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An Experimental Study on Behaviour of Piled Raft Foundation

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Abstract
Piles in piled raft are often considered as settlement reducers, not load bearing members. The experimental study focuses on the behaviour of piled raft foundation subjected to vertical load. The model rafts were made of mild steel plates with plan dimension 160 mm ×160 mm × 10 mm. The model piles used in this test were non-displacement piles of diameter 10 mm. Three lengths of piles were used in the experiment to represent slenderness ratio, L/D of 10, 15 and 20, respectively. The testing program includes tests on models of unpiled raft and rafts on 1, 4 and 9 piles. The influence of a number of piles and pile lengths on the load improvement ratio and foundation stiffness are presented and discussed. The results of the tests show that as the number of piles underneath the raft increases, load improvement ratio and foundation stiffness increases and percentage of load carried by the raft decreases. Theload improvement ratio and the foundation stiffness also increases with increase in pile length, while the pile length has a significant effect on the load carried by the raft.

Keywords: *Raft, Piles, piled raft, model test*

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INTRODUCTION

When an adequate bearing stratum is available at a shallow depth, then rafts are suitable foundation. Piles could be included for the purpose of reducing the raft settlement, in a piled raft foundation system. The concept of using piles as "settlement reducers" was first proposed by Burland in Ref.[1]. Several reports were published on the use of piles as settlement reducers [2–7].

Cooke investigated the behaviour of piled raft foundation system and compared the same with that of the free standing piled group and unpiled raft, through model tests on piled raft [8]. Horikoshi and Randolph [5] conducted a centrifuge test on piled raft foundation system on clay soil to study the load-settlement behaviour of piled raft foundation. Horikoshi studied the load-settlement behaviour and the load sharing between the piles and the raft in the piled raft system, through the centrifuge test on piled raft foundation system on sandy soil subjected to horizontal and vertical loading [9]. Conte et al.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 [10]. Lee and Chung [11] investigated the behaviour of piled raft foundation due to the effect of pile installation and interaction between the raft and pile through experiments on piled raft foundation system on sand soil.

Bajad and Sahu [12] investigated the effect of pile length and the number of piles on load sharing between the pile and the raft and settlement reduction through 1 g model test on a piled raft foundation on soft clay. Fioravante et al. performed a centrifuge test on the unpiled rigid circular raft and raft on 1, 3, 7 and 13 piles on sand soil to study the role of piles as a settlement reducer and load sharing between the raft and piles [13]. Fioravante and Giretti studied the load transfer mechanism between the raft and the pile in sand soil, through centrifuge test on piled raft foundation [14]. El-Garhy and Galil performed an experiment on model piled raft foundation on sand soil to investigate the behaviour of the raft on settlement reducing piles, due to the influence of raft-soil stiffness [15].

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

EXPERIMENTAL SETUP

Figure 1 shows the steel tank and test setup which measured 850 mm × 850 mm × 500 mm in plan.

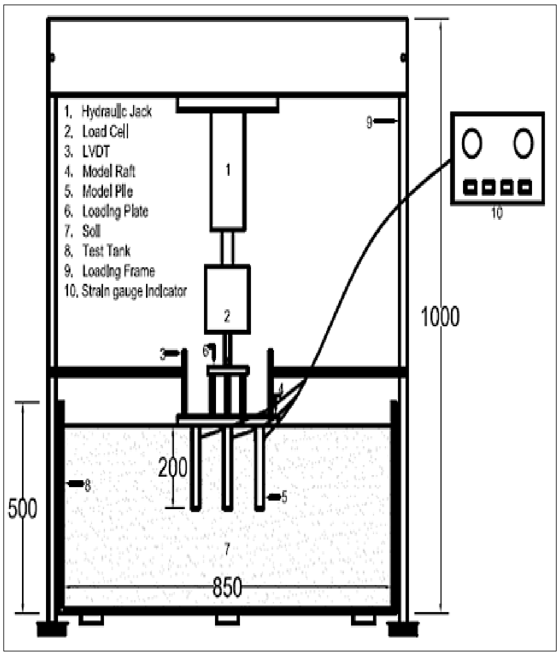

Fig. 1: *Model Test Setup (All Dimensions are in mm).*

A clean sand was 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 particle size distribution were determined using the dry sieving method and results are shown in Figure 2.

