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Behavior of raft on settlement reducing piles: Experimental model study

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ABSTRACT

An experimental program is conducted on model piled rafts in sand soil. The experimental program is aimed to investigate the behavior of raft on settlement reducing piles. The testing program includes tests on models of single pile, unpiled rafts and rafts on 1, 4, 9, or 16 piles. The model piles beneath the rafts are closed ended displacement piles installed by driving. Three lengths of piles are used in the experiments to represent slenderness ratio, *L/D*, of 20, 30 and 50, respectively. The dimensions of the model rafts are 30 cm × 30 cm with different thickness of 0.5 cm, 1.0 cm or 1.5 cm. The raft-soil stiffness ratios of the model rafts ranging from 0.39 to 10.56 cover flexible to very stiff rafts. The improvement in the ultimate bearing capacity is represented by the load improvement ratio, *LIR*, and the reductions in average settlement and differential settlement are represented by the settlement ratio, *SR*, and the differential settlement ratio, *DSR*, respectively. The effects of the number of settlement reducing piles, raft relative stiffness, and the slenderness ratio of piles on the load improvement ratio, settlement ratio and differential settlement ratio are presented and discussed. The results of the tests show the effectiveness of using piles as settlement reduction measure with the rafts. As the number of settlement reducing piles increases, the load improvement ratio increases and the differential settlement ratio decreases.

1. Introduction

Piles can be used with a raft foundation in order to provide adequate bearing capacity or to reduce settlements to an acceptable level. The common design of piled raft is based on the assumption that the total load of the superstructure is supported by the piles, ignoring the bearing contribution of the raft. This results in a conservative estimate of the foundation performance, and therefore an overdesign of the foundation. A different approach, involving the use of piles as settlement reducers, has been reported by Randolph (1994), Burland (1995), Sanctis et al. (2002), and Fioravante et al. (2008). The basic concept of this approach is that the foundation comprises only a number of piles that are necessary to reduce settlements to a tolerable amount and the loads from the structure are transmitted, via a raft, in part to the piles and in part to the foundation soil (load shared between the raft and piles). This approach allows the piled raft design to be optimized and the number of piles to be significantly reduced.

Fig. 1 shows schematically the principles behind the design of piles to reduce differential settlement. Assuming that the structural load is relatively uniformly distributed over the area of the raft, and then there will be a tendency for unpiled raft to dish in the center. A few piles, added beneath the central area of the raft and probably loaded to about their ultimate capacity, will reduce central settlement, and thus minimize differential settlement. However, a relatively small number of piles could raise the problems of high bending moments and cracking in the raft and a concentration of axial stresses in the pile heads (Wong et al., 2000).

Many researchers have conducted numerical analysis of piled rafts (e.g. Russo and Viggiani, 1998; Horikoshi and Randolph, 1999; Poulos, 2001; Viggiani, 2001; Mandolini, 2003; Randolph, 2003; Randolph et al., 2004; Badelow et al., 2006; Sanctis and Mandolini, 2006; Sanctis and Russo, 2008). But only limited information is available in the open literature on the experimental data of piled rafts (e.g. Horikoshi et al., 2003; Lee and Chung, 2005; Bajad and Sahu, 2008; Fioravante et al., 2008; Phung, 2010). The experimental data are helpful in verifying the results of numerical analysis of piled rafts.

Horikoshi et al. (2003) investigated the load-settlement behavior and the load sharing between the piles and the raft in the

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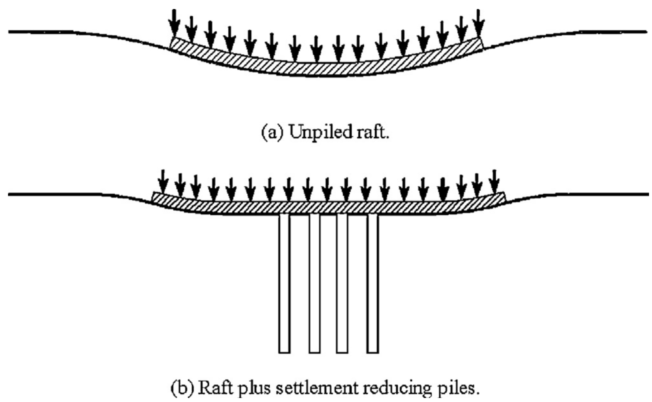

Fig. 1. Central piles to reduce differential settlement.

piled-raft system through a series of static loading tests (vertically and horizontally) on piled raft models in sand by using a geotechnical centrifuge. Lee and Chung (2005) pointed out that for a proper pile group design, factors such as the interaction among piles, the interaction between cap and piles, and the influence of pile installation method all need to be considered. Lee and Chung (2005) studied the effect of these factors on the performance of pile groups in sand soil through model tests on single pile, single-loaded center piles in groups, unpiled footing, free standing pile groups, and piled footings. Bajad and Sahu (2008) investigated the effect of pile length and number of piles on load sharing and settlement reduction behavior of piled rafts resting on soft clay through 1 g model tests on piled rafts (i.e. 10 cm × 10 cm raft with different thickness on four (2 × 2), nine (3 × 3), and sixteen (4 × 4) piles). Fioravante et al. (2008) investigated the behavior of rafts on settlement reducing piles through a centrifuge model test on rigid circular piled rafts resting on a bed of loose and very fine silica sand. The testing program included an unpiled raft, rafts on 1, 3, 7 or 13 piles. Phung (2010) presented the data of three extensive series of large-scale field model tests performed on piled footings in non-cohesive soil in order to clarify the overall cap-soil-pile interaction and the load settlement behavior of piled footing. All the pile groups were square and consisted of five piles (i.e. one center and four corner piles).

In this paper, the behavior of piled raft (i.e. raft with a limited number of piles beneath the central raft area called settlement reducing piles) is investigated through model tests on piled raft in loose sand. Model tests on single pile and unpiled raft are also carried out for the purpose of comparison.

2. Experimental program

A series of laboratory tests were performed on models of single pile, unpiled raft and central piled raft (i.e. raft on settlement reducing piles). The experimental program consists of forty tests. One test was carried out on single pile, three tests were carried out on unpiled rafts and thirty six tests were carried out on central piled rafts. Tests on unpiled raft and central piled raft are presented in Table 1. The piles configurations and model rafts dimensions of the studied cases of central piled rafts are shown in Fig. 2. The dimensions of the test mold and model rafts were selected to ensure no effect of the boundary walls on the stresses in the soil, and the height of the soil was selected 2 times greater than the maximum pile length to ensure insignificant effect of a rigid base on the behavior of piles (Horikoshi and Randolph, 1999).

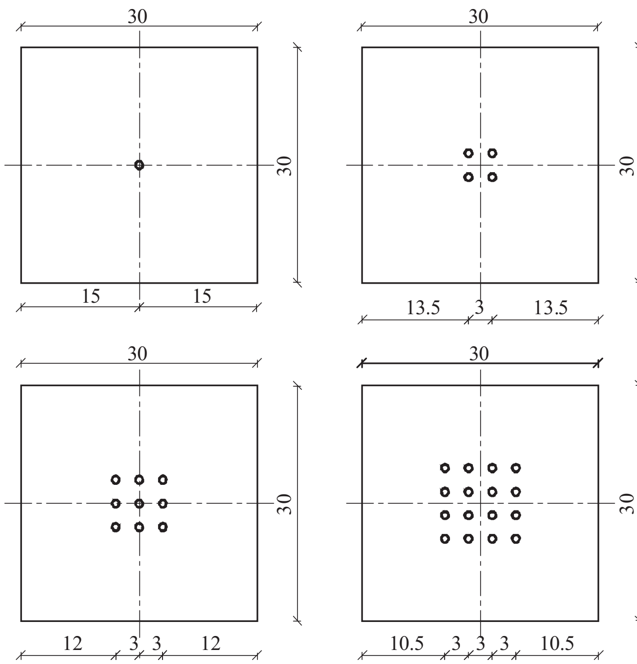

Fig. 2. Studied cases of central piled rafts (unit: cm).

