Bearing Capacity and Settlement Study on Small-Scale Piled-Raft Groups in Sand

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ABSTRACT: Pile group foundation with a pile cap can be considered as a piled-raft foundation. Previous studies indicate that in a piled-raft foundation, the piles contributes to reduce settlement of the raft whereas the raft provides an additional bearing capacity of the pile group. Laboratory testings were performed to investigate the performance of piled-raft group from bearing capacity and settlement point of views. Instrumented laboratory models of 2x2 and 3x3 piled-raft group were loaded vertically to obtain load vs. settlement curves and load-transfer to raft, to pile shaft, and to pile tip. From the load-settlement curves of piled-raft group, the performance of bearing capacity and settlement was then observed and quantified. The laboratory test results indicated that the presence of piles reduced the settlement of raft significantly, whereas the presence of raft provided additional bearing capacity to the pile.

Keywords: Piled-raft group, Small-scale test, Instrumented test, Bearing capacity, Settlement.

1. INTRODUCTION

A pile group is constructed by utilizing a cap to combine the piles as one group. When the bottom of the pile cap is in contact with soil, this type of pile group foundation forms a piled-raft group. In a piled-raft group, the load is shared between the piles and the raft (Sengara, 1997; Phung, 2011). In other words, the raft provides an additional bearing capacity to the pile group.

At some soil conditions, raft foundation has adequate bearing capacity but exhibits excessive settlement. In this soil, piles can be used to reduce the settlement of the raft (e.g. Zeevaert, 1957; Hooper, 1973).

Several methods have been proposed to quantify the piled-raft group behaviour. Poulos and Davis (1980) suggested an analytical solution based on the theory of elasticity to predict settlement of piled-raft group. Randolph (1983, 1994) presented an analytical solution based on the theory of elasticity to quantify load shared by the piles and the raft. Poulos (1991) and Clancy and Randolph (1993) came up with an analytical method to analyze load transfer and settlement of piled-raft system. The soil and piles are modelled as springs whereas the raft was modelled as plate element. Ta and Small (1996) used finite element method to analyze load transfer and settlement of piled-raft system. The raft is modelled using plate element whereas the piles are modelled using solid elements. Long (2016) proposed a simplified design method for load shared between piles and raft. Nguyen et al. (2013) proposed a design method of piled-raft foundations under vertical load considering interaction effects between the pile group and the raft. These two methods utilizing finite element analyses. Several other methods (e.g. strip superposition method (Brown and Wiesner, 1975), plate on piles and continuum method (Hain, 1975), simplified finite element analyses (Hooper, 1973; Desai et al., 1974), have been proposed to analyzed either load transfer, settlement, or both. In addition, Sengara (1992) has performed a finite element study on soil-structure interaction analyses.

The previous proposed methods concentrate on the use of analytical and numerical approaches to predict load shared between pile group and raft or settlement of piled-raft group. In spite of these methods, tests on instrumented piled-raft group are required to support the theoretical approach of pile-group. However, the instrumented load test on piled-raft group to study the bearing capacity and settlement in piled-raft group is quite rare.

This paper presents laboratory tests on instrumented small-scale piled-raft groups in sand. The emphasis of this paper is on the study of the effect of raft to provide an additional bearing capacity to the pile group that occurs simultaneously with the role of piles to reduce the settlement of the raft.

2. METHODOLOGY

Laboratory tests were performed to investigate the bearing capacity and settlement of small-scale piled group models. Two configurations of piled-raft group models were studied: 2×2 and 3×3 piled-raft group models. Schematic diagrams of the piled-raft group models are shown in Figures 1 and 2 for 2×2 and 3×3 piled-raft group models, respectively. Steel pipe piles with 48.6 mm in diameter, 1 mm in thickness, and 1000 mm in length were used in both piled-raft groups (Figures 1b and 2b). The piles, thus, have a ratio of length to diameter, L/d equal to 20.6. The steel pipe piles have modulus of elasticity, E equal to 2.1×10^8 kN/m^2. The piles have closed lower end and have the shaft covered by sand papers. In 2×2 piled-raft groups, all piles are instrumented with a pair of axial (longitudinal) and lateral (hoop) strain gauges at the top, middle, and bottom of piles (Figure 1b). In 3×3 piled-raft group, piles nos. 1, 2, 3, 4, and 9 (Figure 2a) were instrumented a pair of axial and lateral strain gauges at the top, middle, and bottom of piles (Figure 2b) whereas piles nos. 5, 6, 7, and 8 with a pair of axial and lateral strain gauges only at the top of piles.

A steel square raft with the length and width of 520 mm × 520 mm and 13 mm in thickness was used in both 2×2 and 3×3 piled-raft groups. The steel raft has modulus of elasticity, E equal to 2.1×10^8 kPa. Four load cells (LC1, LC2, LC3, and LC4) with capacity of 0.392 kN/m^2 kg each load cell were installed in the raft (Figures 1a and 2a).

Sand with two relative densities, D_r (D_r = 50% and D_r = 80%) were used in the laboratory tests. Sand with relative density, D_r equal to 50%, is categorized as medium dense sand whereas sand with relative density, D_r equal to 80% is categorized as dense sand (Lambe and Whitman, 1969; Coduto, 1994). Several index properties tests were performed based on ASTM standard (ASTM 1998). These tests are grain size distribution test (ASTM D422), maximum density test (ASTM D4253), and minimum density test (ASTM D4254). In addition, Consolidated Drained (CD) triaxial tests (ASTM D7181) were performed to obtain effective friction angle for sands with relative densities, D_r equal to 50% and 80%. From the values of maximum and minimum dry densities obtained from the laboratory test, dry density, γ_d for relative densities, D_r equal to 50% and 80% were calculated. Triaxial test specimens were compacted in a specimen mould to achieve the density correspond to the relative density, D_r equal to 50% and 80%.

Three confining pressures: 98.1 kN/m², 196.2 kN/m², and 392.4 kN/m² were used in triaxial test. Average modulus of elasticity at initial strain, $E_{i\ avg}$, at 50% ultimate deviatoric stress, $E_{50\ avg}$, and at ultimate deviatoric stress, $E_{u\ avg}$ for confining pressures of 98.1 kN/m², 196.2 kN/m², and 392.4 kN/m² were calculated for both sands with relative densities, D_r equal to 50% and 80%.

In the small-scale piled-raft laboratory model test, sand was contained in a steel box with the length and width of 2200 mm × 2200 mm and 1500 mm in height (Figures 1b, 2b, and 3a). To ensure that during the piled-raft group loading the box did not deformed excessively, several steel reinforcements were provided (Figure 3e).

Piles were installed by firstly placing them on top of the compacted sand (Figures 3b and 3c). A certain mass of sand was then spread in the box around the piles and the sand was then compacted to achieve a certain volume. By this method, the target density can be achieved. A hand compactor powered by air pressure was used in the compaction process. The compaction process was performed to achieve a unit dry weight, γ_d correspond to relative densities, D_r equal to 50% and 80%. The thickness of each compacted layer was 150 mm. Holtz et al. (2011) indicates that for various soil types the thickness of each compacted layer ranges from 150 mm to 500 mm. It is expected that by using 150 mm layer thickness, a uniform soil can be achieved as the thickness of 150 mm represents the thinnest layer from the range of 150 mm to 500 mm. The raft was then installed when the sand had reached the upper end of the pile group (Figure 3d). A linear variable differential transformer (LVDT) was installed on top of raft (Figure 3e) to measure the axial displacement of the raft during loading.

