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Research Paper

INVESTIGATION OF THE BEHAVIOR OF PILED RAFT IN SAND: AN EXPERIMENTAL STUDY

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In order to understand the load-settlement behavior and load sharing of piled raft resting on sand soil, experimental tests on model piled raft were conducted. The parameter studied were the influence of raft size and number of piles. The testing program includes tests on models of unpiled raft and rafts on 1, 4 and 9 piles. The model piles beneath the raft are non-displacement piles. The improvement in load bearing capacity is represented by load improvement ratio, foundation stiffness and reduction in settlement is represented by settlement reduction ratio. The influence of raft size and number of piles on the load improvement ratio, foundation stiffness and settlement reduction ratio are presented and discussed. The results of this tests shows that as the number of piles increases, the load improvement ratio, foundation stiffness and settlement reduction ratio increases and as the raft size increases, the load improvement ratio, foundation stiffness and settlement reduction ratio decreases.

Keywords: Raft, Piled raft, Raft size, Sand soil, Model tests

INTRODUCTION

In the conventional pile foundation design, the load carrying capacity of pile cap is not taken into account and the piles transfers the total load to the lower foundation parts. Piled rafts were developed to utilized the capacities of both raft and piles as a more optimized and efficient foundation type with a new designing strategy (Cooke,1986; Randolph, 1994). Several examples have been reported for piled raft application in to high rise buildings and bridge foundations (Horikosh *et al.,* 1996, Katzenbach *et al.,* 2000; Poulos, 2001; Yamashita *et al.,* 2010).

The load carrying capacity of piled rafts have been studied experimentally and analytically by several researchers (Conte *et al.,* 2003, Giretti, 2010, Horikoshi, 1996, Katzenbach *et al*., 2005, Randolph, 1994). Conte *et al.* (2003) studied the effect of variation in piles and raft geometry to determine the stiffness of piled raft foundation, through centrifuge test on piled raft foundation system. The strategic placement of the piles

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underneath the central area of the raft can reduce differential settlement under uniform loading condition (Horikoshi *et al*., 1996, Reul *et al.*, 2004). The load carrying capacity and the load sharing behavior of the foundation can change depending on specific settlement level.

In this paper, the load-settlement behavior and the load sharing mechanism between the piles and raft is investigated through a model test on piled raft foundation system on sand.

MODEL TESTS

Total 12 tests were conducted in the laboratory. Three tests was carried out on unpiled raft and nine tests were carried out on piled rafts. The program of laboratory model test on unpiled raft and piled raft foundations are presented in Table 1. The pile configurations and dimensions of a model raft of piled raft are shown in Figure 1. The dimensions of model pile and raft were chosen to ensure no stress concentration at the boundary of the tank. The height of soil was two times greater than the pile length to avoid the effect of a rigid base of the soil tank on the behavior of piles (Horikoshi and Randolph, 1999).

Figure 2 shows the steel tank and test set up, which measured 500 mm deep and 850 mm x 850 mm in plan, used in the test. The piles are instrumented with strain gauges located at the pile top, just below the raft, to measure the load transmitted from the raft to the piles.

The load was transferred to model raft through loading plate, placed on the raft. Then, four LVDTs were placed two at the edge of the raft and two at the middle side of the raft, to measure vertical displacement. A calibrated

Table 1: Program of Model Tests

Test Explanation	Model Raft Dimensions (mm x mm x mm)	L/D	S/D	Number of Test Performed
Unpiled raft	110 x 110	-	-	3
	160 x 160			
	200 x 200			
Raft + 1 pile	110 x 110		-	3
	160 x 160	20		
	200 x 200			
Raft + 4 piles	110 x 110		4	3
	160 x 160	20		
	200 x 200			
Raft + 9 piles	110 x 110		4	3
	160 x 160	20		
	200 x 200			

Figure 1: Studied Cases of Piled Raft Foundation (all dimensions are in mm)