2.1. Tested soil

Dry sand was used as foundation soil in this study. Sieve analysis tests were carried out on three random samples to determine the grain size distribution curve of the tested soil. The grain size distribution curve parameters are: D_{10} = 0.30 mm, D_{30} = 0.45 mm, D_{60} = 0.60 mm, C_u (coefficient of uniformity) = 2.0, and C_c (coefficient of curvature) = 1.125. According to the Unified Soil Classification System (USCS), the tested soil is classified as poorly graded sand, SP. The direct shear tests were carried out on four samples to determine the angle of internal friction of the tested sand. The sand is poured in the direct shear test mold on layers to give a unit weight of 15.5 kN/m^3. The angle of internal friction is determined to be 33°.

2.2. Model of rafts and piles

Three square steel plates, with different thickness, served as model rafts. The dimensions of the rafts were 30 cm × 30 cm × 0.5 cm, 30 cm × 30 cm × 1.0 cm, and 30 cm × 30 cm × 1.5 cm, respectively. The modulus of elasticity and Poisson's ratio of the steel plates were 2.1 × 10^8 kPa and 0.20, respectively. The model piles used in the experiments were steel hollow pipes of 10 mm in outside diameter and 1.5 mm in wall thickness. The modulus of elasticity and Poisson's ratio of the steel pipe were 2.1 × 10^8 kPa and 0.20, respectively, as determined from the data sheet of the technical department of the manufactured company. The embedded pile lengths of 200 mm, 300 mm, and 500 mm were used in the experiments. These lengths represent L/D ratios of 20, 30, and 50, respectively. Top head of each pile was provided with a bolt of 10 mm in diameter and 40 mm long to connect the pile to the cap through two nuts to ensure a complete fixation between the pile and the cap. In addition, the pile tip was provided with a steel conical shoe to facilitate the pile driving, as shown in Fig. 3.

Table 1
Summary of the model tests on unpiled and piled rafts.

Studied cases	Raft model dim. (cm × cm × cm)	No. of piles	L/D	S/D	No. of tests
Unpiled raft	30 × 30 × 0.5	–	–	–	3
	30 × 30 × 1.0	–	–	–	
	30 × 30 × 1.5	–	–	–	
Raft +1 central pile	30 × 30 × 0.5	1	50	–	3
		1	30	–	
		1	20	–	
	30 × 30 × 1.0	1	50	–	3
		1	30	–	
		1	20	–	
	30 × 30 × 1.5	1	50	–	3
		1	30	–	
		1	20	–	
Raft +4 central piles	30 × 30 × 0.5	4	50	3	3
		4	30	3	
		4	20	3	
	30 × 30 × 1.0	4	50	3	3
		4	30	3	
		4	20	3	
	30 × 30 × 1.5	4	50	3	3
		4	30	3	
		4	20	3	
Raft +9 central piles	30 × 30 × 0.5	9	50	3	3
		9	30	3	
		9	20	3	
	30 × 30 × 1.0	9	50	3	3
		9	30	3	
		9	20	3	
	30 × 30 × 1.5	9	50	3	3
		9	30	3	
		9	20	3	
Raft +16 central piles	30 × 30 × 0.5	16	50	3	3
		16	30	3	
		16	20	3	
	30 × 30 × 1.0	16	50	3	3
		16	30	3	
		16	20	3	
	30 × 30 × 1.5	16	50	3	3
		16	30	3	
		16	20	3	

3. Testing setup components

3.1. Steel tank and main frame

The test mold consists of a steel tank and a main frame. The steel tank rests on a movable rolling frame base. The tank was 1.0 m long, 1.0 m wide, and 1.0 m high. The tank was provided by four horizontal stiffeners (L 40 × 40) at 0, 20 cm, 50 cm, and 85 cm levels from the bottom base of the tank as shown in Fig. 4. The main frame was 150 cm in clear width, 215 cm in clear height, and consisted of two vertical columns and one horizontal beam as shown in Fig. 4.

3.2. Measuring devices

Three dial gauges of 0.01 mm accuracy were used to measure the vertical settlements. One dial gauge was located near the center and two were located at the middle sides of the raft. The dial gauges were fixed to the raft by means of steel rods. The steel rod consisted of a vertical rod connected to the horizontal beam of the main frame and a horizontal rod which carried the dial gauge. The two rods were connected to each other by hollow tubes which had two screw grooves as shown in Fig. 5. This rod system had the ability to support the dial gauge at any horizontal plane.

Loads were applied by a hydraulic jack fixed at the middle of the horizontal beam of the main frame as shown in Figs. 4 and 5. The hydraulic jack was used manually to produce the incremental load. Calibrated proving rings with different capacities were attached to the jack to measure the loads.

During tests on single pile a vertical loading bar was attached to the proving ring to produce point central vertical load. During tests on unpiled raft and central piled raft, the vertical loading bar transmitted the jack load to the tested raft model through a special loading cap. The loading cap was composed of a square steel plate, of dimensions 30 cm × 30 cm × 2 cm, supported by nine steel columns. Each column was 2.54 cm in diameter and 26 cm in height. The central spacing between columns was 10 cm as shown in Fig. 5.

4. Test procedures

(1) Each experiment started with placing the sand soil in the steel tank in layers. The maximum layer thickness was 10 cm. The total height of the tank was divided into intervals from the inner side by making signs every 10 cm height to help to put a specified weight in a specified volume to get the required sand density by compaction. A pre-weighted quantity of sand was compacted by means of a specified compaction tool in the steel tank. The compaction continued until the soil was compacted to fill the first 10 cm layer. A steel arm with circular plate of

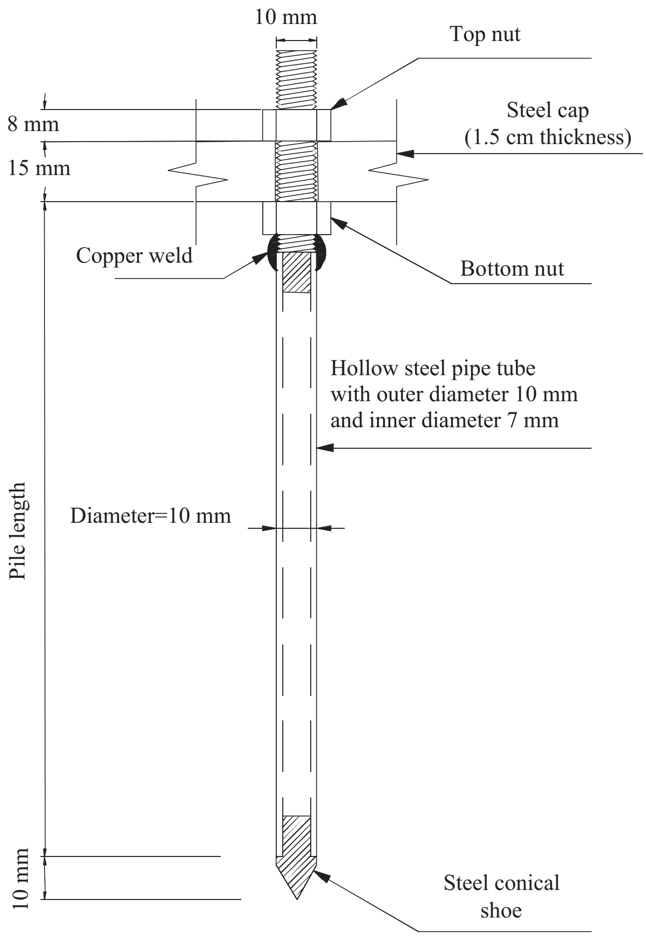

Fig. 3. Connection between the pile and the cap.