Thus the laboratory test setup provided a distance of 840 mm (i.e. 1.6 times the raft width) from the edge of the raft to the box wall, a distance of 920 mm (i.e. 18.9 times the pile diameter) from the outer pile shaft to the box wall, and a distance of 500 mm (i.e. 10.3 times the pile diameter) from the bottom of pile to the bottom of box. With this piled-raft group and box dimension, it is expected that the ultimate bearing capacity of the piled raft group model can be mobilized with a minimum boundary effect from the box.

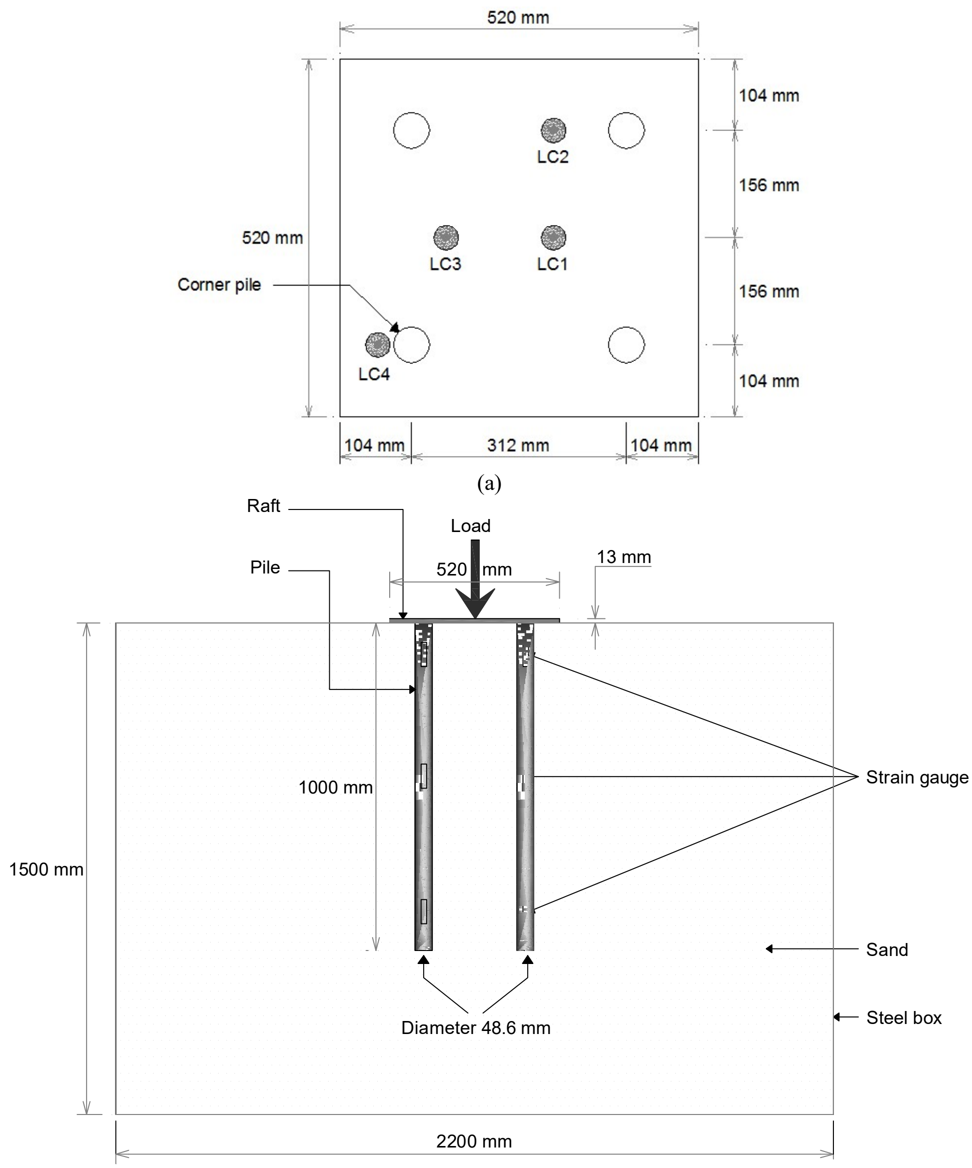
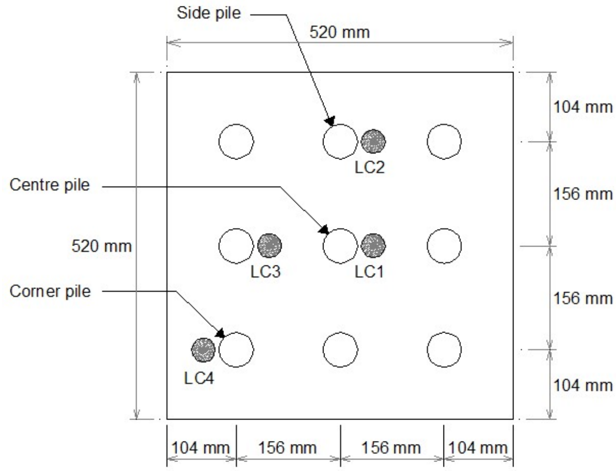
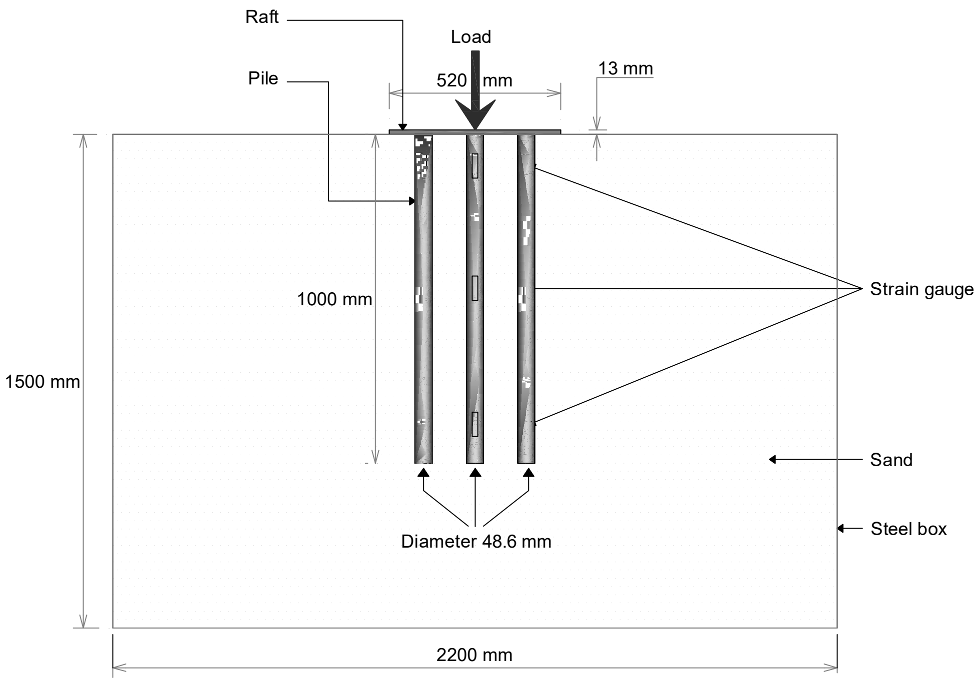


Figure 1 Schematic diagram of laboratory 2x2 group piled-raft model: (a) Plan view; (b) Cross section view



(a)



(b)

Figure 2 Schematic diagram of laboratory 3x3 group piled-raft model: (a) Plan view; (b) Cross section view

Both 2×2 and 3×3 piled-raft groups were loaded vertically to obtain load vs. settlement curves. The laboratory test setup is shown in Figure 3. Two sets of computer systems were used in the loading system (Figure 3a): one set (Computer 1) was used for data logging process and one set (Computer 2) was used for a real time monitoring of load vs. settlement curve during the loading process. The loading process was performed at a loading rate of 0.24 mm/min. This loading rate is comparable with the loading rate of a CD triaxial test. The load piston and the load cells reading were performed every 4 sec for Test 1 and every 8 sec for Tests 2 and 3. The loading process was performed a settlement of about 25 mm was achieved. In engineering practice, a settlement criterion of 25 mm is usually used as a limiting value for serviceability of an isolated shallow foundation (European Committee for Standardization, 1994).