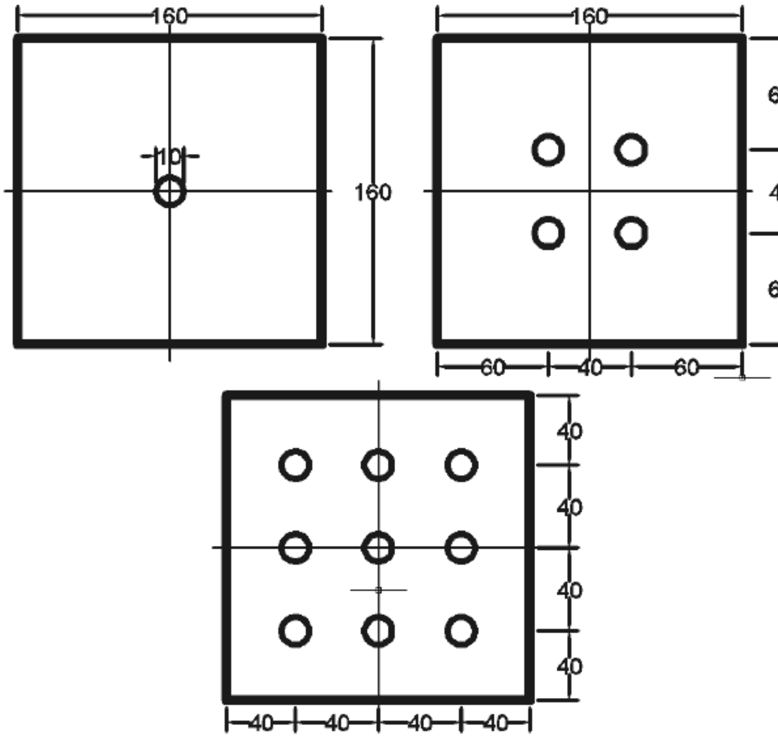
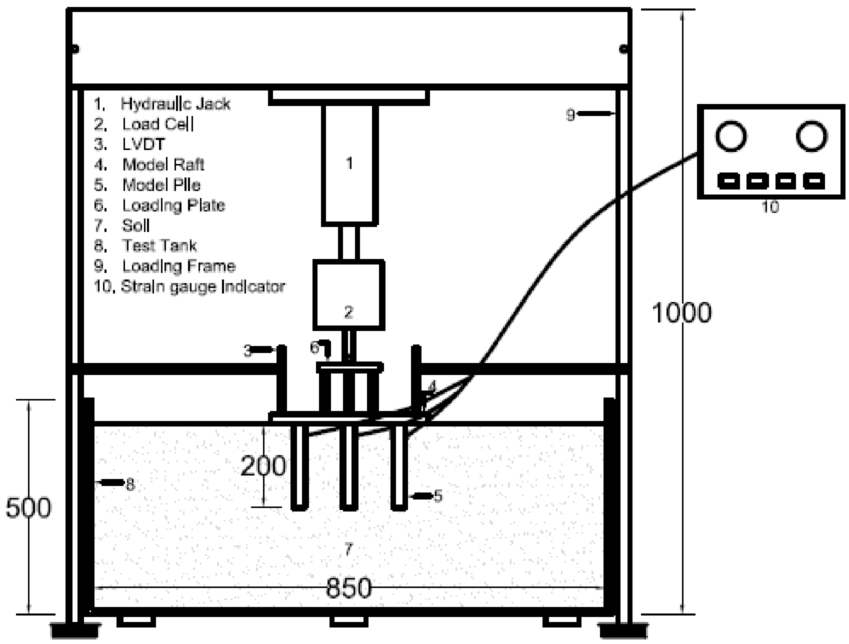


Figure 2: Model Test Set Up (all dimensions are in mm)



load cell of 25 kN capacity was connected to hydraulic jack. The model raft was loaded incrementally and at the end of each load increment vertical settlement was measured. The rate of loading was 0.1 kN/min.

The model raft was made up of mild steel plates having a square shape different dimensions with thickness of 10 mm. The model piles were made up of the mild steel of diameter 10 mm. The modulus of elasticity and Poisson's ratio of the mild steel raft and pile were 1.8 x 10^5 MPa and 0.2, respectively. To ensure rigid connection between the pile and raft, top head of each pile was provided with a bolt of 6 mm diameter and 25 mm long to connect the pile to the raft through nuts.

A clean sand was used as the foundation soil. The specific gravity of sand was found to be 2.65. The minimum and maximum dry unit weights of sand were found to be 14.40 kN/m^3 and 16.90 kN/m^3, respectively. The uniformity coefficient (C_u) and coefficient of curvature (C_c) for the sand were 1.36 and 1.03, respectively. According to the Indian standard soil classification, the soil is classified as poorly graded sand (SP). The sand was poured into the tank at a unit weight of 15.80 kN/m^3, i.e., at 60% relative density. The angle of internal friction at a unit weight of 15.80 kN/m^3 was found to be 36.5 p.