The uniformity coefficient (C_u) and coefficient of curvature (C_c) for the sand were found to be 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 °. The secant modulus (E_{50}) at unit weight 15.80 kN/m^3 was found to be 10.725 MPa, determined from the triaxial test.

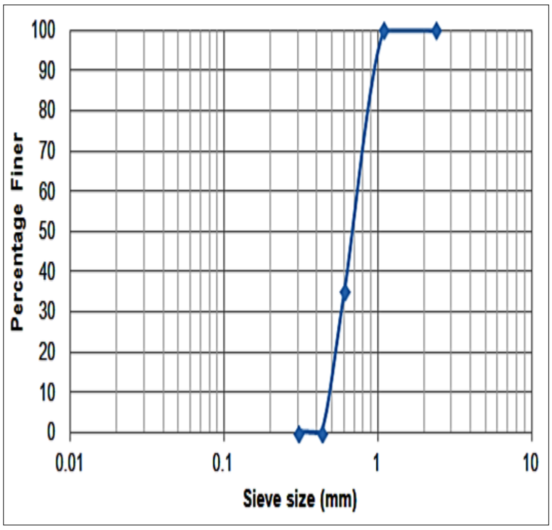

Fig. 2: *Particle Size Distribution Curve.*

The model raft was made up of mild steel plates having a square shape with dimension of 160 mm ×160 mm ×10 mm. The model settlement reducing piles were made up of the mild steel of diameter 10 mm. Three pile lengths of 100 mm,150 mm and 200 mm were used in the experiments to represent slenderness ratio, L/D of 10,15 and 20 respectively. The modulus of elasticity and Poisson’s ratio of the mild steel raft and pile were 1.8 × 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.

Instrumentation and Loading System

The piles were 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, two LVDTs were placed at the middle side of the raft to measure vertical displacement. A calibrated load cell of 10 kN capacity was connected to the 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 loading was continued till the raft settlement reaches 20 mm.

Experimental Program

10 tests were conducted in the laboratory. One test 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 foundation are presented in Table 1.The pile configurations and dimensions of a model raft of piled raft are shown in Figure 3.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 behaviour of piles [16].

Table 1: *Summary of the Model Tests on Unpiled and Piled Rafts.*

Test explanation	Model raft dimensions (mm × mm × mm)	L/D	S/D	Number of test performed
Unpiled raft	160 ×160 ×10	-	-	1
Raft + 1 pile		10 15 20	-	1 1 1
Raft + 4 piles		10 15 20	4	1 1 1
Raft + 9 piles		10 15 20	4	1 1 1

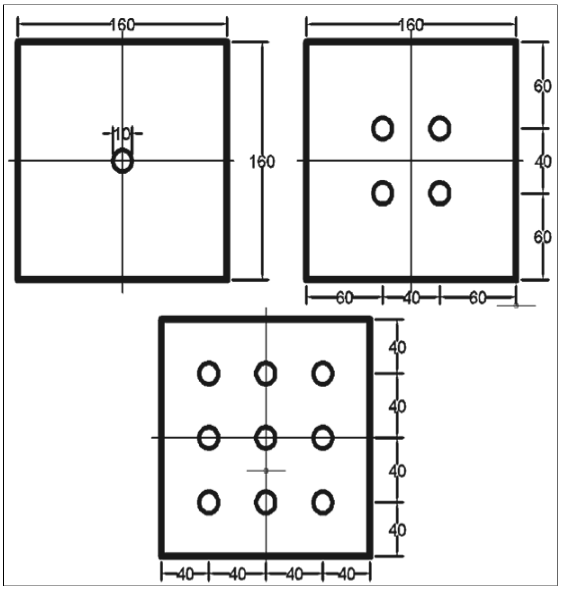

Fig. 3: *Studied Cases of Piled Raft Foundation (All Dimensions are in mm). Test Procedure.*

1. Sand was poured in tank by rainfall method in order to achieve the required density in all tests. The total height of the tank was divided into intervals of 50 mm. The sand was poured in tank up to a height of 450 mm with height of fall 600 mm, to achieve a unit weight of 15.80 kN/m^3.
2. As the piles are non-displacement piles, at first, sand was poured up to a required height from the bottom of the tank. Then, piles having length 100 mm, 150 mm and 200 mm were placed in vertical position with 10 mm penetration into sand to ensure proper seating. The sequence of pile installation starts with inner pile, followed by corner piles and finally edge piles. The piles were held in position till the tank was filled up.
3. After installation of model piles, model raft was placed and connected to each pile by nuts.
4. The load was transferred to model raft through loading plate, placed on the raft. Then, two LVDTs were placed at the middle side of the raft to measure vertical displacement.
5. A calibrated load cell of 10 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.