Three load vs. settlement curves were obtained: load carried by the piled-raft group vs. settlement curve, load carried by the pile group vs. settlement curve, and load carried by the raft vs. settlement curve. Load carried by the piled-raft group was obtained from the loading piston (Figure 3a) reading. Load carried by the raft was obtained by averaging the load measured by tree load cells installed on top of the raft (Figures 1a, 2a, and 3a). Load carried by the piles was calculated by subtracting load carried by the raft from the load carried by the piled-raft group. In addition to this, the load carried by the piles calculated utilizing top strain gauges readings was obtained as a checking for the load carried by the piles calculated using the above method. The stresses on top of piles were calculated using the strain gauges reading. The load on top of each pile was calculated as a product of stress on top of each pile and cross section area of each pile. The summation of load carried by all piles gives the load carried by the piles. Those three load vs. settlement curves were obtained and used to investigate and to quantify the performance of the piles in terms of bearing capacity and settlement.

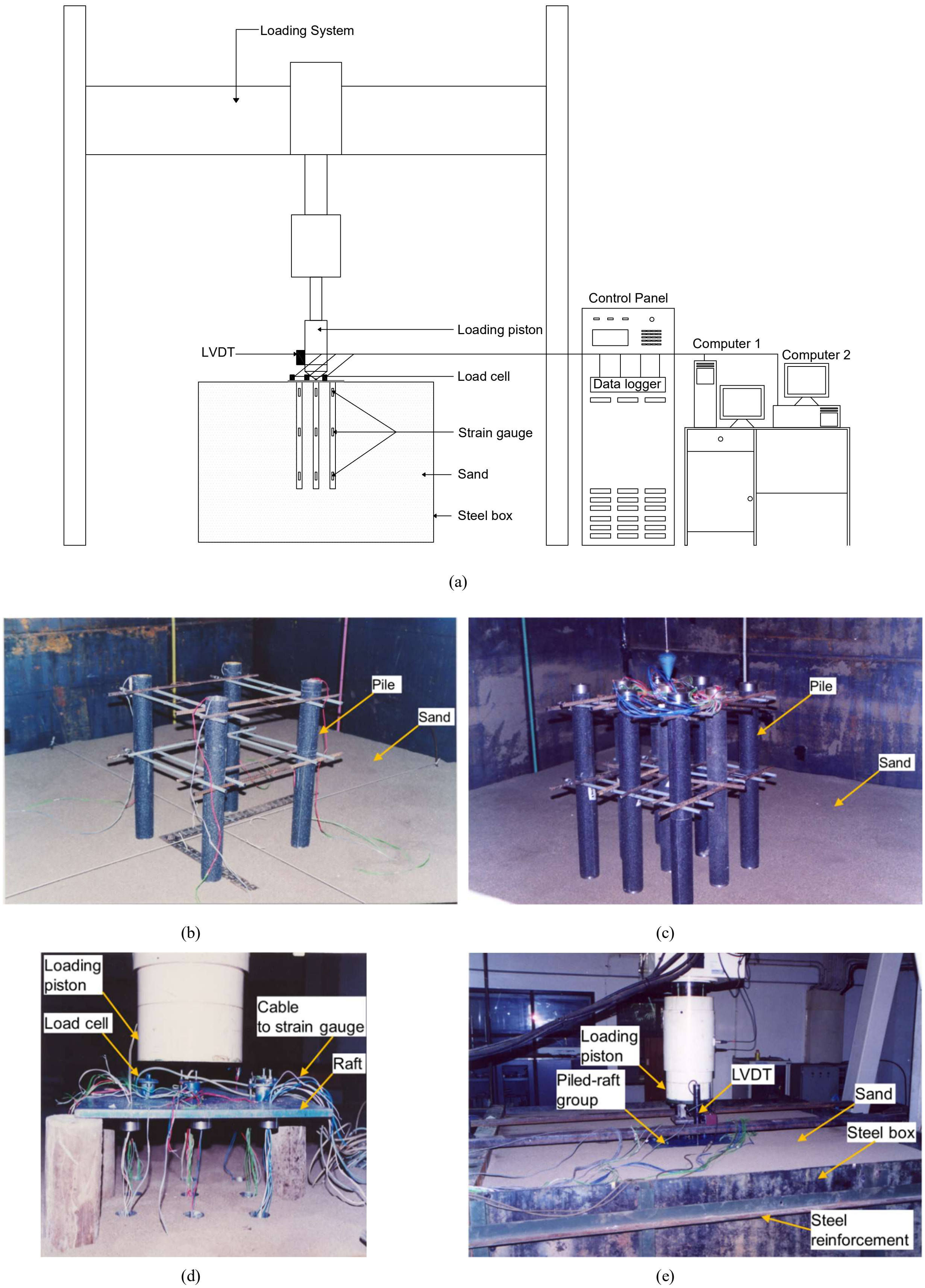


Figure 3 Laboratory tests setup: (a) General setup; (b) Installation of 2×2 group piled-raft; (c) Installation of 3×3 group piled-raft; (d) Raft installation of 3×3 group piled-raft with load cells; (e) Load application process

Three laboratory tests were performed as summarized in Table 1. Test nos. 1 and 3 were performed to observe the effect of pile number on the load vs. settlement curve of piled-raft group. Test nos. 2 and 3 were performed to observe the effect of an increase in relative density (which affects the soil bearing capacity) on the load vs. settlement curve of group piled-raft group. In this paper, it is assumed that the load carried by raft vs. settlement curve measured in a piled-raft group represents the load vs. settlement curve of the raft without piles.

Table 1 Laboratory testing program

Test No.	Pile Configuration	Relative Density of Sand, D_r (%)
1	Piled-raft group 2×2 Pile length = 1000 mm	80
2	Piled-raft group 3×3 Pile length = 1000 mm	50
3	Piled-raft group 3×3 Pile length = 1000 mm	80

3. RESULTS AND DISCUSSIONS

Soil properties used in this study are shown in Table 2. From the minimum and maximum dry unit weights, the dry unit weight, γ_d correspond to D_r equal to 50% and 80% are calculated as 12.5 kN/m^3 and 13.5 kN/m^3, respectively.