TESTS RESULTS AND DISCUSSION

The experimental results obtained from laboratory tests are analyzed and discussed in this section. The load was applied incrementally until reaching failure. Each load increment was maintained at a constant value until the raft settlement had stabilized. The relative improvement of the raft performance when supported on a pile is represented using a non dimensional factor, called the Load Improvement Ratio (LIR). This factor is defined as the ratio of the load carried by the raft to the load carried by the unpiled raft at the same settlement level. The foundation stiffness were also evaluated at a given settlement levels. The raft settlement (S) is expressed in the nondimensional form in terms of the raft width (B) as the ratio (S/B, %). For comparisons of the piled raft response with the studied parameters, three levels of settlement ratios (S/B), at 1% , 5% and 10% were considered.

Influence of Raft Size

Figure 3 shows the load-settlement behavior of unpiled raft and raft with 1, 4 and 9 piles for raft size 110 mm x 110 mm, 160 mm x 160 mm and 200 mm x 200 mm. It can be noted that, when raft size increases, the bearing capacity of piled raft increases.

Figure 4 shows the Influence of raft size on load improvement ratio at a given levels of settlement ratio for raft with 1, 4 and 9 piles. It can be noted that as raft size increases, the load improvement ratio decreases for raft with 1, 4 and 9 piles (e.g., at S/B=1% for raft with 4 piles, LIR decreases by 21% and 14.5% when raft width increases from 110 mm to 160 mm and 160 mm to 200 mm). This phenomenon is due to the increase of contact surface area with the soil as the raft size increases, hence more load will be taken by raft.

Figure 5 shows the Influence of raft size on foundation stiffness at a given levels of settlement ratio for raft with 1, 4 and 9 piles. It can be noted that as the raft size increases, the relative increase in foundation stiffness

Figure 3: Influence of Raft Size on Load Settlement Curves for (a) Unpiled raft (b) Raft with 1 pile (c) Raft with 4 piles (d) Raft with 9 piles

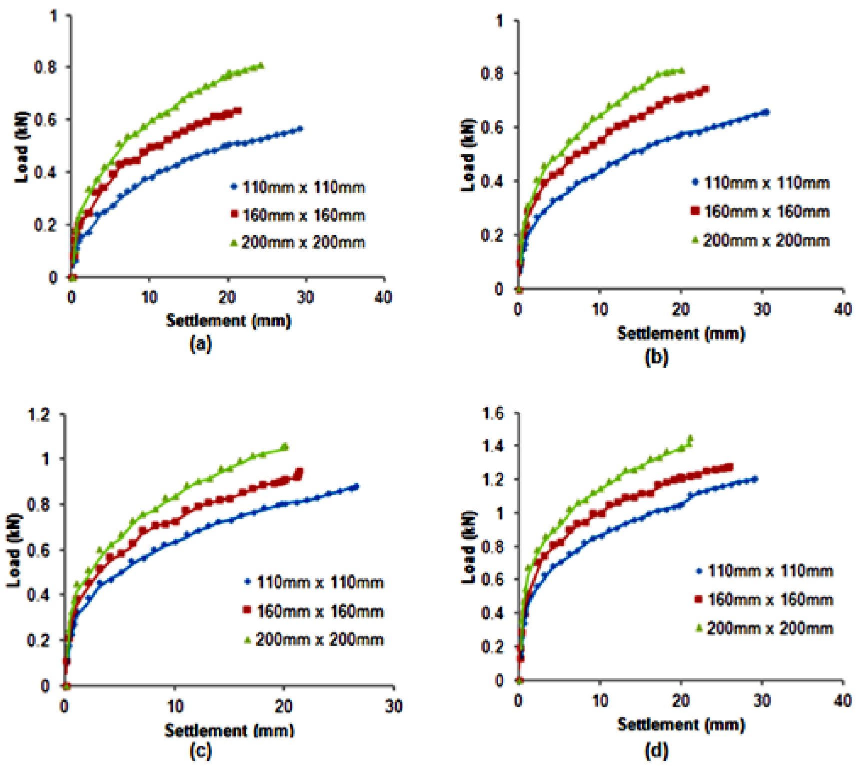


Figure 4: Variation of Load Improvement Ratio (a) Raft with 1 pile (b) Raft with 4 piles (c) Raft with 9 piles

