve for single pile

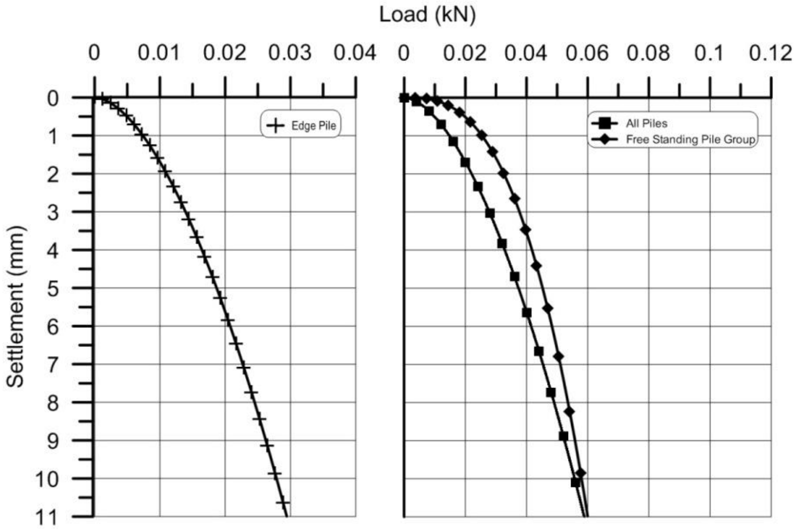

Fig. 10 Load-settlement curves for (1×2) free standing pile group

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.

15. Load carrying capacity of single pile

In order to make a comparison between single pile and pile group, loading test was carried out on a single pile. The load-settlement curve is presented in Fig. 9.