Table 2 Soil properties of sands used in this study

D_{10} (mm)	0.10
D_{30} (mm)	0.22
D_{60} (mm)	0.35
Soil classification according to Unified Classification System (USCS)	SP (poorly graded sand)
Minimum dry unit weight, $\gamma_{d(min)}$ (kN/m^3)	11.1
Maximum dry unit weight, $\gamma_{d(min)}$ (kN/m^3)	14.3
Average modulus of elasticity of sand with D_r = 50% at initial strain, $E_{i\ avg}$ (kN/m^2)	5.58 ×10^4
Average modulus of elasticity of sand with D_r = 50% at 50% ultimate strain, $E_{50\ avg}$ (kN/m^2)	3.79 ×10^3
Average modulus of elasticity of sand with D_r = 50% at ultimate strain, $E_{u\ avg}$ (kN/m^2)	3.30 ×10^3
Effective friction angle, ϕ' (deg) of sand with D_r = 50%	37.8
Sand-pile interface friction angle, δ (deg)	25.4
Average modulus of elasticity of sand with D_r = 80% at initial strain, $E_{i\ avg}$ (kN/m^2)	6.20 ×10^4
Average modulus of elasticity of sand with D_r = 80% at 50% ultimate strain, $E_{50\ avg}$ (kN/m^2)	4.98 ×10^4
Average modulus of elasticity of sand with D_r = 80% at ultimate strain, $E_{u\ avg}$ (kN/m^2)	3.52 ×10^4
Effective friction angle, ϕ' (deg) of sand with D_r = 80%	40.0
Sand-pile interface friction angle, δ (deg)	27.2

The corresponding void ratio, *e* are 1.19 and 1.02 for D_r equal to 50% and 80%, respectively. In the triaxial test, sand specimens were compacted to achieve dry densities equal to 12.5 kN/m^3 and 13.5 kN/m^3 for specimens with D_r equal to 50% and 80%, respectively. Sand with D_r equal to 50% has $E_{i\ avg}$, $E_{50\ avg}$, and $E_{u\ avg}$ equal to 5.58×10^4 kN/m^2, 3.79×10^3 kN/m^2, and 3.30×10^3, respectively whereas Sand with D_r equal to 80% has $E_{i\ avg}$, $E_{50\ avg}$, and $E_{u\ avg}$ equal to 6.20×10^4 kN/m^2, 4.98×10^4 kN/m^2, and 3.52 ×10^4 kN/m^2, respectively. Effective friction angle of sands, ϕ' are 37.8^o and 40.0^o for sand with D_r equal to 50% and 80%, respectively. Sand-pile shaft interface friction angle, δ are 25.4^o and 27.2^o for sand with D_r equal to 50% and 80%, respectively (Sengara et al., 1997).

The load vs. settlement curves obtained from the laboratory tests are shown in Figures 4 to 6. It is clear from the load vs. settlement curves shown in Figures 4 to 6 that the piled-raft group, the pile group and the raft ultimate bearing capacities in each test have not reached a condition of a constant load with increasing settlement as the criterion of ultimate bearing capacity (Terzaghi et al., 1996). Therefore, the ultimate bearing capacity of the piled-raft groups has not been achieved. The ultimate bearing capacity of each piled-raft group, pile group, and raft was predicted using the Chin's method (Chin, 1978). Chin's method was selected because it provides a regression curve to obtain a load vs. settlement curve as well as the ultimate bearing capacity. In addition, the change of the slope in the load vs. settlement curve (i.e. the yielding point occurred in the load-settlement curve) has been considered in this method. The ultimate bearing capacities of piled-raft group, pile group, and raft are shown in Table 3.

Figure 4 Load vs. settlement curves of 2×2 piled-raft group in sand with D_r = 80% (Test 1)

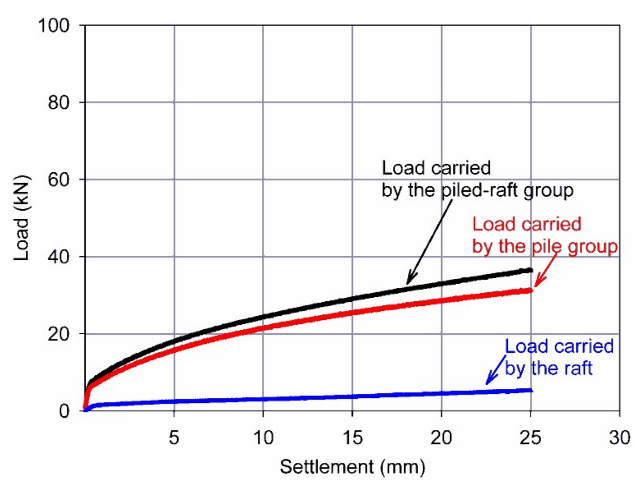


Figure 5 Load vs. settlement curves of 3×3 piled-raft groups in sand with D_r = 50% (Test 2)

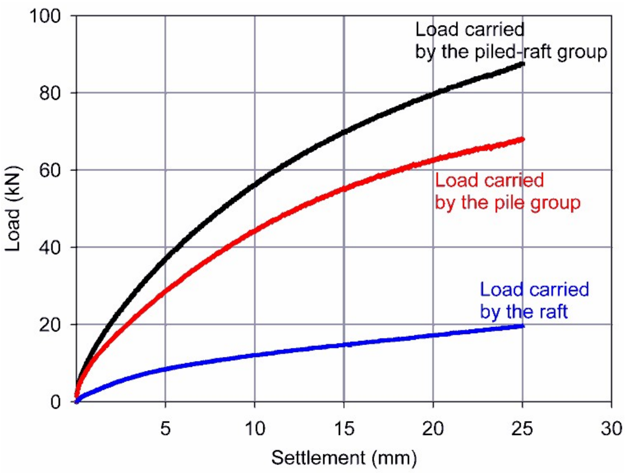


Figure 6 Load vs. settlement curves of 3×3 piled-raft group in sand with D_r = 80% (Test 3)

As a check to the piled-raft group, the pile group and the raft ultimate bearing capacities predicted using Chin's method, the piled-raft group ultimate bearing capacity was recalculated as a summation of the pile group and the raft ultimate bearing capacities. The piled-raft group ultimate bearing capacity calculated as a check is shown in the fifth column of Table 3. It is obvious that the piled-raft group ultimate bearing capacity predicted using Chin's method is close to the piled-raft ultimate bearing capacity calculated as a summation of the pile group and the raft ultimate bearing capacities. These close values indicate the appropriateness of Chin's method to predict the ultimate bearing capacities in this study.

To verify for the results in Figures 4 to 6, load carried by raft was also calculated utilizing the strain gauges reading. The stress at pile top was calculated as the product of strain and modulus of elasticity of pile materials. Load (column 3 in Tables 4 to 6) was calculated as the product of stress at pile top and pile cross section. The loads were calculated for center pile, edge piles, and corner piles. Total load per pile type was calculated as the product of number of pile of each type and load per pile of each type (column 4 in Tables 4 to 6). Load carried by pile group was calculated as the summation of total load per pile type. Load carried by raft was calculated from the applied load minus the load carried by pile group (column 4 in Table 7). The applied load was obtained from the loading piston reading (Figures 4 to 6). The measured load carried by raft (column 5 in Table 7) was obtained from the load cells reading (Figures 4 to 6). Comparison of load carried by raft calculated using both methods is shown in Figure 7. The differences between the measured and calculated load carried by raft are still within 1.45 kN which is 10% of the lowest raft ultimate bearing capacity among Tests 1 to 3 (Column 4 Table 3). Therefore, the load carried by raft calculated using both methods is consistent indicating the reliability of the measurement performed in this study.