RESULTS AND DISCUSSION

The model test results obtained from the 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 level. The raft settlement (S) is expressed in the non-dimensional form in terms of the raft width (B) as the ratio S/B%. For comparison of the piled raft reponse with the studied parameters, three levels of settlement ratios (S/B), at 1% , 5% and 10% were considered.

Influence of Pile Length

Figure 4 shows the load-settlement curves of unpiled raft and raft for the different pile lengths. The figure clearly shows that the inclusion of piles underneath the raft improves the initial stiffness of the load-settlement curves. However, the load improvement ratio at the same settlement level are greater with longer piles. Also, for the same raft load, the settlement decreases significantly for the piles connected underneath the raft, e.g., comparing the curves of Figure 6(a) and (c) for the load 0.4 kN, the settlement decreases from 15 mm(unpiled case) to 4 mm,2 mm and 1 mm when using piles of L/D = 10,15 and 20 respectively underneath the raft.

Figure 5 shows the variations in LIR with normalized pile length, L/D at settlement ratios of 1%, 5% and 10%, e.g., comparing the curve of Figure 5(b), LIR increases by 19%, 21.5% and 21% at settlement ratios of 1%, 5% and 10%, when using piles of L/D =10 to 15 underneath the raft. The raft resting on piles have stiffer load-settlement response than the unpiled raft.