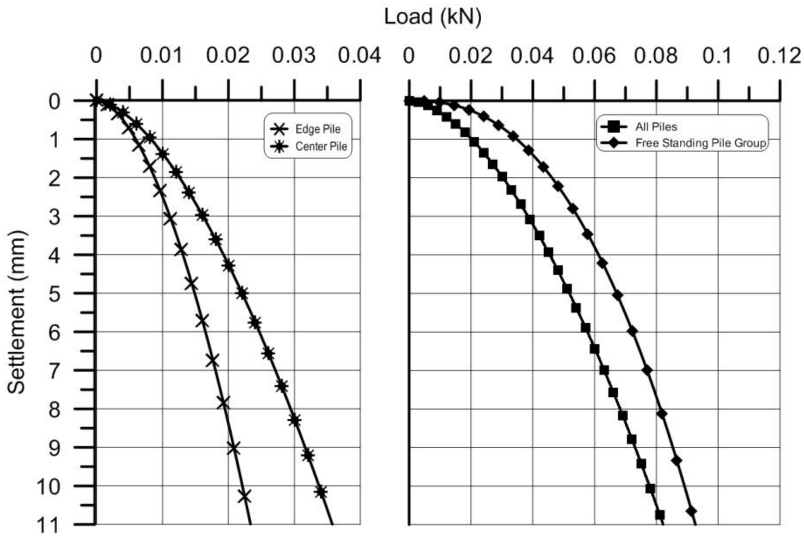

Fig. 11 Load-settlement curve for (1×3) free standing pile group

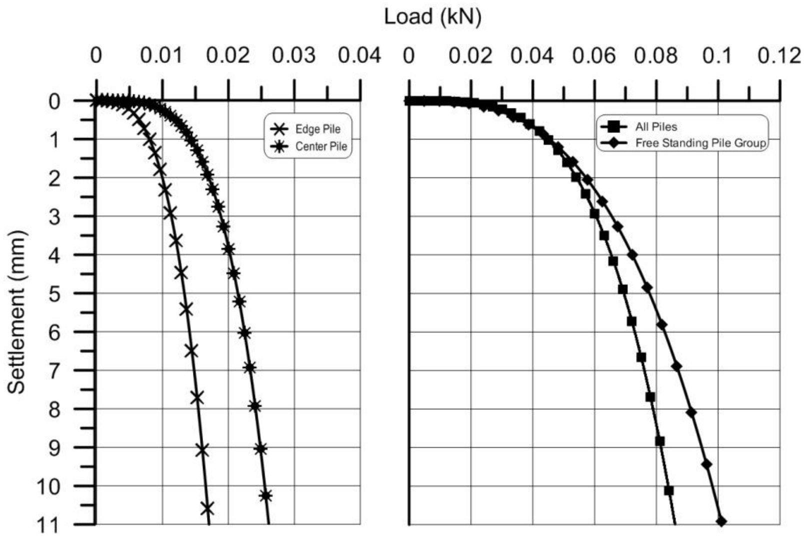

Fig. 12 Load-settlement curve for (1×4) free standing pile group

16. 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, Figs. 10 to 15 are drawn for (1×2), (1×3), (1×4), (2×2), (2×3) and (2×4) group, respectively. It is seen that the load-settlement relationships are almost non-linear.

From Figs. 10 to 15 one can see 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).

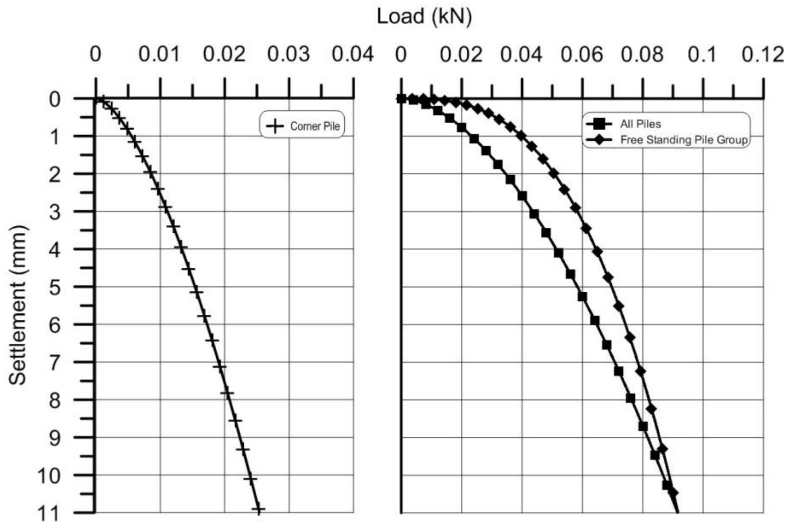

Fig. 13 Load-settlement curves for (2×2) free standing pile group

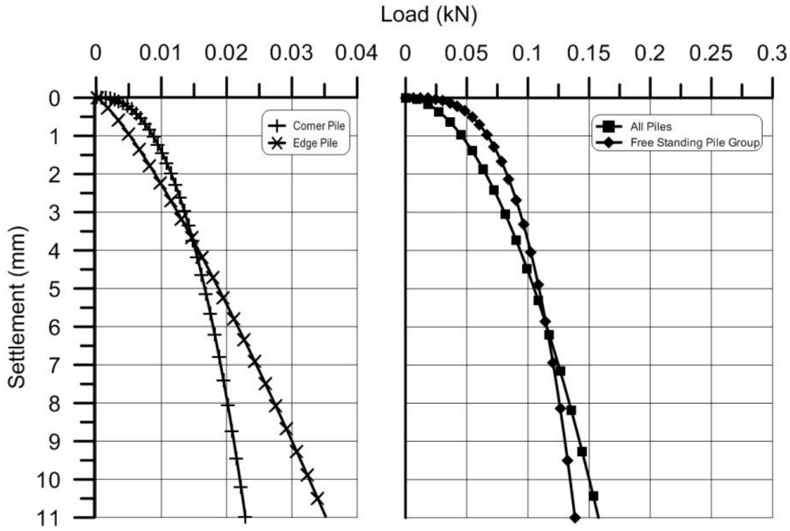

Fig. 14 Load-settlement curves for (2×3) free standing pile group

Figs. 16 to 18 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 (3×3), (3×4) and (4×4) 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 Fig. 17 which deals with (3×4) 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. This may be attributed to soil confinement around the pile which depends on pile location.