15 cm in diameter and 0.8 cm in thickness was used for compaction. The process was repeated until reaching the height of the steel tank (i.e. 95 cm). The final soil layer was 5 cm thick to avoid soil overflowing during the compaction process.

(2) For the cases of central piled raft, wooden templates were used to locate the piles in the correct positions, and then each pile was inserted vertically into the sand by driving with a steady succession of bellows on the top of the pile using a steel hammer weighting 2 kg. The inclinations of the piles were checked carefully by a level during driving. The sequence of piles installation started with the inner piles, then corner piles, and finally the edges piles.

(3) After the installation of piles to the required depth, the wooden templates were removed. Then, the raft model was placed on the sand surface and the horizontality of the raft model was adjusted by a level and each pile was connected to the raft model by two nuts.

(4) The loading cap was placed on the raft. Then, three dial gauges were located (one dial gauge near the center and two at the middle sides of the raft).

(5) A vertical loading bar and a calibrated proving ring, of 50 kN maximum capacity, were connected to the hydraulic jack. The jack arm was lowered slowly toward the loading cap, until the dial gauge of the proving ring started to respond. The raft model was then loaded incrementally by using the hydraulic jack. The vertical settlements were recorded at the end of each load increment. The rate of loading was 0.1 kN/min. The loading was continued till the settlement reached about 25 mm.

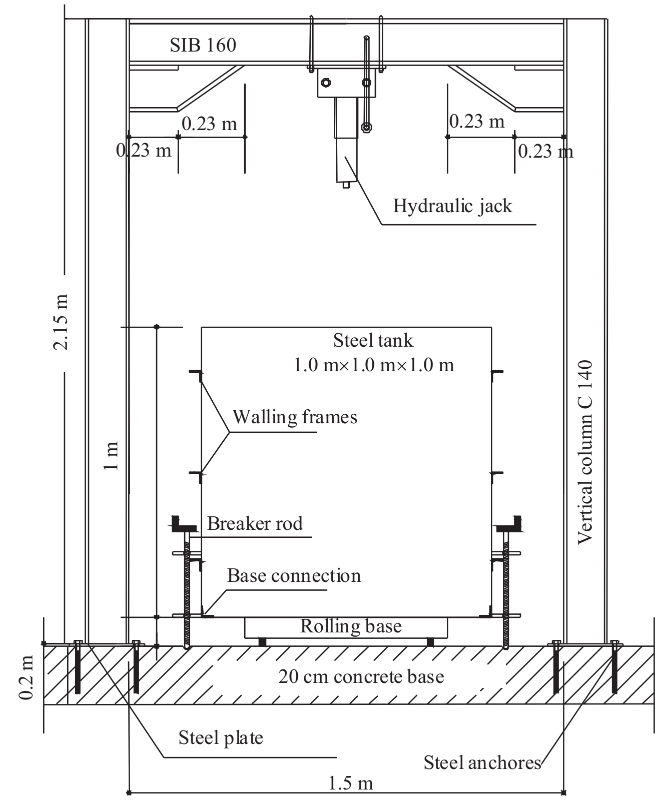

Fig. 4. Vertical cross section in the steel tank and main frame.

5. Raft-soil stiffness ratio

The shear modulus of the tested sand soil was determined from back analysis of the measured load-settlement curves for single pile with *L*/*D* ratio of 50. The shear modulus of sand soil was assumed to change linearly with the depth from 300 kPa at the ground surface (i.e. beneath the model raft) to G_l at the end of the pile length. The computer program PGROUP developed by El-Garhy (2002) was used to predict the elastic load-settlement curve of single pile at different values of G_l. The best match between measured and predicted values was obtained at the value of G_l equal to 500 kPa. Therefore, the value of shear modulus, G, in kPa at any depth, z,

Fig. 5. Photograph showing loading cap and measuring devices.

Table 2
Raft-soil stiffness ratios, K_{rs}, for tested raft models.

Raft model dimensions (cm × cm × cm)	K_{rs}	Flexibility of raft
30 × 30 × 0.50	0.39	Flexible
30 × 30 × 1.0	3.13	Stiff
30 × 30 × 1.50	10.56	Very stiff

below the ground surface can be determined from the following linear equation:

$$G = 300 + 400z \quad (1)$$

Poisson's ratio of the tested sand soil was taken as 0.30 as recommended by Bowles (2001). The modulus of elasticity of the tested soil, E_s, can be calculated from the soil shear modulus and Poisson's ratio:

$$E_s = 2G(1 + \nu_s) \quad (2)$$

The relative flexibility of a raft is expressed by the raft-soil stiffness ratio, K_{rs}, proposed by Hain and Lee (1978):

$$K_{rs} = \frac{4}{3\pi}\frac{E_r(1-\nu_s^2)}{E_s}\frac{B}{L}\left(\frac{t_r}{L}\right)^3 \quad (3)$$

where B and L are the width and length of the raft, respectively; and t_r is the raft thickness. The values of K_{rs} ranging from 0.01 to 10 cover very flexible to very stiff rafts (Hain and Lee, 1978). The raft-soil stiffness ratios for the tested raft models were calculated by Eq. (3). In the calculation of K_{rs}, the modulus of elasticity at a depth of an equivalent circular raft radius (i.e. 17 cm) was used, as recommended by Horikoshi and Randolph (1999). The values of K_{rs} for the tested raft models are presented in Table 2.

6. Results and discussions

The experimental results obtained from the laboratory tests are analyzed and discussed in this section. The shapes of the measured load-settlement curves indicate that the load at failure was not achieved. Therefore, the allowable and the ultimate raft capacities were determined from the load-average settlements of 10 mm and 25 mm, respectively. The settlement values of 10 mm and 25 mm are considered acceptable for allowable and ultimate loads (Bowles, 2001).

6.1. Unpiled raft

The experimental load-average settlement curves for the unpiled raft models of different relative stiffness, K_{rs}, are illustrated in Fig. 6. From Fig. 6, it can be noted that the increase in raft relative stiffness causes a slight increase in the load carrying capacity of unpiled raft with a reduction in settlement (e.g. at 25 mm average settlement, the increase of raft relative stiffness from 0.39 to 3.13 causes an increase in the raft load by 5.5% and the increase of raft relative stiffness from 0.39 to 10.56 causes an increase in the raft load by 13%).

The differential settlement of a square raft is defined as the difference between settlements at the center and the mid-side points of the raft. The results of the present tests indicate that the raft with K_{rs} equal to 10.56 almost had no differential settlement. This result is expected because the raft with K_{rs} equal to 10.56 is classified as too rigid (Hain and Lee, 1978).

In this paper, the differential settlement is normalized by the average settlement of the raft. Fig. 7 shows the variation of normalized differential settlement with the relative stiffness of the raft. As expected, the normalized differential settlement decreases as the raft relative stiffness increases.