Table 3 Ultimate bearing capacities predicted from test

Test No.	Ultimate Bearing Capacity of Piled-Raft Group (kN)	Ultimate Bearing Capacity of Pile Group (kN)	Ultimate Bearing Capacity of Raft (kN)	Ultimate Bearing Capacity of Pile Group + Ultimate Bearing Capacity of Raft (kN)	Bearing Capacity Ratio
(1)	(2)	(3)	(4)	(5)	(6) = (2)/(4)
1	61.4	29.0	32.3	61.3	1.9
2	58.8	47.4	14.5	61.9	4.1
3	139.3	103.9	32.4	136.3	4.3

Table 4 Results of top strain gauge readings of Test 1: (a) Applied load = 8.40 kN; (b) Applied load = 24.80 kN; (c) Applied load = 37.60 kN

(a)

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Corner pile	4	1.72	6.89
		Σ (kN) =	6.89

(b)

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Corner pile	4	4.35	17.38
		Σ (kN) =	17.38

(c)

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Corner pile	4	5.57	22.27
		Σ (kN) =	22.27

Table 5 Results of top strain gauge readings of Test 2 at applied load = 29.70 kN

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Center pile	1	2.92	11.69
Edge pile	4	2.92	11.67
Corner pile	4	2.92	11.69
		Σ (kN) =	26.28

Tables 4 to 6 indicate that the load was distributed uniformly among piles. Previous studies (e.g. Beredugo, 1966; Butterfield and Banerjee, 1971a, Butterfield and Banerjee, 1971b) indicate that for a relatively stiff raft and large number of piles, there is a significant difference between the load carried by the center pile and that by the corner piles. The ratio between raft-soil stiffness (calculated using the method of Poulos and Davis, 1974) and pile-soil stiffness (calculated using the method of Poulos and Davis, 1980) in this study is 7.49 10-5. This very small stiffness ratio indicates the low stiffness of the raft. The low stiffness of the raft and the small number of piles in the group may cause the relatively similar load distribution among piles in this study. Poulos and Mattes (1971) study of load distribution among piles in a pile group with a flexible cap indicates that the smaller number of pile in a pile-group, the more uniform load distribution among piles. The results of Poulos and Mattes' research (1971) provide an additional support about the load distribution among piles in this study.

Table 6 Results of top strain gauge readings of Test 2: (a) Applied load = 26.10 kN; (b) Applied load = 64.80 kN

(a)

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Center pile	1	2.24	8.97
Edge pile	4	2.24	8.96
Corner pile	4	2.23	8.91
		Σ (kN) =	20.12

(b)

Pile Type	Number of pile	Load per pile (kN)	Total Load per Pile Type (kN)
(1)	(2)	(3)	(4) = (2) × (3)
Center pile	1	5.71	22.85
Edge pile	4	5.73	22.90
Corner pile	4	5.70	22.80
		Σ (kN) =	51.42

Table 7 Comparison of load carried by raft obtained from two approaches

Test	Applied Load (kN)	Measured Load Carried by Pile Group (kN)	Calculated Load Carried by Raft (kN)	Measured Load Carried by Raft (kN)
(1)	(2)	(3)	(4) = (2) – (3)	(5)
Test 1	8.40	6.89	1.51	1.42
Test 1	24.80	17.38	7.42	7.24
Test 1	37.60	22.27	15.33	15.48
Test 2	9.90	9.50	0.40	1.50
Test 2	29.70	27.01	2.69	3.73
Test 3	26.10	20.12	5.98	5.96
Test 3	64.80	51.42	13.38	13.54

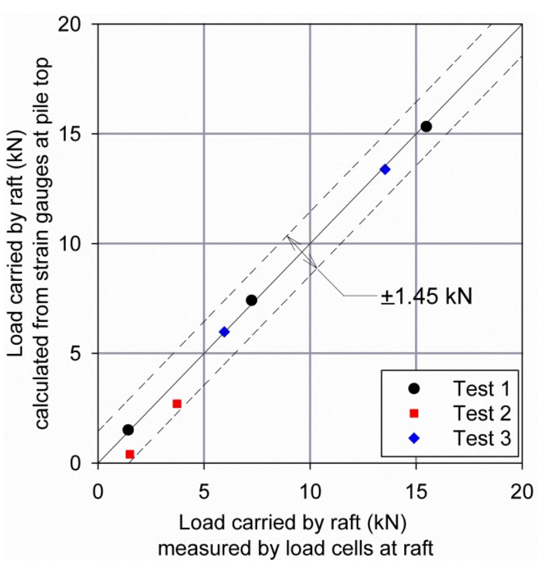


Figure 7 Comparison of load transfer to raft

Table 3 shows that the piled-raft group ultimate bearing capacities of Tests 1 and 2 are close whereas the piled-raft group ultimate bearing capacities between Test 3 and both of Tests 1 and 2 are significantly different. A comparison between Test 1 (2×2 group piled-raft in sand with D_r = 80%) and Test 2 (3×3 group piled-raft in sand with D_r = 50%) reveals that piled-raft group in Test 2 has more piles (9 piles) than piled-raft group in Test 1 (4 piles). The increase of number of piles causes the increase of pile group ultimate bearing capacity. Another condition between Tests 1 and 2 is sand used in Test 1 is denser (D_r = 80%) than sand used in Test 2 (D_r = 50%). Table 2 shows that sand used in Test 1 has more friction angle than sand used in Test 2. The higher sand friction angle of Test 1 causes the higher single pile ultimate capacity of piles in soil in Test 1 than the single pile ultimate capacity of piles in soil in Test 2. The higher number of pile in Test 2 than 1 causes the higher pile group ultimate bearing capacity in Test 2 than that in Test 1 if the sands in both test are in the same density. However, sand used in Test 2 has lower density (D_r = 50%) than sand used in Test 1 (D_r = 80%). The lower sand density causes the lower single pile ultimate bearing capacity. In this study these two counteract conditions results in a higher pile group bearing capacity of Test 2 then pile group bearing capacity of Test 1 (29.0 kN in Test 1 compare to 47.4 kN in Test 2). The results of Tests 1 and 2 also shows that the ultimate bearing capacity of pile group increases, but the ultimate bearing capacity of raft decreases (32.3 kN in Test 1 compare to 14.5 kN in Test 2). The higher pile group ultimate bearing capacity in Test 2 than that in Test 1 and with the higher raft ultimate bearing capacity in Test 1 than that in Test 2 result in a close value of ultimate bearing capacity of piled-raft group between Tests 1 and 2. From the results of Tests 1 and 2, it is learned that an increase in sand density causes an increase in raft bearing capacity.

A comparison between Tests 2 and 3 results in Table 3 shows the effect of an increase in sand relative density in the piled-raft group ultimate bearing capacity (58.8 kN in Test 2 compare to 139.3 kN). There is an increase in the pile group bearing capacity due to the increase in density of sand (47.4 kN in Test 2 compare to 103.9 kN). There is also an increase in the raft bearing capacity due to the increase in density of sand (14.5 kN in Test 2 compare to 32.4 kN in Test 3). Therefore, it is clear that the increase in sand relative density causes an increase in the piled-raft group, the pile group, and the raft ultimate bearing capacities.

A comparison between Tests 1 and 3 results in Table 3 reveals the effect of the increase in number of piles in sand with the same relative density on the increase of the pile group ultimate bearing capacity. A significant increase in the pile group ultimate bearing capacity due to the effect of the increase of number of pile is obvious (29.0 kN in Test 1 compare to 103.9 kN in Test 3). The raft ultimate bearing capacities between Tests 1 and 3 are relatively similar (32.3 kN in Test 1 compare to 32.4 kN in Test 3). This similarity in the raft ultimate bearing capacity can be attributed to the same sand relative density (and effective friction angle) in Tests 1 and 2. The difference in the pile group ultimate bearing capacity and the similarity in the raft ultimate bearing capacity of Tests 1 and 2 results in an increase in the piled-raft group ultimate bearing capacity (61.4 kN in Test 1 compare to 139.3 kN in Test 3). Thus it is obvious that the increase of number of pile causes an increase in the ultimate bearing capacity of piled-raft group of the sand with the same density.