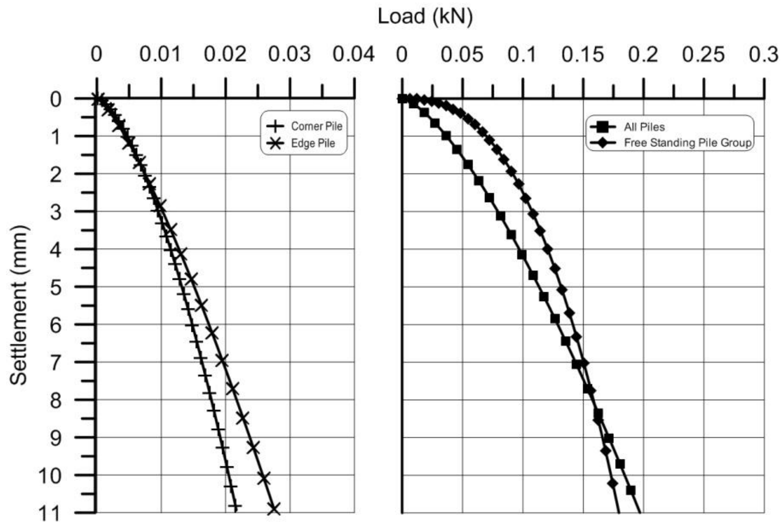

Fig. 15 Load-settlement curves for (2×4) free standing pile group

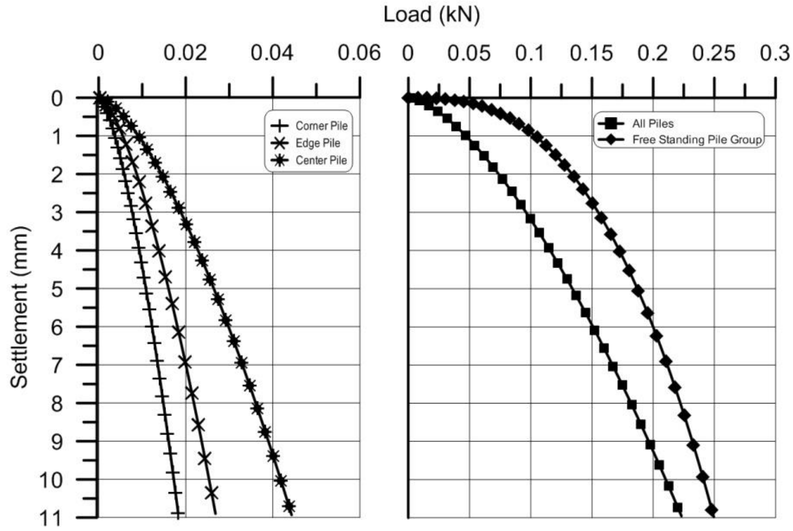

Fig. 16 Load-settlement curves for (3×3) free standing pile group

17. Load carrying capacity of piled raft

In this study, the piles are arranged in different configurations. It is expected that the arrangement of the same number of piles within a group has an effect on its behaviour. Figs. 19 to 24 show the load-settlement relations for (1×2), (1×3), (1×4), (2×2), (2×3) and (2×4) groups, respectively. The load-settlement performance and the ultimate bearing capacity of a piled raft are totally different from those of a single pile, these features depend on the configuration of the piles forming the group and the position of the pile within the group.

For Figs. 20 and 21, the center pile load equals 2.5 that of edge pile load, while in Figs. 26 and 27, the edge pile load equals 1.5 that of corner pile. For Figs. 19 to 21, adding the values