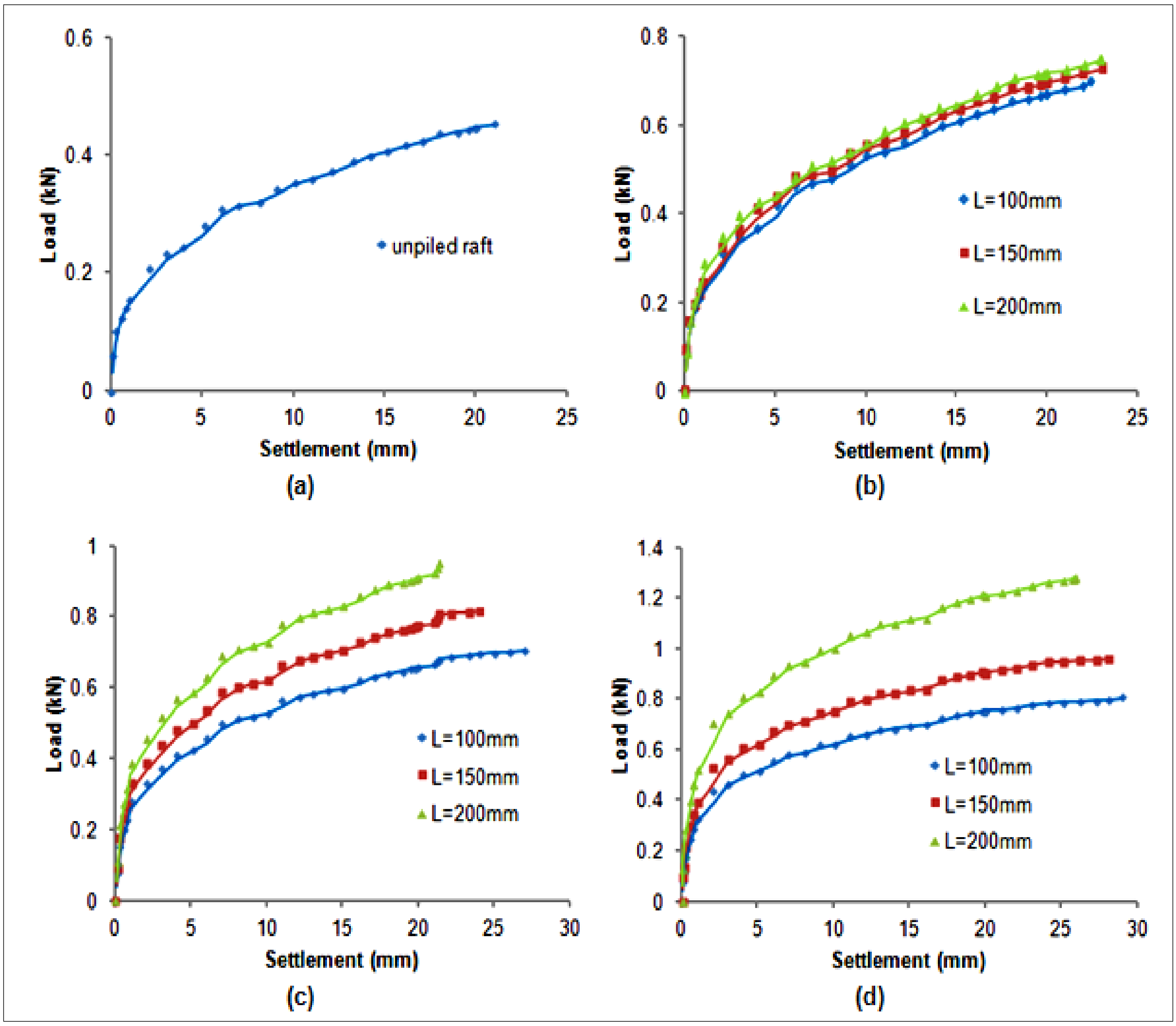

Fig. 4: *Influence of Pile Length on Load-Settlement curves for (a) Unpiled raft (b) Raft with 1 pile (c) Raft with 4 piles (d) Raft with 9 Piles.*

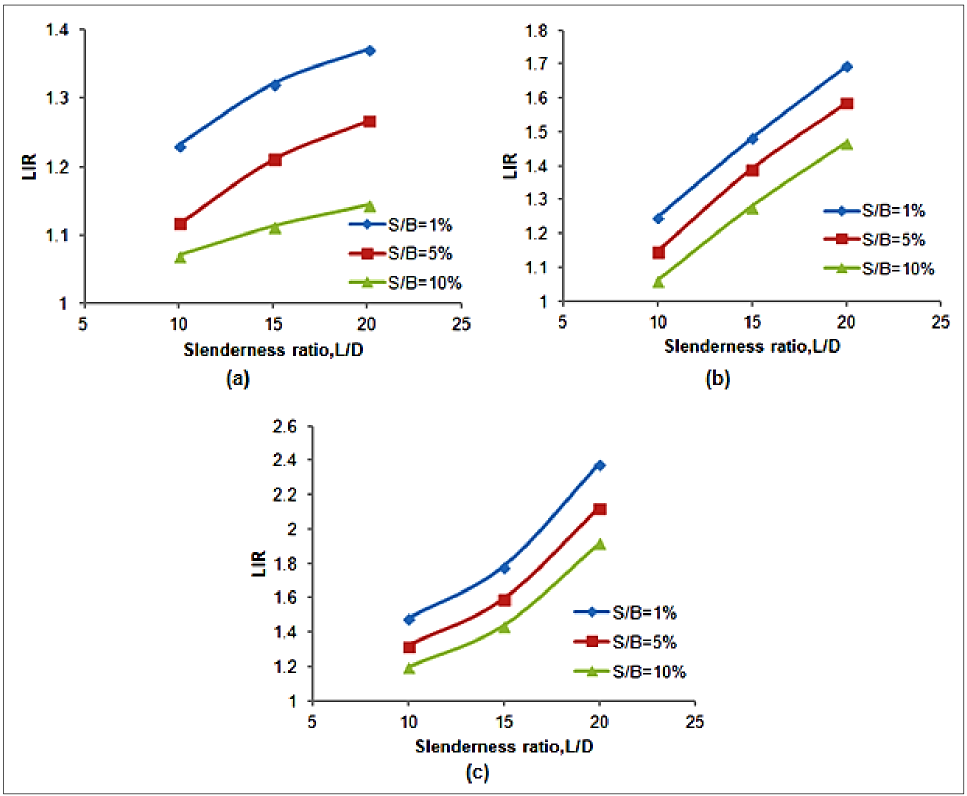

Fig. 5: *Variation in LIR with L/D at Different S/B Ratios*
(a) Raft with 1 Pile (b) Raft with 4 Piles (c) Raft with 9 Piles.