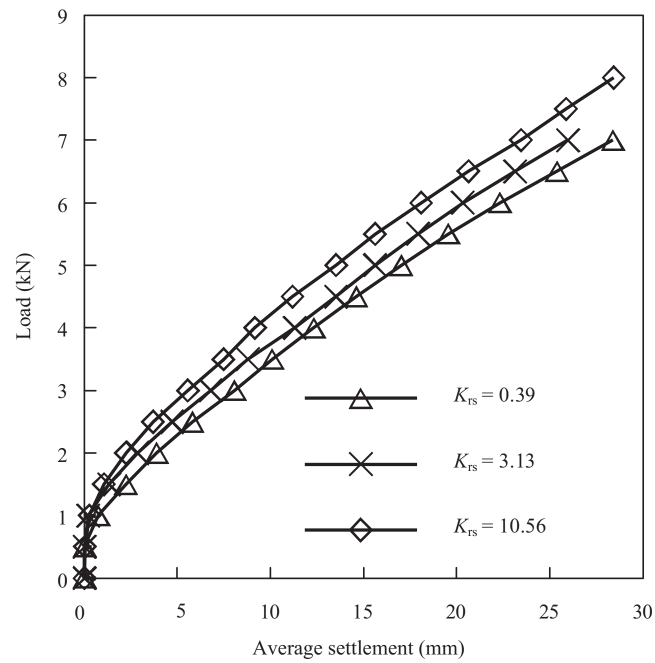

Fig. 6. Experimental load-average settlement curves for unpiled rafts.

6.2. Raft on settlement reducing piles

In the following sections, the effects of number of piles, L/D ratio, and raft relative stiffness, K_{rs}, on the behavior of raft on settlement reducing piles are analyzed and discussed.

6.2.1. Effect of number of piles

Figs. 8–16 show the load-average settlement curves for all the studied cases of unpiled rafts and rafts on settlement reducing piles. As shown in these figures, the load carrying capacity of piled raft increases as the number of settlement reducing piles increases, for all the studied cases. This increase is mainly due to the increase in the portion of load carried by the central piles due to the increase of the number of piles.

In this study, the improvement in the load capacity of the raft, at 10 mm and 25 mm settlements, due to the presence of settlement

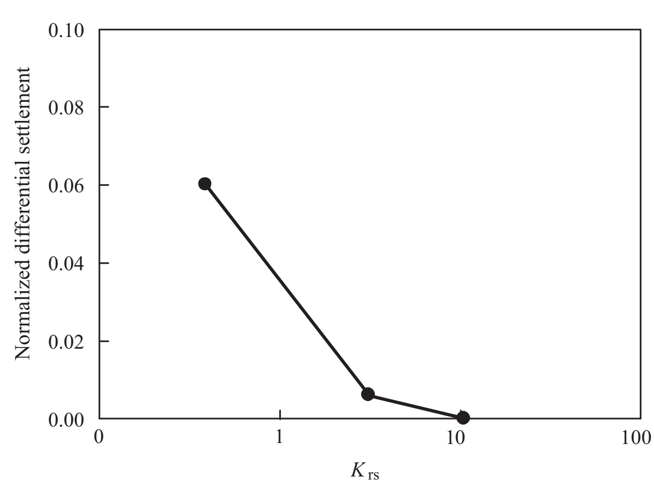

Fig. 7. Variation of normalized differential settlement with the relative stiffness for unpiled rafts.

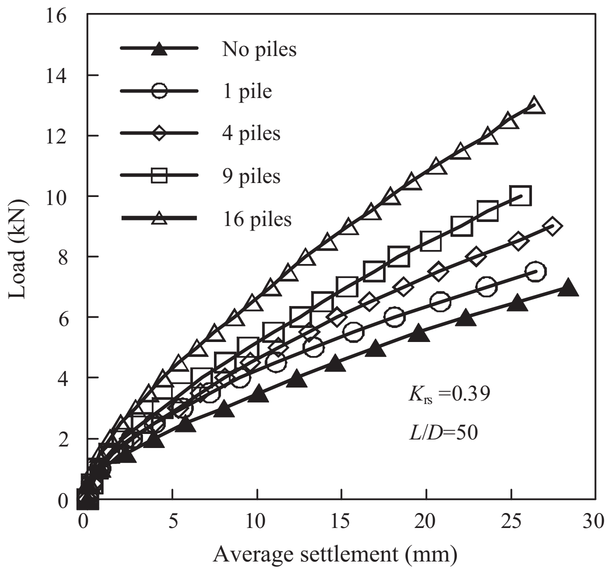

Fig. 8. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 0.39, L/D = 50).

reducing piles is represented by a non-dimensional parameter called load improvement ratio, *LIR*, as follows:

$$LIR = \frac{P_{pr}}{P_r} \tag{4}$$

where P_r and P_{pr} are the loads of unpiled raft and central piled raft at 10 mm and 25 mm settlements, respectively.

Figs. 17 and 18 show the variation of the load improvement ratio, *LIR*, with the number of settlement reducing piles at 10 mm and 25 mm settlements, respectively. From these figures, it can be noted that: (1) at the same raft relative stiffness and L/D ratio, the value of *LIR* increases as the number of piles increases (e.g. at 25 mm settlement, for raft of 0.39 relative stiffness, installing 9 settlement reducing piles with L/D = 50 causes an increase in the raft load by 55%, while installing 16 piles with the same L/D ratio increases the raft load by 95%); (2) for all the studied cases, the value of *LIR* at 10 mm settlement is greater than that at 25 mm settlement. This is clearly shown in Fig. 19 that the variation of *LIR* with the raft relative stiffness for the raft on 4, 9 and 16 settlement reducing piles with L/D ratio of 50 can be observed. A similar observation has been reported by Phung (2010) from experimental test results on piled rafts. This explains the mechanism of load sharing between raft and piles (i.e. at the beginning of central piled raft loading, the piles carry major portion of the load, and with the settlement increasing, the load is transferred to the raft).

In practice, the inverse of the load improvement ratio, 1/*LIR*, (i.e. equal to the proportion of load carried by raft) presented in this paper can be used in a preliminary design stage to estimate the load-settlement curve of piled raft as described by Poulos (2001).

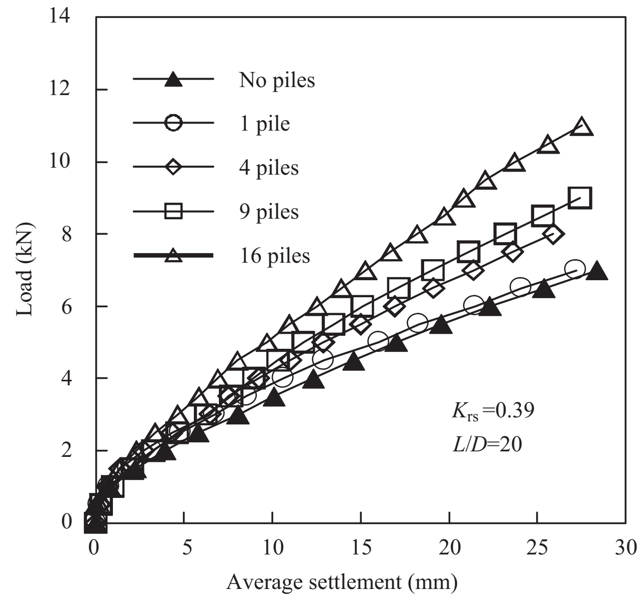

Fig. 10. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 0.39, L/D = 20).