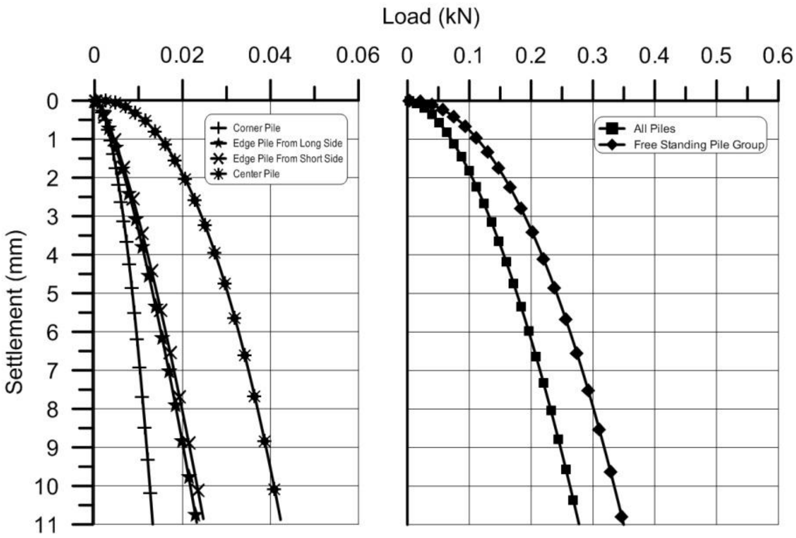

Fig. 17 Load-settlement curves for (3×4) free standing pile group

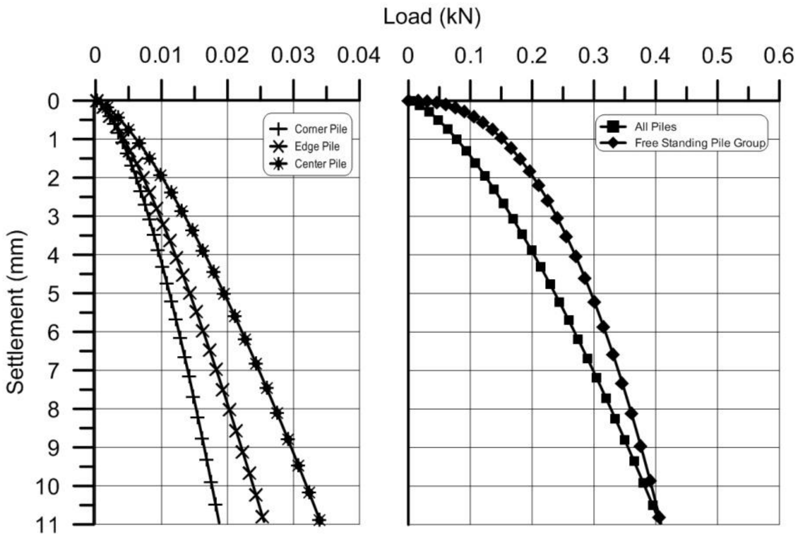

Fig. 18 Load-settlement curves for (4×4) free standing pile group

corresponding to curve representing the pile load with those of the curve representing (all piles+unpiled raft), results in approximately the curve representing (piled raft). In Figs. 22 to 24, there is a slight difference between the summation of the curves (all piles+unpiled raft) and (piled raft) which may be attributed to measurement accuracy. Figs. 25 to 27 display the load-settlement relationships for group of (3×3), (3×4) and (4×4) piles, respectively. In Fig. 25, it is noticed that the center pile load equals 8 times the corner pile load, and the center pile load equals 2.8 times the edge pile load. Fig. 26 shows that the edge pile from short side carries a little load greater than the edge pile from long side. In Fig. 27, the center pile load equals 1.7 times the corner pile load, while the center pile load equals 1.25 times the edge pile load.