Table 3 also shows that for each test, the piled-raft group ultimate bearing capacity is higher than the raft ultimate bearing capacity. A parameter named "bearing capacity ratio" is defined to quantify the ratio of the piled-raft group ultimate bearing capacity to the raft ultimate bearing capacity in a piled-raft group as follows:

$$bearing\ capacity\ ratio = \frac{Q_{u-prg}}{Q_{u-r}} \tag{1}$$

where $Q_{u\text{-}prg}$ is the piled-raft group ultimate bearing capacity in a piled-raft group; and $Q_{u\text{-}r}$ is the raft ultimate bearing capacity in a piled-raft group. The bearing capacity ratios of the three tests are shown in the sixth column of Table 3. As in the above observation, it is clear that the presence of piles causes an increase in the piled-raft group ultimate bearing capacity as compared to the raft bearing capacity. The bearing capacity ratio of Test 1 is 1.9 whereas bearing capacity ratios of Tests 2 and 3 are 4.1 and 4.3, respectively. It can be seen that bearing capacity ratio of Test 1 is closer to 1 than bearing capacities of Tests 2 and 3. The closer bearing capacity to 1 indicates that the increase of bearing capacity of raft due to the presence of piles is small.

In addition to the comparison of the ultimate bearing capacity, the load vs. settlement behaviour is compared as shown in Figures 8 and 9. Figure 8 shows a comparison between the load vs. settlement curves of Tests 1 and 3 whereas Figure 9 shows a comparison between the load vs. settlement curves of Tests 2 and 3. Figure 8 shows that the load vs. settlement curve of the raft for Test 1 is relatively the same as that for Test 3. This similarity in the load vs. settlement curve indicated that the presence of piles did not affect the load vs. settlement and the raft ultimate bearing capacity. This indicated the appropriateness of the assumption that the load carried by the raft vs. settlement curve measured in piled-raft groups in this study (2×2 and 3×3 pile configurations) represented the load vs. settlement curve of the raft without piles. The value rank of the piled-raft group, the pile group and the raft bearing capacities at any settlement varies in the same manner as that of the ultimate bearing capacity; the piled-raft group bearing capacity is the highest followed by the pile group bearing capacity and the raft bearing capacity. Thus, the bearing capacity ratio as indicated in Table 3 occurs not only at the ultimate bearing capacity, but also at lower bearing capacities. This can be explained by re-written Eq. (1) in the following form:

$$bearing\ capacity\ ratio = \frac{Q_{u\,piled-raft\,group}/FS}{Q_{u\,raft}/FS} \quad (2)$$

It is clear from Eq. (2) that any values of factor of safety, *FS* produce the same bearing capacity ratio. Therefore, bearing capacity ratio is the same as the variation of factor of safety, *FS*.

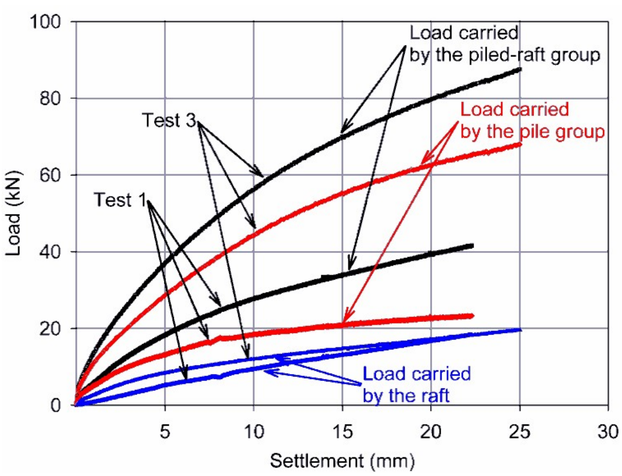


Figure 8 Comparison of load vs. settlement curves of 2×2 and 3×3 piled-raft groups in sand with D_r = 80% (Tests 1 and 3)

To analyze the effect of the presence of pile to reduce the raft settlement, the data shown in Figures 8 and 9 are replotted in Figures 10 and 11. Figure 10 shows the effect of the pile configuration on the raft and piled-group settlements in sand with D_r equal to 80% (comparison between Tests 1 and 3). Figure 11 shows the effect of relative density of sand to the raft and the piled-group settlements (comparison between Tests 2 and 3). Each value of settlement was calculated for the load correspond to the ultimate bearing capacity of the raft (the fourth column in Table 3) divided by a factor of safety for the raft ultimate bearing capacity, FS_{raft}.

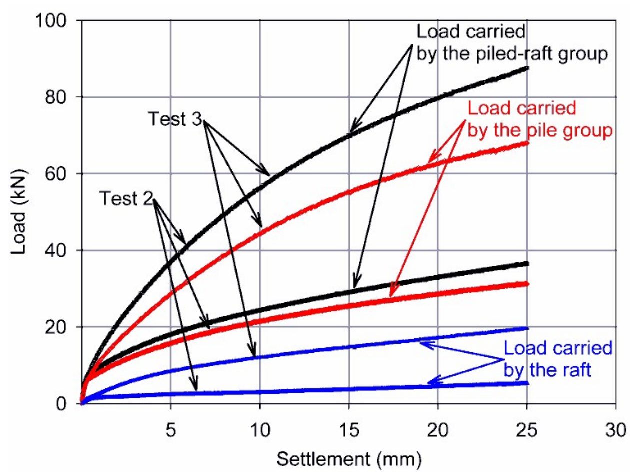


Figure 9 Comparison of load vs. settlement curves of 3×3 piled-raft groups in sand with D_r = 80% and in sand with D_r = 50% (Tests 2 and 3)

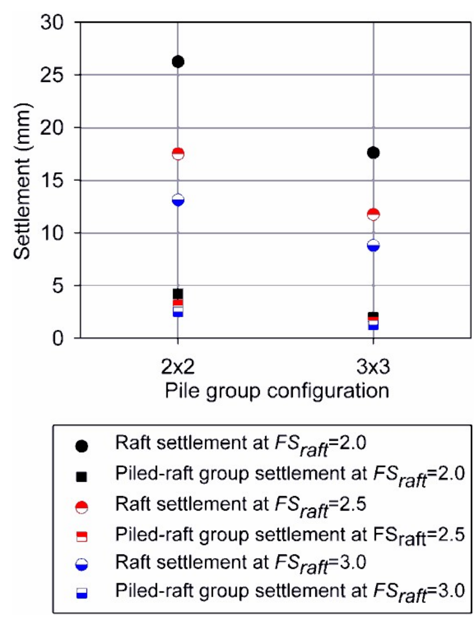


Figure 10 Effect of the pile configuration to the settlement of the raft and the piled-groups in sand with D_r = 80% (comparison between Tests 1 and 3): (a) At FS_{raft} = 2.0; (b) At FS_{raft} = 2.5; (c) At FS_{raft} = 3.0

Three factors of safety for raft ultimate bearing capacity (i.e. FS_{raft} = 2.0, 2.5, and 3.0) were used in the calculation of settlement shown in Figures 10 and 11. At FS_{raft} equal to 2.0, the raft settlement at 2×2 and 3×3 piled-raft groups in sand with relative densities, D_r equal to 80% are 26.2 mm and 17.6 mm, respectively, whereas the raft settlement at 3×3 piled-raft groups in sand with relative densities, D_r equal to 50% is 45.6 mm. At load correspond to FS_{raft} equal to 2.0, the corresponding piled-raft group settlement are 4.2 mm, 2.0 mm, and 2.2 mm. At FS_{raft} equal to 2.5, the raft settlement at 2×2 and 3×3 piled-raft groups in sand with relative