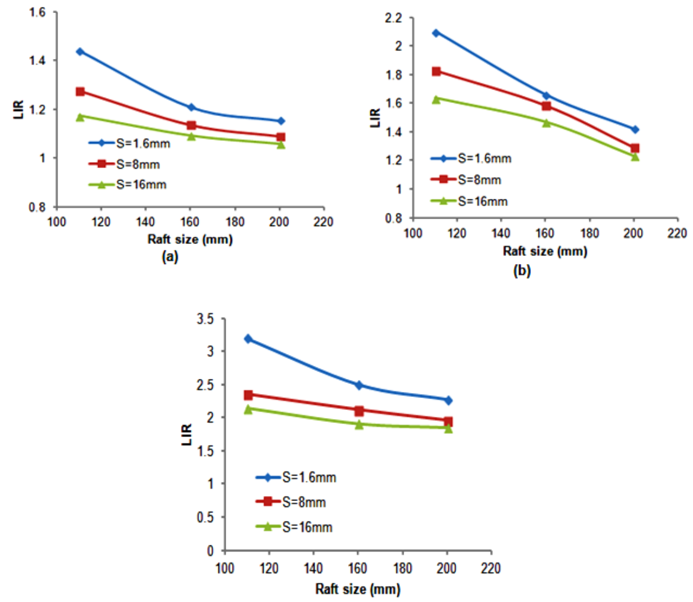
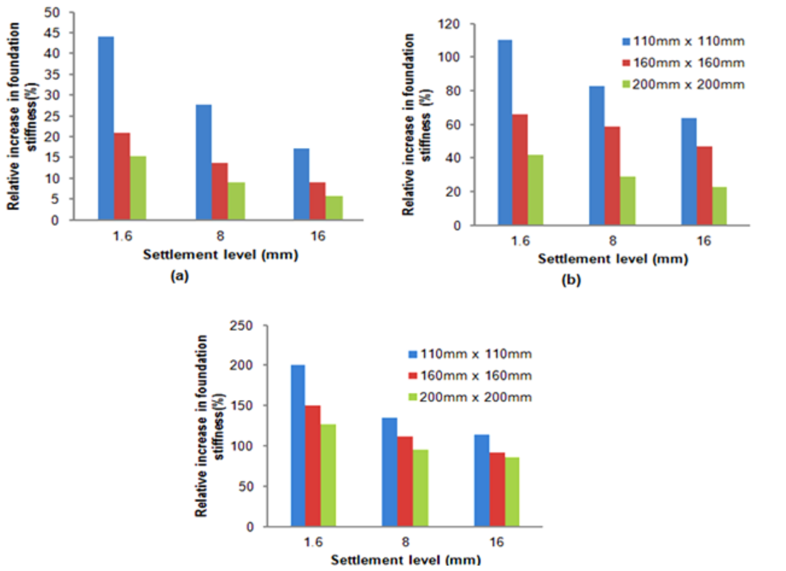


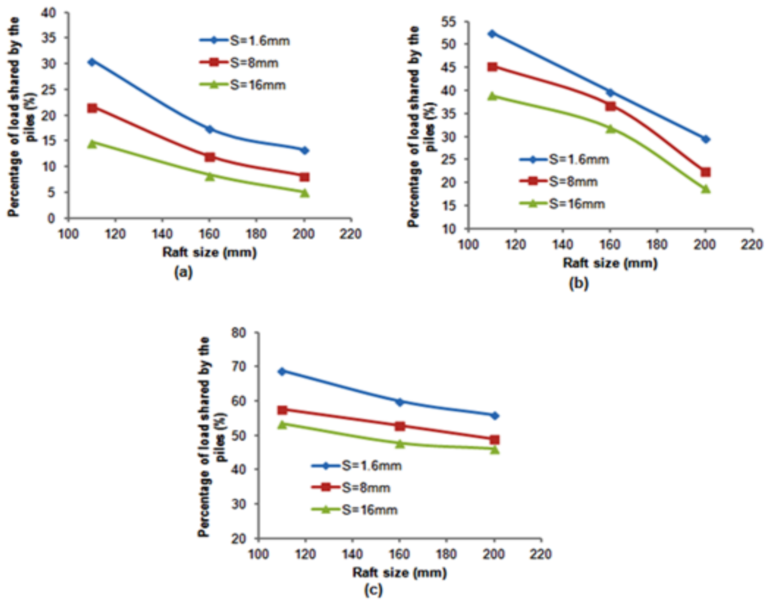
Figure 5: Variation of Foundation Stiffness (a) Raft with 1 pile (b) Raft with 4 piles (c) raft with 9 piles



decreases for raft with 1, 4 and 9 piles (e.g., at S/B = 1% for raft with 4 piles, foundation stiffness decreases by 40% and 35% when raft width increases from 110 mm to 160 mm and 160 mm to 200 mm).