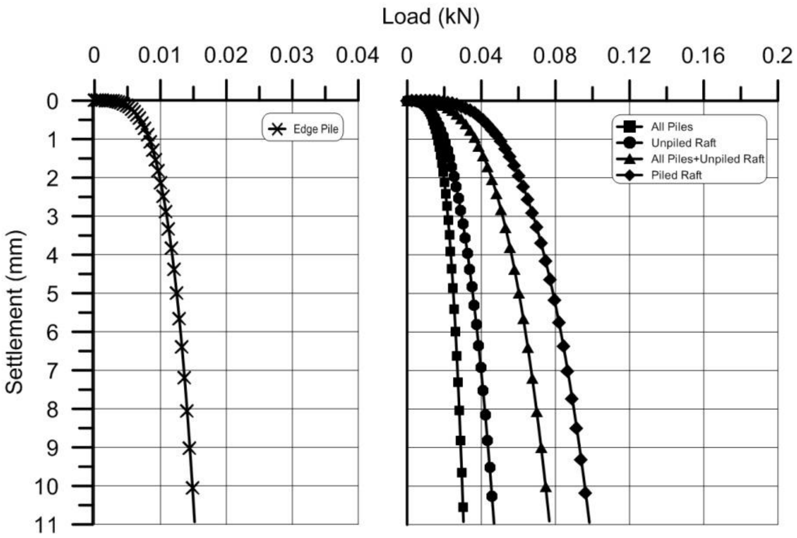

Fig. 19 Load-settlement curves for (1×2) piled raft

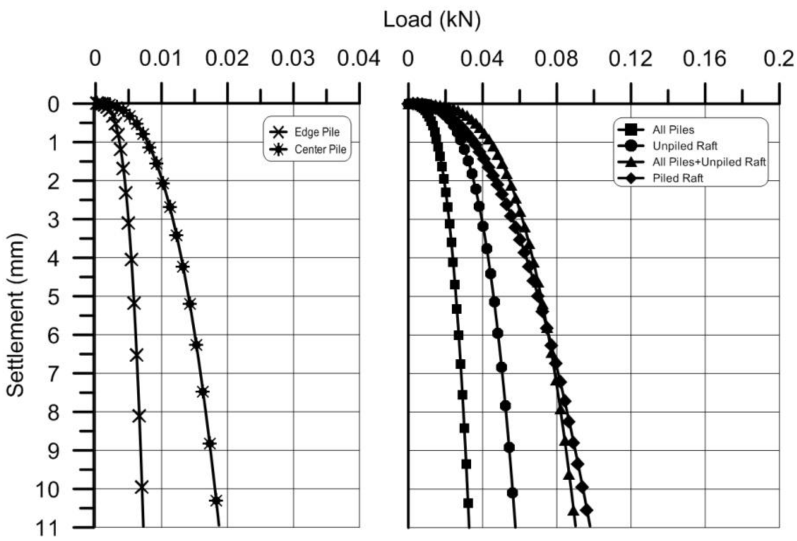

Fig. 20 Load-settlement curves for (1×3) piled raft

18. 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, 8 and 9 for free standing pile group and piled raft.

It can be concluded that the load sharing mechanism shows that the percentage load carried by piles depends on raft geometry and distribution of piles within the group. As the number of piles in the group increases, the percentage load carried by piles increases due to soil confinement surrounding the piles.