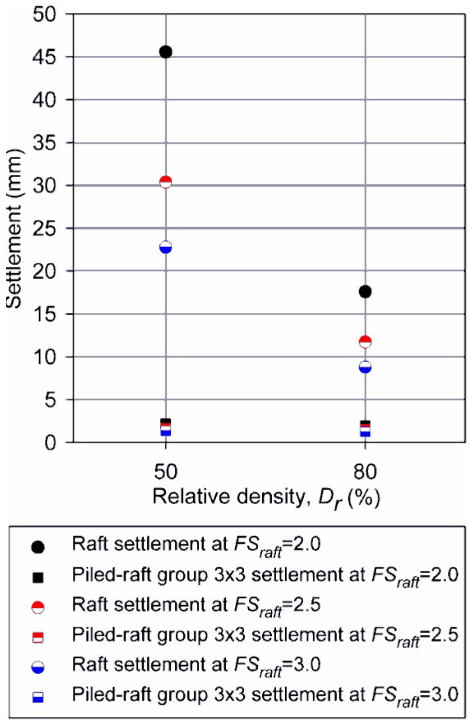


Figure 11 Effect of the relative density of sand to the settlement of the raft and the piled-groups (comparison between Tests 2 and 3): (a) At FS_{raft} = 2; (b) At FS_{raft} = 2.5; (c) At FS_{raft} = 3.0

densities, D_r equal to 80% are 17.5 mm and 11.7 mm, respectively, whereas the raft settlement at 3×3 piled-raft groups in sand with relative densities, D_r equal to 50% is 30.4 mm. At load correspond to FS_{raft} equal to 2.5, the corresponding piled-raft group settlement are 3.1 mm, 1.5 mm, and 1.7 mm. At FS_{raft} equal to 3.0, the raft settlement at 2×2 and 3×3 piled-raft groups in sand with relative densities, D_r equal to 80% are 13.1 mm and 8.8 mm, respectively, whereas the raft settlement at 3×3 piled-raft groups in sand with relative densities, D_r equal to 50% is 22.8 mm. At load correspond to FS_{raft} equal to 3.0, the corresponding piled-raft group settlement are 2.5 mm, 1.3 mm, and 1.4 mm. It is obvious that the piled-raft groups have a significantly lower settlement than the raft settlement. This reduction in settlement can be attributed to the presence of piles in a piled-raft group. The piled-raft group settlements at three values of FS_{raft}, at both pile group configuration (2×2 and 3×3 piled-raft groups), and at both relative densities of sand (D_r = 50% and D_r = 80%) are lower than 5 mm, and the values differ by only about 1 to 2 mm. Thus, the addition of piles to a raft reduce the settlement significantly as compared to the raft settlement at the same load but the addition of more piles (from 4 piles to 9 piles) did not result in a further significant reduction. The role of piles to reduce settlement is also shown to be independent of the relative density of sand.

The above discussion shows that in a piled-raft group, the presence of piles causes a lower settlement in the piled-raft group as compared to the settlement of the raft. At the same time, the presence of piles increases the ultimate bearing capacity of the piled-raft as compared to the ultimate bearing capacity of raft. Therefore, an optimum condition for a piled-raft group occurs when the settlement of the piled-raft group is significantly smaller than the settlement of the raft, and the ultimate bearing capacity of the piled-raft group is close to the ultimate bearing capacity of the raft. Based on this condition, a hypothetical optimum piled-raft group in terms of settlement reduction behaviour for a raft and ultimate bearing capacity is shown in Figure 12. Considering the optimum piled-raft group shown in this figure piled-raft group 2×2 in sand with D_r equal to 80% (Test 1) seems more efficient to serve as a settlement reducer compared to the other two piled-raft groups (Tests 2 and 3). It has smaller settlement compared to the raft settlement, and it has bearing capacity ratio closest to one compared to other piled-raft groups investigated in this study.

Table 3 indicates the presence of piles causes an increase of the bearing capacity of group piled-raft compared to the bearing capacity of raft. This increase is quantified in the bearing capacity ratio parameter (the sixth column of Table 3). Test 1 has the bearing capacity ratio closest to one. The piled-raft groups that have bearing capacity ratio much larger than one (e. g. Tests 2 in 3 in Table 3), can be seen from different points of view. For these piled-raft groups, the presence of raft provides an additional bearing capacity to the pile group. In other words, for the piled-raft group that has a bearing capacity ratio much larger than one, instead of considering the presence of piles functions to reduce settlement it is more appropriate to consider the presence of raft to provide an additional bearing capacity to the pile group.

From the above discussion, it can be concluded that in terms of bearing capacity and settlement, there are two types of piled-raft group. The first type of piled-raft group is the piled-raft group that has a bearing capacity ratio close to one. It is more appropriate to quantify this type of piled-raft group in terms of settlement. Thus, the presence of piles in a piled-raft group reduces the settlement of raft without piles. This condition applies when the soil below the raft has high bearing capacity (such as a dense sand). The second type of piled-raft group is the piled-raft group that has a bearing capacity ratio much larger than one. It is more appropriate to quantify this type of piled-raft group in terms of bearing capacity. In this type of piled-raft group, the presence of raft provides an additional bearing capacity to the pile group.

Experimental results presented in this paper can be used in the numerical analysis to study piled-raft foundation behavior numerically. Load vs. settlement curves of piled-raft group, pile group and raft indicates the load transfer between pile group and raft in a piled-raft group. The load transfer is influenced by the pile and raft stiffness used in the experiment.

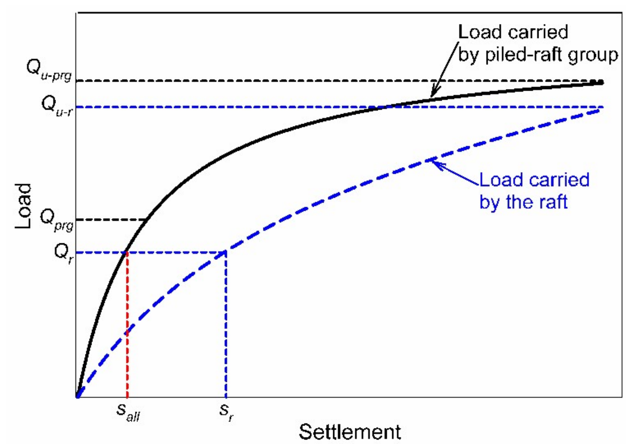


Figure 12 Hypothetical optimum piled-raft group in terms of settlement reduction behaviour for a raft and ultimate bearing capacity

The loading tests in this study were performed in a 1 g condition. Scaling factors are needed to convert the dimension, the stress, and the force of the small-scale piled-raft group foundation model to a full-scale piled-raft group foundation prototype (Altaee and Fellenius, 1994). The scaling factors for length, stress, force and void ratio are n, N, nN^2, and

$$e_m = e_p + \lambda \ln(N) \quad , \tag{3}$$

respectively; where n is the geometric scale ratio from the small-scale piled-raft group foundation model to the full-scale piled-raft group foundation prototype; e_m is the void ratio of soil at the small-scale model; e_p is the void ratio of the soil at the full-scale prototype; λ is the critical state line (CSL) slope; N is the stress scale ratio (Altaee and Fellenius, 1994; Fellenius and Altaee, 1994; Sedran et al., 2001).