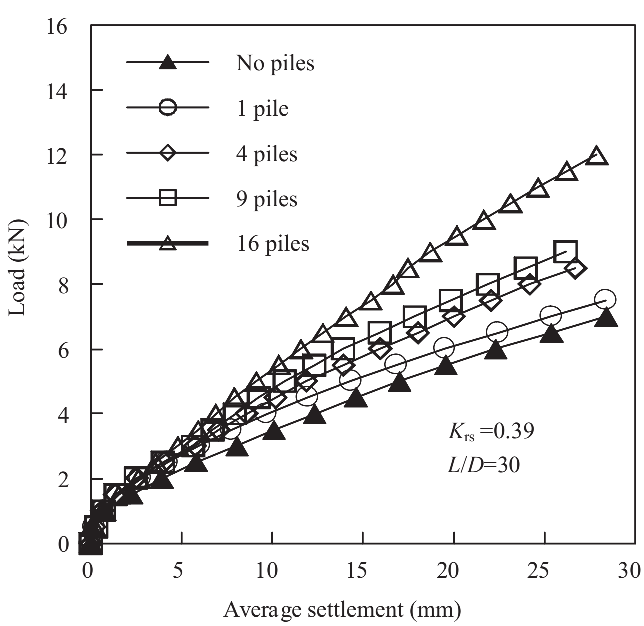

Fig. 9. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 0.39, L/D = 30).

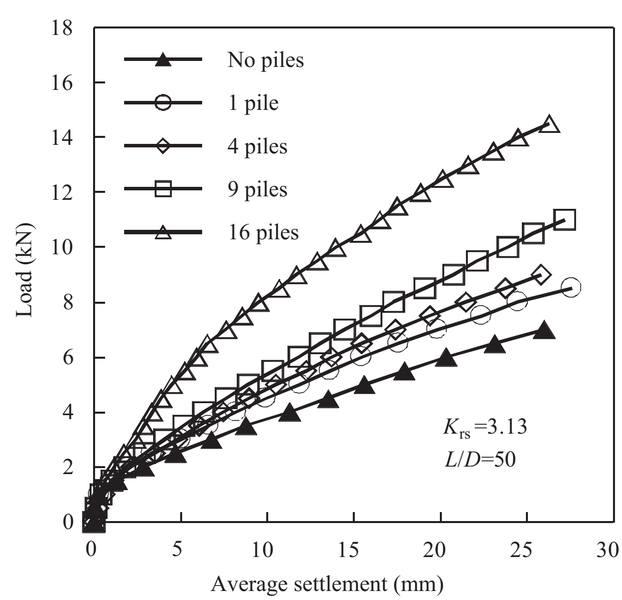

Fig. 11. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 3.13, L/D = 50).

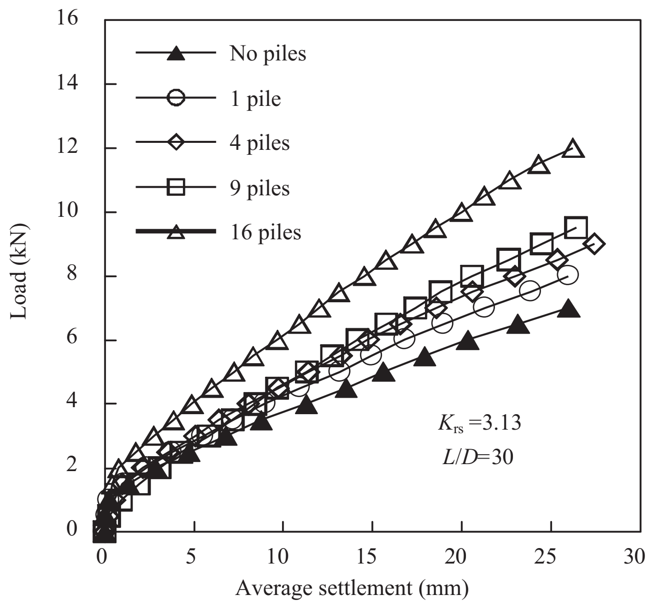

Fig. 12. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 3.13, L/D = 30).

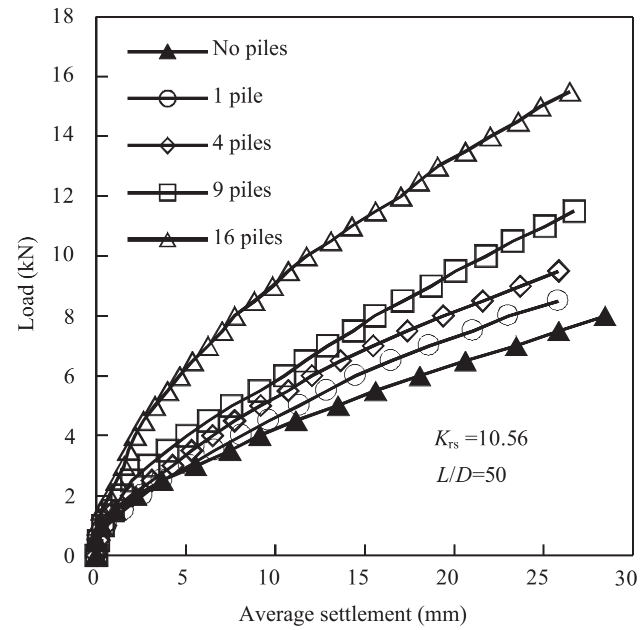

Fig. 14. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 10.56, L/D = 50).

Fig. 20 shows the variation of the proportions of loads carried by piles and raft with the number of settlement reducing piles for raft model with relative stiffness of 0.39. Similar figures can be obtained from experimental results for raft models with relative stiffness of 3.13 and 10.56 but not presented here for space limitation. The proportion of load carried by piles increases as the number of piles increases, and inversely the proportion of load carried by raft decreases as the number of piles increases as shown in Fig. 20.

In order to analyze the reduction in average and differential settlements due to the presence of piles under the central area of the raft, average and differential settlements of raft on settlement reducing piles and unpiled raft corresponding to a constant load, P (i.e. the load corresponding to 25 mm settlement for unpiled raft) are obtained for all the studied cases.

The reductions in average and differential settlements of raft due to the presence of settlement reducing piles are represented by non-dimensional factors, called settlement ratio, SR, and differential settlement ratio, DSR, as follows:

$$SR = \frac{w_{pr}}{w_r} \tag{5}$$

$$DSR = \frac{\Delta w_{pr}}{\Delta w_r} \tag{6}$$

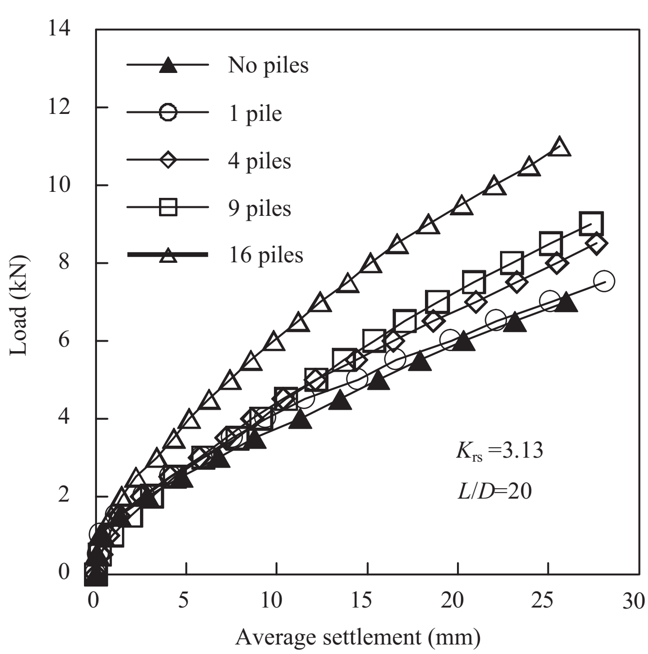

Fig. 13. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 3.13, L/D = 20).