Figure 6 shows the Influence of raft size on the percentage of load shared by the piles at a given levels of settlement ratio for raft with 1,4 and 9 piles. It can be noted that as raft size increases, the percentage of load shared by

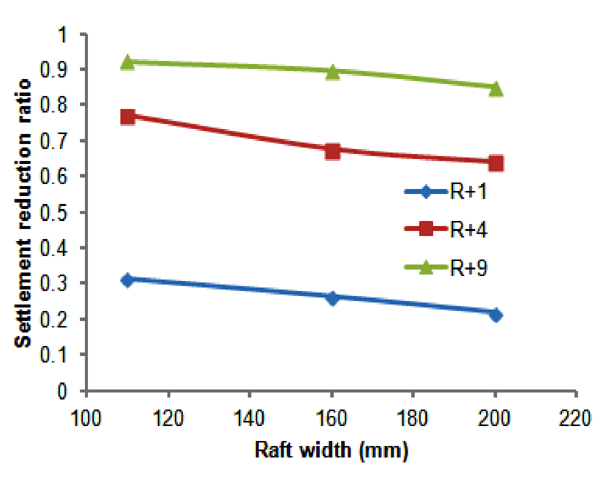
Figure 6: Influence of Raft Size on Load Sharing Between Raft and Piles (a)Raft with 1 pile (b)Raft with 4 piles (c) Raft with 9 piles



the piles decreases, for raft with 1,4 and 9 piles (e.g., at S/B = 1% for raft with 4 piles, the percentage of load shared by the piles decreases by 24% and 25% when raft width increases from 110 mm to 160 mm and 160 mm to 200 mm). This phenomenon is due to the increase in stiffness of raft as the size of raft increases. In this tests, the stiffness of the piles was not change while study the influence of raft width, hence the ratio of stiffness of the piles to the stiffness of the raft decreases due to increase in width of the raft. It can be argued that this ratio has a significant effect on the load sharing between the piles and raft.

Figure 7 shows the Influence of raft on settlement reduction ratio at a given load for raft with 1,4 and 9 piles. It can be noted that as raft size increases settlement reduction ratio decreases (e.g., for raft with 4 piles, settlement reduction ratio decreases by 12% and 4% when raft width increases from 110 mm to 160 mm and 160 mm to 200 mm).

Figure 7: Variation of Settlement Reduction Ratio with Raft Size



Influence of Number of Piles

Figure 8 shows the Influence of number of piles on load improvement ratio at settlement ratio S/B = 1%, 5% and 10% for a raft size 160 mm x 160 mm. It can be noted that as the number of piles increases, load improvement ratio increases (e.g., load improvement ratio increases by 43.5%, 33.8% and 25.5%, while installing 4 piles to 9 piles at settlement ratio S/B = 1%, 5% and 10%). This phenomenon occurs because at the initial loading stage pile carries the maximum load and as the settlement increases, load was transferred to raft, hence load improvement ratio decreases as settlement level increases.

Figure 8: Variation of Load Improvation Ratio with Number of Piles

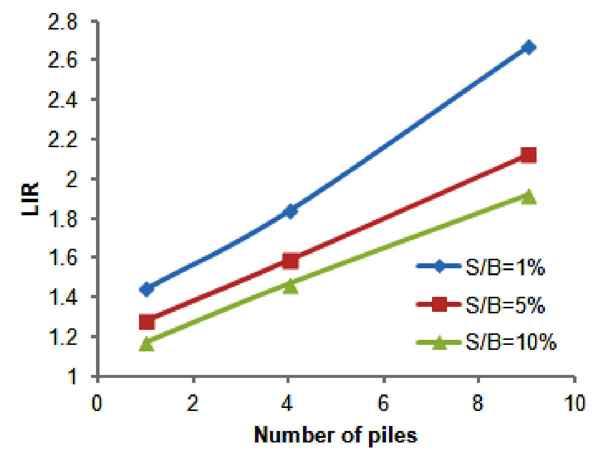
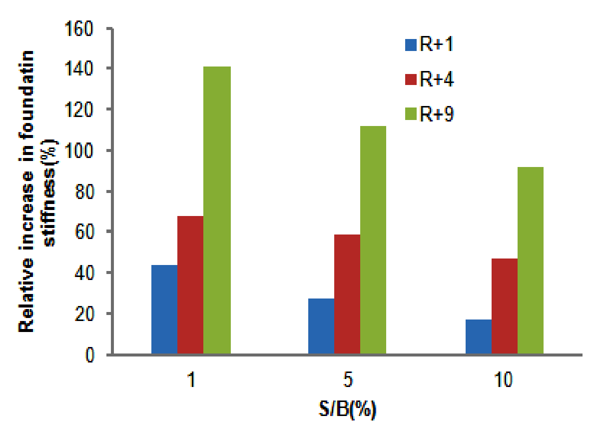