The CSL slope, λ (calculated using the method of Schofield and Wroth, 1968) calculated from the test results (Sengara et al., 1997) are 6.67×10^{-3} and 3.51×10^{-3} for sand with D_r equal to 50% and 80%, respectively. A stress scale ratio, N equal to 3 was used in this study. This value is the ratio of effective stress at the top, the mid, and the bottom of pile of the small-scale piled-raft group foundation model and those of the full-scale piled-raft foundation prototype with geometric ratio, n equal to 3 (i.e. the full-scale foundation prototype length is three times the small-scale foundation model). Using Eq. (3), it was obtained that the void ratio of the sand with D_r equal to 50% (e = 1.19) and 80% (e = 1.02) used in the small-scale piled-raft foundation (this study) correspond to the void ratio of 1.18 and 1.02, respectively for the sand in a full-scale piled-raft foundation. Void-ratios of 1.18 and 1.02 are close to the void ratios of the sand used in this study. In addition, with such values of CSL slope, λ ,the void ratio of the soil at the full-scale prototype, e_p is not sensitive to the change of the stress scale ratio, N. Therefore, the results obtained from this study can be used for most of the sand relative density encountered in a full-scale piled-raft foundation.

4. CONCLUSIONS

The piled-raft group ultimate bearing capacity is higher than the raft ultimate bearing capacity. The difference in the ultimate bearing capacities between the piled-raft group and the raft can be attributed to the presence of piles. In addition, an increase in number of pile causes an increase in the ultimate bearing capacity of piled-raft group of the sand with the same density. In this study, the increase in bearing capacity of the piled-raft group compared to the raft is quantified in the *bearing capacity ratio* parameter. The closer *bearing capacity ratio* parameter to one, the smaller the increase in bearing capacity of the piled-raft group compared to the raft

It is clear that the presence of 2×2 and 3×3 piled-raft group reduces the settlement significantly. In this study, the presence of piles reduce the settlement from above 15 mm (at FS_{raft} equal to 2.0) to less than 5 mm. An increase in number of piles reduces the piled-raft group settlement significantly compared to the raft settlement.

A scaling analysis indicated that the experimental results of the small-scale model presented in this study were comparable to a full-scale piled-raft foundation. Therefore, the results of this study can be used in the numerical analysis to analyze piled-raft foundation behavior numerically.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Altaee, A. and Fellenius, B. H. (1994) "Physical modeling in sand", Canadian Geotechnical Journal, Vol. 31, No. 3, pp. 420-431.

ASTM (1998) Annual Book of ASTM Standards, Vol. 04.08 (Philadelphia, PA).

Berdugo, Y. O. (1966) "An experimental study on the load distribution in pile groups in sand", Canadian Geotechnical Journal, Vol. 3, No. 3, pp. 145-166.

Brown, P. T. and Wiesner, T. J. (1975) "The behavior of uniformly loaded piled strip footings", Soils and Foundations, Vol. 15, No. 4, pp. 13-21.

Brown, P. T., Poulos, H. G., and Wiesner, T. J. (1975) "Piled raft foundation design", Proceedings of Symposium on Raft Foundations CSIRO, Australia, pp. 13-21.

Butterfield, R. and Banerjee, P. K. (1971a) "The elastic analysis of compressible piles and pile groups", Géotechnique, Vol. 21, No. 1, pp. 43-60.

Butterfield, R. and Banerjee, P. K. (1971b) "The problem of pile group-pile cap interaction", Géotechnique, Vol. 22, No. 1, pp. 135-142.

Chin, F. K. (1978) "Diagnosis of pile condition", Geotechnical Engineering, Vol. 9, pp.85-104.

Clancy, P., and Randolph, M. F. (1993) "An approximate analysis procedure for piled raft foundations", International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 17, pp. 849-869.

Coduto, P. D. (1994) Foundation Design, Principles and Practices, Prentice-Hall, New Jersey, 796 p.

Davis, E. H., and Poulos, H. G. (1972) "The analysis of pile-raft systems", Australian Geomechanics Journal, Vol. G2, No. 1, pp. 21-27.

Desai, C. S., Johnson, L. D., and Hargett, C. M. (1974) "Analysis of pile supported gravity lock", Journal of Geotechnical Engineering Division ASCE, Vol. 100, No. GT9, pp. 1009-1029.

European Committee for Standardization (1994) Basis Design and Actions on Structures, Eurocode 1, Brussels, Belgium.

Hain, S. J. (1975) "Analysis of rafts and raft pile foundations", Proceedings of Symposium in Soil Mechanics: Recent Developments, University of New South Wales, Australia, pp. 213-254.

Holtz, R. D., Kovacs, W. D., and Sheahan, T. C. (2011) An Introduction to Geotechnical Engineering Second Edition, Pearson, New Jersey, 863 p.

Hooper, J. A. (1973) "Observations on the behavior of a piled raft foundation on London clay", Proceedings of Proceedings of the Institution of Civil Engineers, Part 2, Vol. 55, pp. 855-877.

Lambe, L. T. and Whitman, R. V (1969) Soil Mechanics, John Wiley and Sons, New York, 553 p.

Long, D. C. (2016) "Prediction of piled raft foundation settlement – a case study", Geotechnical Engineering Journal SEAGS & AGSSEA, Vol. 47, No. 1, pp. 1-6.

Long, P. D. (2011) "Piled raft - New foundation philosophy for high rise buildings", Proceedings of 1st International Conference Geotechnics for Sustainable Development - Geotec Hanoi 2011, pp. 267-276.

Nguyen, D. D. C., Jo, S-B., and Kim, D. S. (2013) "Design method of piled-raft foundations under vertical load considering interaction effects", Computers and Geotechnics, Vol. 47, DOI: http://dx.doi.org/10.1016/j.compgeo.2012.06.007.

Poulos, H. G. (1993) "An approximate numerical analysis of piled raft interaction", International Journal for Numerical and Analytical Methods in Geo Mechanics, Vol. 18, pp. 73-92.

Poulos, H. G. and Davis, E. H. (1974) Elastic Solutions for Soil and Rock Mechanics, Wiley, New York, 411 p.

Poulos, H. G. and Davis, E. H. (1980) Pile Foundation Analysis and Design, John Wiley and Sons, New York, 397 p.

Poulos, H. G. and Mattes, N. S. (1971) "Settlement and load distribution analysis of pile groups", Australian Geomechanics Journal, Vol. G1, No. 1, pp. 18-28.

Schofield, A. and Wroth, P. (1968) Critical State Soil Mechanics, McGraw-Hill, London.

Sengara, IW. (1992) Finite Element and Experimental Study of Soil-Structure Interface, Ph.D. Dissertation, University of Wisconsin Madison, Department of Civil and Environmental Engineering.

Sengara, IW. (1997) "FE analysis and field load test performance of drilled shaft for 52-story tower foundation design", Proceedings of 3YGEC, Singapore, pp. 295-304.

Sengara, IW., Jayaputra, A. A., Hutapea, B. M., Roesyanto (1997) Experimental and Elasto-Plastic Finite Element Studies for Integrated Analysis of Soil-Structure Interaction in Sand and Clay, Research Report, Graduate Team Research Grant, Directorate General of Higher Education Indonesia (in Indonesian).

Ta, L. D. and Small, J. C. (1996) "Analysis of piled raft systems in layered soils", International Journal for Numerical and Analytical Methods in Geo Mechanics, Vol. 20, pp. 57-72.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996) Soil Mechanics in Engineering Practice Third Edition, John Wiley and Sons, New York, 549 p.

Zeevaert, L. (1957) Foundation design and behaviour of Tower Latino Americana in Mexico City, Géotechnique, Vol. 7, No. 1, pp. 115-133.