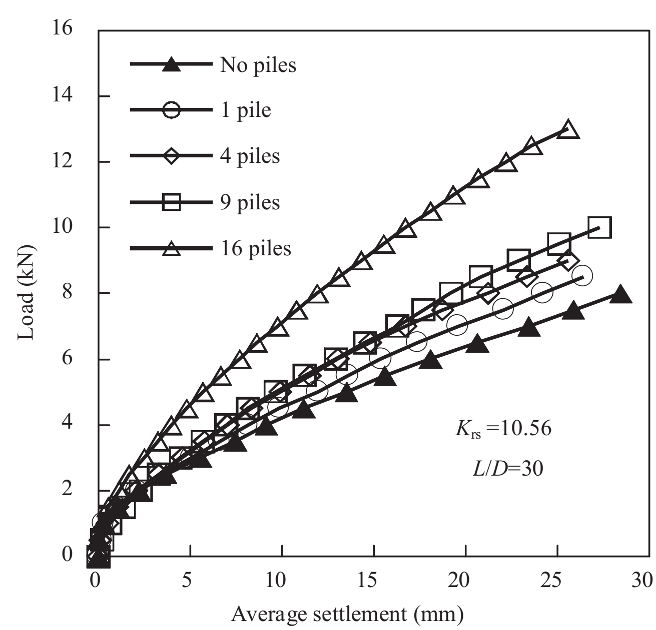

Fig. 15. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 10.56, L/D = 30).

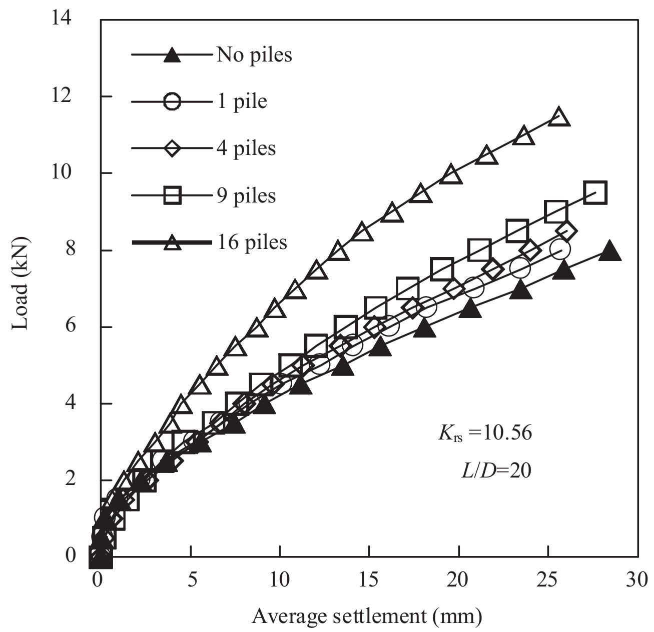

Fig. 16. Effect of number of piles on the load-average settlement curves of central piled raft (K_{rs} = 10.56, L/D = 20).

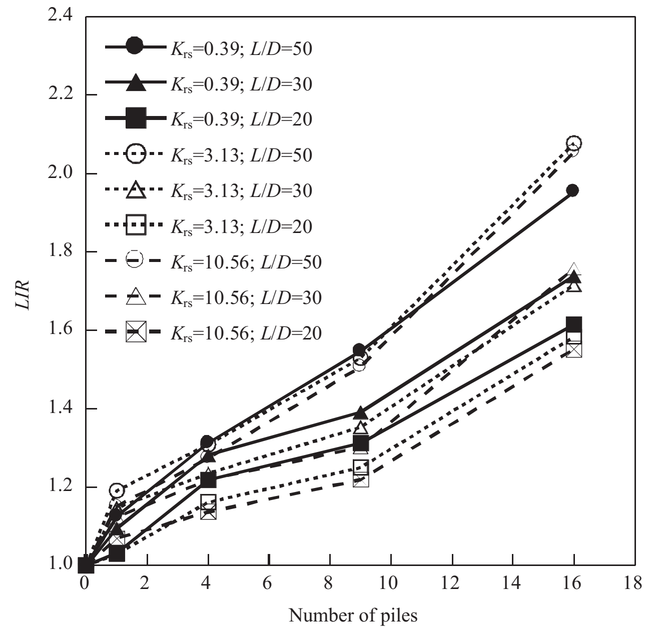

Fig. 18. Variation of load improvement ratio, *LIR*, with the number of piles at 25 mm settlement.

where w_{pr} and w_r are the average and differential settlements of piled raft and unpiled raft, respectively, at the load, *P*.

Fig. 21 shows the variation of settlement ratio, *SR*, with the number of piles for rafts with relative stiffness of 0.39, 3.13 and 10.56. In Fig. 21, it is observed that: (1) the settlement ratio decreases as the number of piles increases (e.g. for the raft with 0.39 relative stiffness, installing 9 piles with L/D = 50 causes a decrease in the average settlement of the raft by 45%, while installing 16 piles with L/D = 50 causes a decrease in the raft settlement by 60%); (2) generally, the rate of decrease of *SR* decreases as the number of settlement reducing piles increases; and (3) for a given number of piles, the settlement ratio decreases as the L/D ratio increases. This confirms the observations reported by Katzenbach et al. (1998) and Poulos (2001) from numerical analyses of raft on different numbers of settlement reducing piles.

An important relationship between the settlement ratio, *SR*, and the proportion of load taken by piles (sometimes called relative cap capacity) was introduced from case histories in Germany (Schmitt et al., 2003; El-Mossallamy et al., 2006; Phung, 2010). The results of the present tests at 25 mm settlement level are plotted on this relationship as shown in Fig. 22 and the results of the present tests match the upper limit curve of the relationship. The settlement ratio versus the relative cap capacity relationship can be

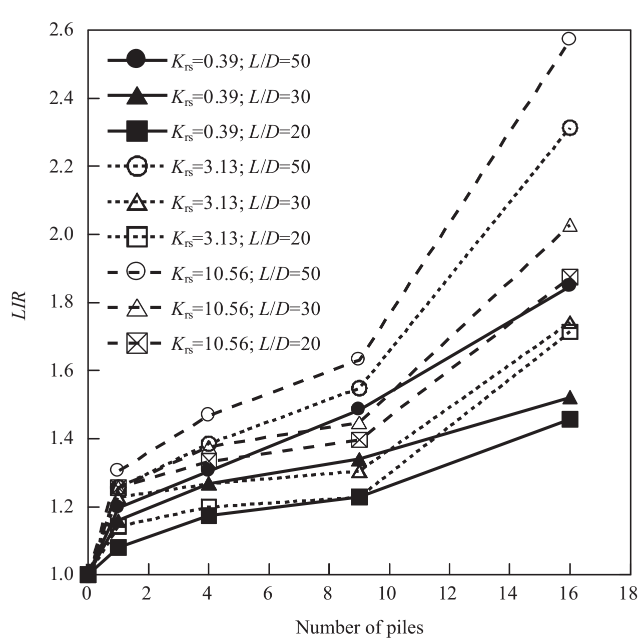

Fig. 17. Variation of load improvement ratio, *LIR*, with the number of piles at 10 mm settlement.