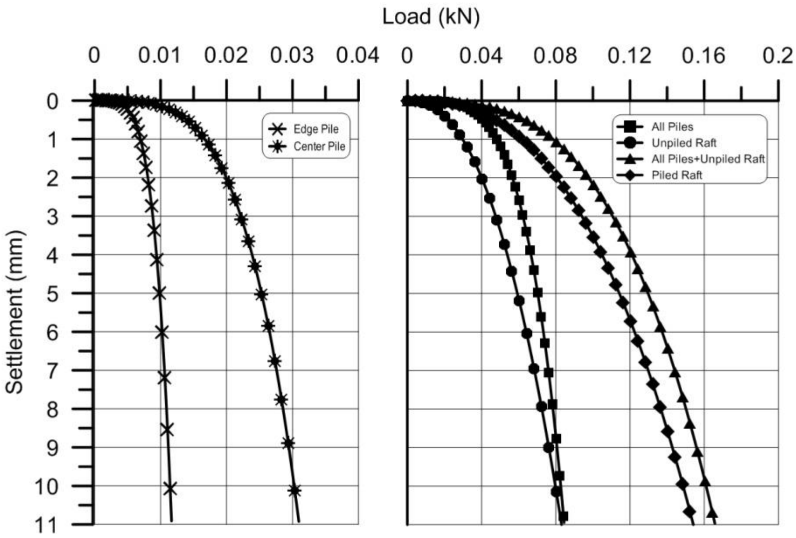

Fig. 21 Load-settlement curves for (1×4) piled raft

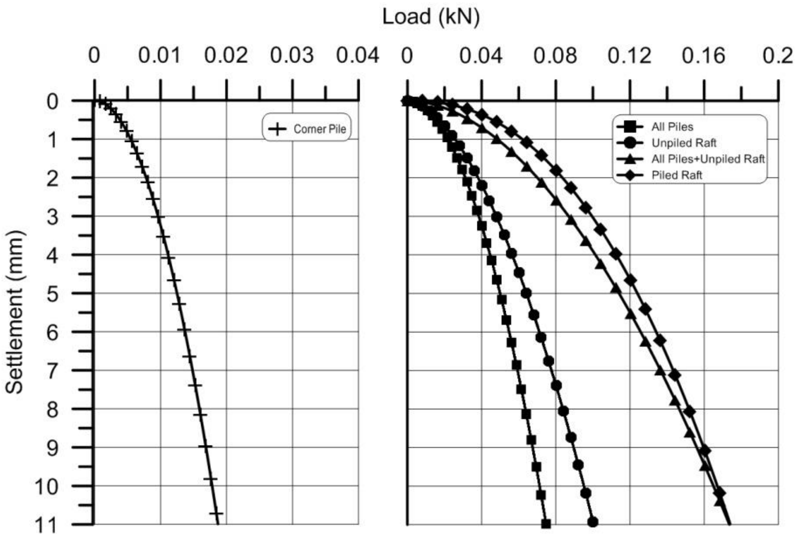

Fig. 22 Load-settlement curves for (2×2) piled raft

19. Effect of configuration

The failure load corresponding to each raft, free standing pile group and piled raft are presented in Fig. 28. On the other hand, in order to study the role of piles as settlement reducers, a settlement corresponding to the load that is equal to 0.05 the diameter of pile, was calculated and presented in Fig. 29 for each case.

Figs. 28 and 29 illustrate the effect of raft configuration and size on failure load and settlement for raft, free standing pile group and piled raft. It is clear that when the raft (pile cap) becomes larger, the failure load will increase and the settlement will decrease, and this effect is greater on