Figure 9 shows the Influence of number of piles on relative increase in foundation stiffness at settlement ratio S/B = 1%, 5% and 10% for a raft size (e.g., relative increase in foundation stiffness increases by 107.5%, 92% and 89.3%, while installing 4 piles to 9 piles at settlement ratio S/B = 1%, 5% and 10%). This phenomenon occurs because at the initial loading stage, stiffness is maximum and as the settlement increases, stiffness of the

Figure 9: Varition of Relative Inrcrease in Founation Stiffness with Number of Piles



foundation system decreases. These results are in confirmation with the results reported by Fioravante *et al.* (2008).

Figure 10 shows the Influence of number of piles on percentage of load shared by the piles at settlement ratio S/B = 1%, 5% and 10% for a given raft size (e.g., the percentage of load shared by the piles increases by 44.5%, 43.2% and 43.34%, while installing 4 piles to 9 piles at settlement ratio S/B = 1%, 5% and 10%).

Figure 10: Influence of Number of piles on Load Sharng Between Raft and Piles

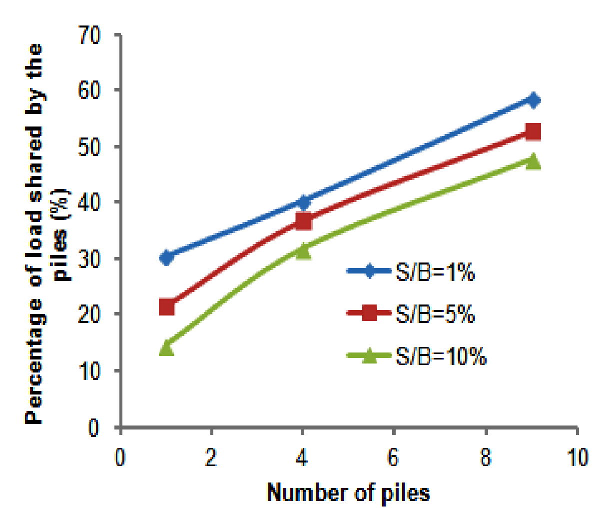
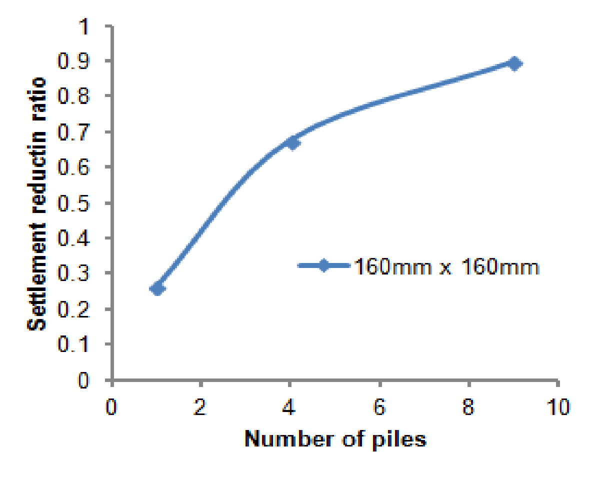


Figure 11 shows the Influence of number of piles on settlement reduction ratio for a given pile spacing (e.g., for a raft width 160 mm, settlement reduction ratio increases by 30%, while installing 4 piles to 9 piles).

Figure 11: Variation of Settlement Reduction Ratio with Number of Piles



CONCLUSION

The paper has presented load test results on model piled raft in sand soil to investigate the load-settlement behavior and load sharing between the piles and raft. From the results of this study, the following conclusions can be drawn:

1) The raft size has a major effect on settlement and load sharing between the piles and raft.
2) At S/B= 1%, 5% and 10%, load improvement ratio, foundation stiffness and load shared by the decreases as raft size increases.
3) At S/B = 1%, 5% and 10%, load improvement ratio, foundation stiffness and load shared by the increases as number of piles increases.
4) The addition of piles beneath the central area of the raft increases the load bearing

capacity of the piled raft and this effect is increases as the number of piles increases.

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