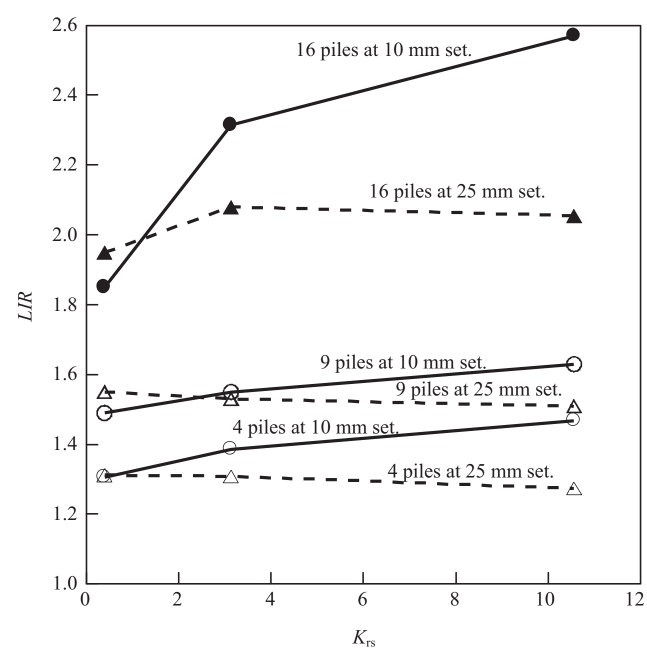

Fig. 19. Variation of load improvement ratio, *LIR*, with raft relative stiffness, K_{rs}, at 10 mm and 25 mm settlements for raft on 4, 9, and 16 piles (L/D = 50).

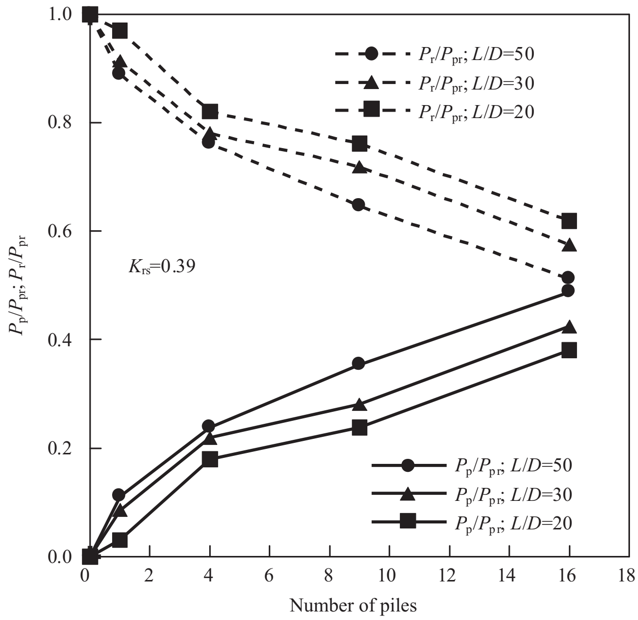

Fig. 20. Load sharing between raft and piles for central piled raft with K_{rs} equal to 0.39.

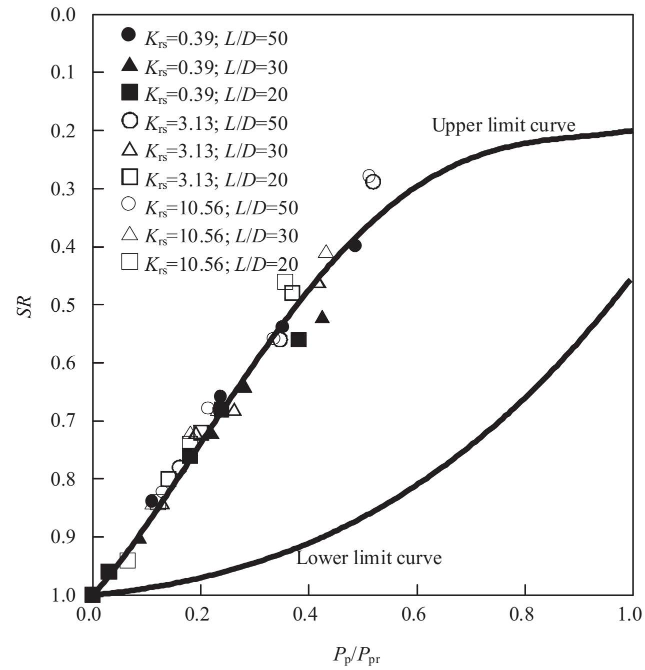

Fig. 22. Settlement ratio, *SR*, versus proportion of load carried by piles, P_p/P_{pr}, at 25 mm settlement.

used in a preliminary design of raft on settlement reducing piles (El-Mossallamy et al., 2006; Phung, 2010).

Fig. 23 shows the variation of differential settlement ratio, *DSR*, with the number of piles for rafts with relative stiffness of 0.39 and 3.13.

From Fig. 23, it is noted that the differential settlement ratio, *DSR*, decreases as the number of piles increases (e.g. for the raft with 0.39 relative stiffness, installing 9 piles with $L/D = 50$ causes a decrease in the differential settlement of the raft by 38%, while installing 16 piles with $L/D = 50$ causes a decrease in differential settlement by 50%). Also, the differential settlement ratio, *DSR*, decreases as the L/D ratio increases, for a given number of piles as shown in Fig. 23. The rate of decrease of *DSR* decreases with increasing number of settlement reducing piles. This means that the optimum performance may be achieved by a small number of piles beneath the central area of the raft instead of using a large number of piles distributed beneath the whole area of the raft.

6.2.2. Effect of raft relative stiffness

Fig. 24 shows the variation of the percentage of load taken by raft, P_r/P_{pr}, with the raft relative stiffness at different numbers of settlement reducing piles and different L/D ratios. As shown in Fig. 24, the effect of raft relative stiffness on the percentage of load

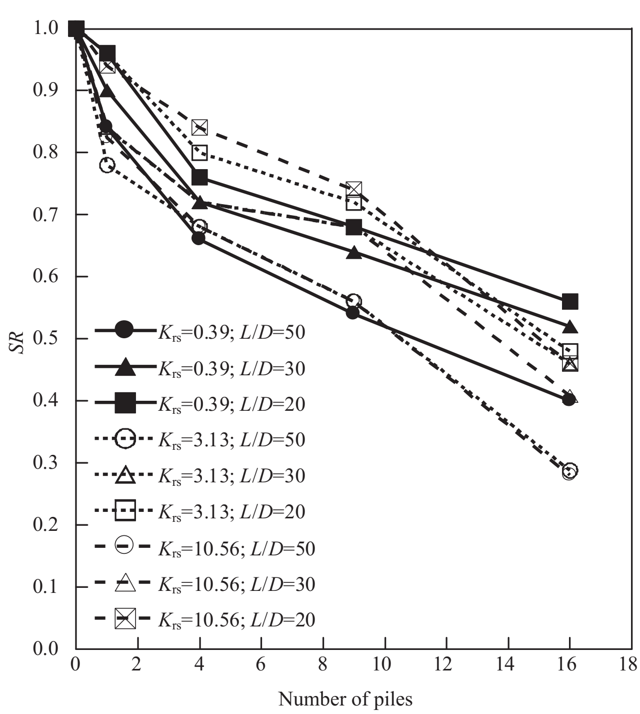

Fig. 21. Variation of settlement ratio, *SR*, with the number of piles.