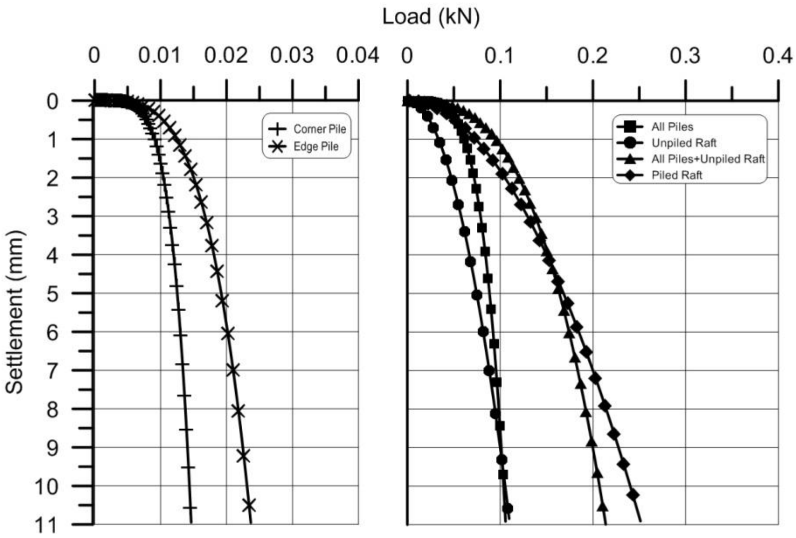

Fig. 23 Load-settlement curves for (2×3) piled raft

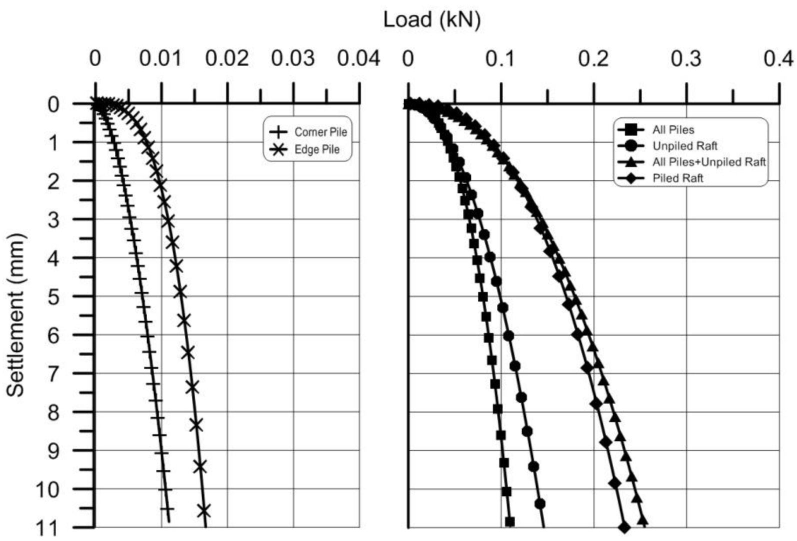

Fig. 24 Load-settlement curves for (2×4) piled raft

the piled raft foundation than the raft and the free standing pile group. It can also be noticed that the configuration that has the same or nearly the same number of piles or raft size like (1×4 with 2×2) and (2×4 with 3×3) reveals approximately the same failure load and settlement.

The effect of piled raft on reducing the settlement vanishes when the number of piles exceeds 6, this means that as the pile number increases further, the decrease in settlement gets smaller and no economical benefit is obtained. This conclusion matches the conclusion of Yilmaz (2010) who found that there is no significant effect of increasing pile number as far as the settlement is concerned and there exists an optimum number of piles that is beyond this value, the settlement no longer decreses significantly.

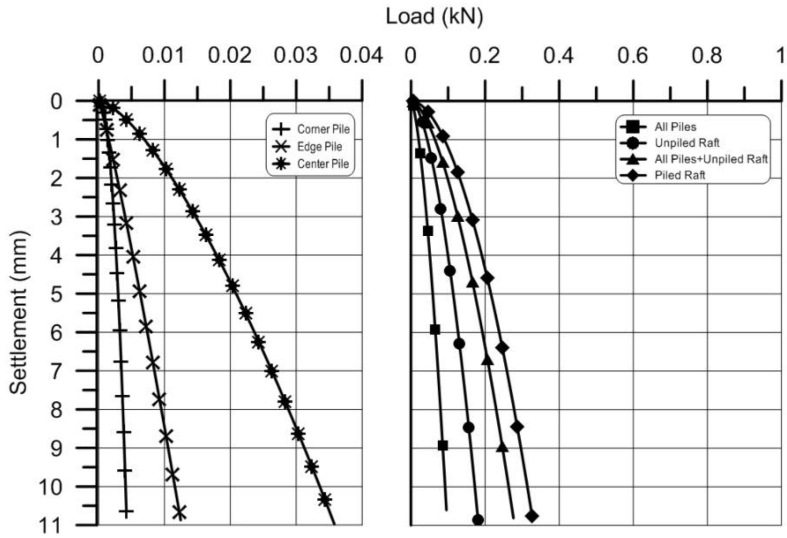

Fig. 25 Load-settlement curves for (3×3) piled raft

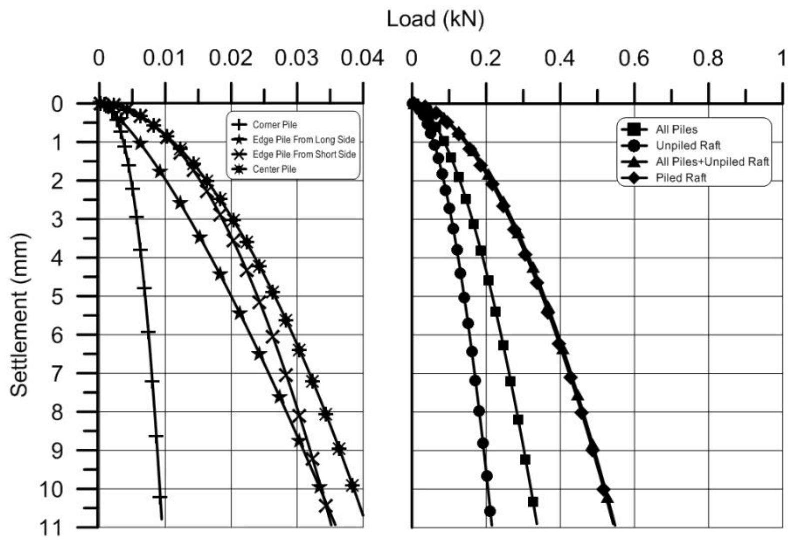

Fig. 26 Load-settlement curves for (3×4) piled raft

20. 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.