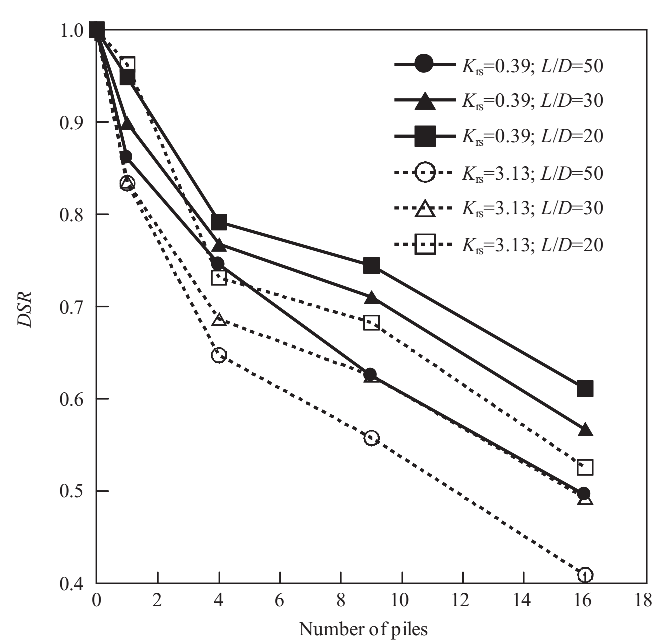

Fig. 23. Variation of differential settlement ratio, *DSR*, with the number of piles.

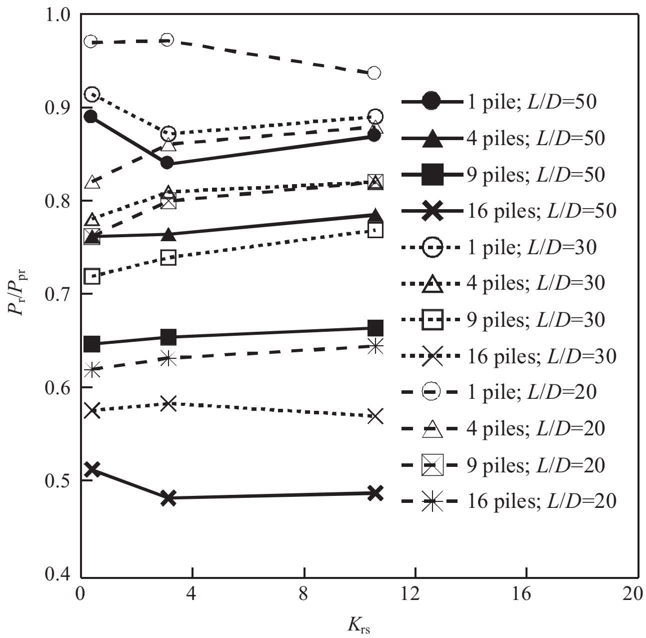

Fig. 24. Variation of the proportion of load carried by raft, P_r/P_{pr}, with raft relative stiffness, K_{rs}.

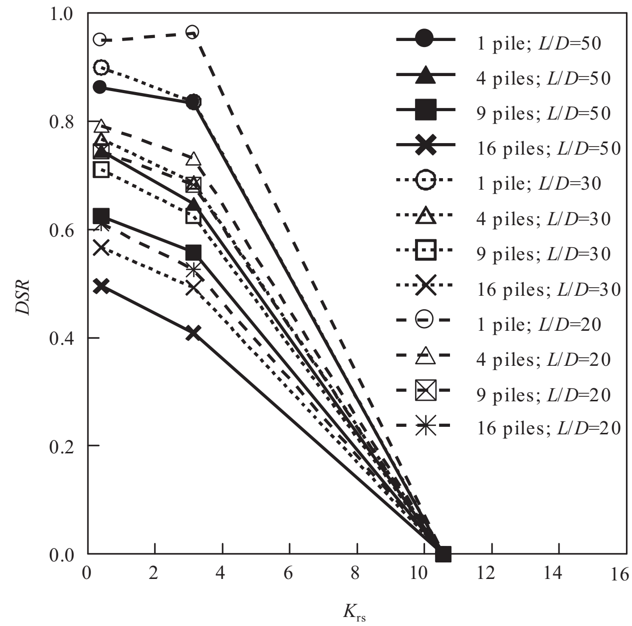

Fig. 26. Variation of differential settlement ratio, *DSR*, with the raft relative stiffness, K_{rs}.

carried by raft is insignificant. Similar observations were obtained by Poulos (2001) and Singh and Singh (2011) from numerical analyses of piled raft with different numbers of piles.

The variation of settlement ratio, *SR*, and differential settlement ratio, *DSR*, with the raft relative stiffness at different numbers of settlement reducing piles and different *L*/*D* ratios are shown in Figs. 25 and 26, respectively. From Fig. 25, it can be observed that the raft relative stiffness has little effect on the average settlement of piled raft. Inversely, as shown in Fig. 26, the raft relative stiffness has a major effect on the differential settlement. The differential settlement ratio, *DSR*, decreases with the increase of raft relative stiffness as shown in Fig. 26. At the raft relative stiffness of 10.56, the differential settlement of raft on settlement reducing piles and unpiled raft is equal to zero, and therefore, the differential settlement ratio, *DSR*, is considered equal to zero.

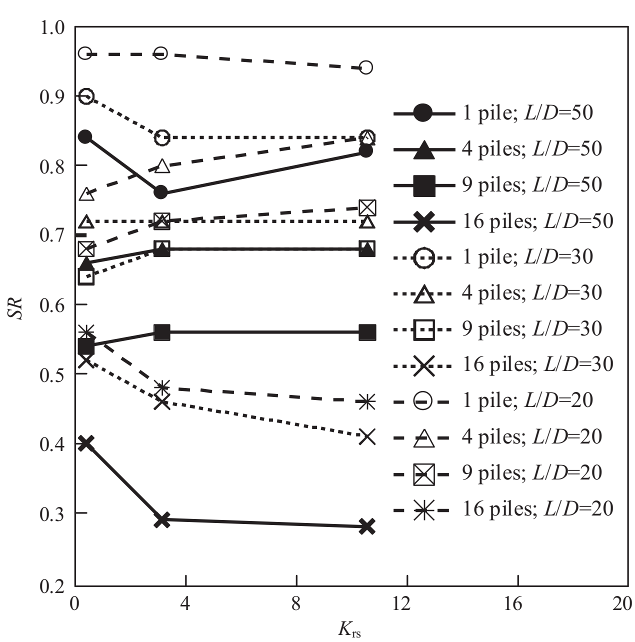

Fig. 25. Variation of settlement ratio, *SR*, with the raft relative stiffness, K_{rs}.

7. Conclusions

The paper has presented experimental results of load tests on model rafts on settlement reducing piles embedded in sand soil. Although there may be some scaling effects, the results of these model tests provide insight into settlement behavior of rafts on settlement reducing piles, and load sharing between piles and raft and may provide some general guidelines for the economical design of raft on settlement reducing piles. Based on the results of model tests, the following conclusions are drawn:

(1) The addition of even a small number of piles beneath the central area of the raft increases the load bearing capacity of the piled raft, and this enhancement effect increases as the number of piles increases and as the slenderness ratio, *L*/*D*, of the piles increases.
(2) At 10 mm and 25 mm settlements, the load improvement ratio, *LIR*, increases as the number of settlement reducing piles increases and as the *L*/*D* ratio increases.
(3) The raft relative stiffness (i.e. raft thickness) has a major effect on differential settlement, but has insignificant effect on the average settlement and the load sharing between raft and piles.

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