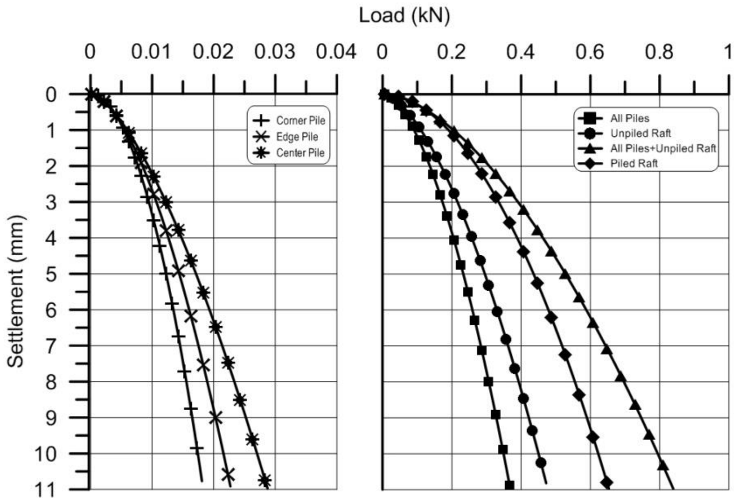

Fig. 27 Load-settlement curves for (4×4) piled raft

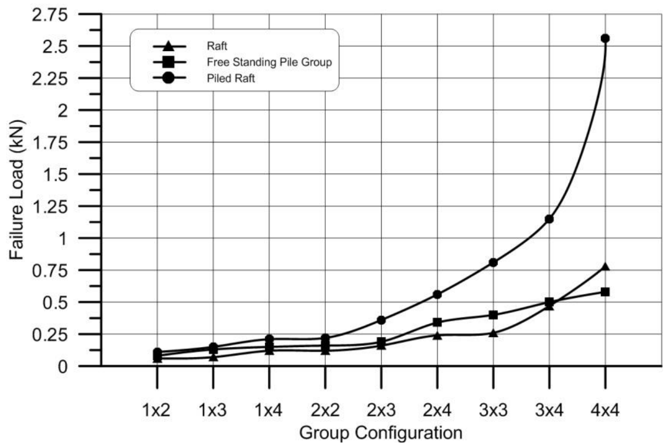

Fig. 28 Effect of configuration on the failure load for raft, free standing pile group and piled raft

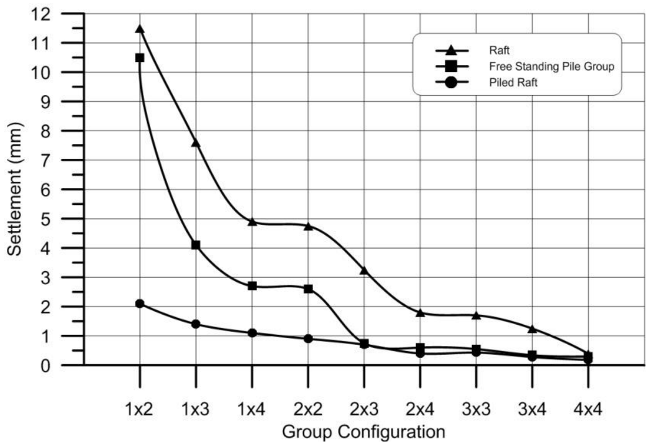

Fig. 29 Effect of configuration on the settlement for raft, free standing pile group and piled raft

3. The pile group configuration that has the same or nearly the same number of piles (1×4 with 2×2) and (2×4 with 3×3) reveals approximately the same failure load and settlement.

4. 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 because the area occupied by piles is large compared to the raft are. The failure load for a piled raft consisting of 9 piles is approximately 100% greater than free standing pile group containing the same number of piles. This difference increases to about 4 times for 16 pile group.

5. 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 because the area occupied by piles is large compared to the raft are. The settlement can be increased by about 8 times in (1×2) 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.

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