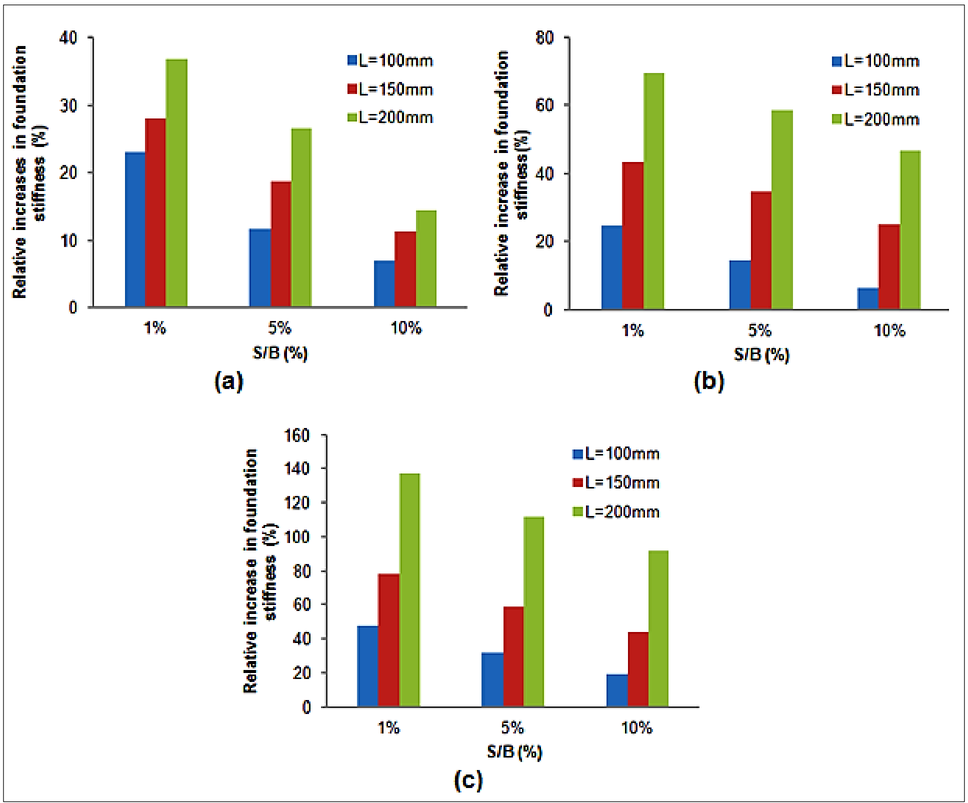

Fig. 6: *Relative Increase in Foundation Stiffness with Addition of Piles*
(a) Raft with 1 Piles (b) Raft with 4 Piles (c) Raft with 9 Piles.

The foundation stiffness indicated by the inverse slope of load-settlement curve increases with the inclusion of piles as reinforcement and settlement of the raft are reduced accordingly. A comparison of the relative increase in foundation stiffness with varying pile lengths at settlement ratios, S/B (S = Ssettlement of the plate;B = Width of the plate) of 1%, 5% and 10% is shown in Figure 6. It was noted that the increase in foundation stiffness, in terms of percentage change, from the addition of the piles was more significant when the settlement of the raft was small. At large settlement levels, the increase in foundation stiffness becomes smaller, possibly because of an increased lateral movement of the sand at large applied loads. Figure 7 shows the proportion of load carried by the piles with an increase in pile length. It can be observed that as the pile length increases, the load carried by the pile increases. This is because the load transfer are being more taken care by the longer piles due to skin friction than the shorter piles. These results are in confirmation with the results reported in Refs. [17–18].

Figure 8 shows the variations of the load improvement ratio with the number of piles at S/B =1%, 5% and 10%. It can be observed that the load improvement ratio increases as number of piles beneath the raft increases. This is because as the number of piles beneath the raft increases, more load will be taken by the piles, e.g., at S/B =1%, for pile length 150 mm, load improvement ratio increases by 13.7% and 24.5%, while installing 1 central pile to 4 piles and 4 piles to 9 piles, respectively.

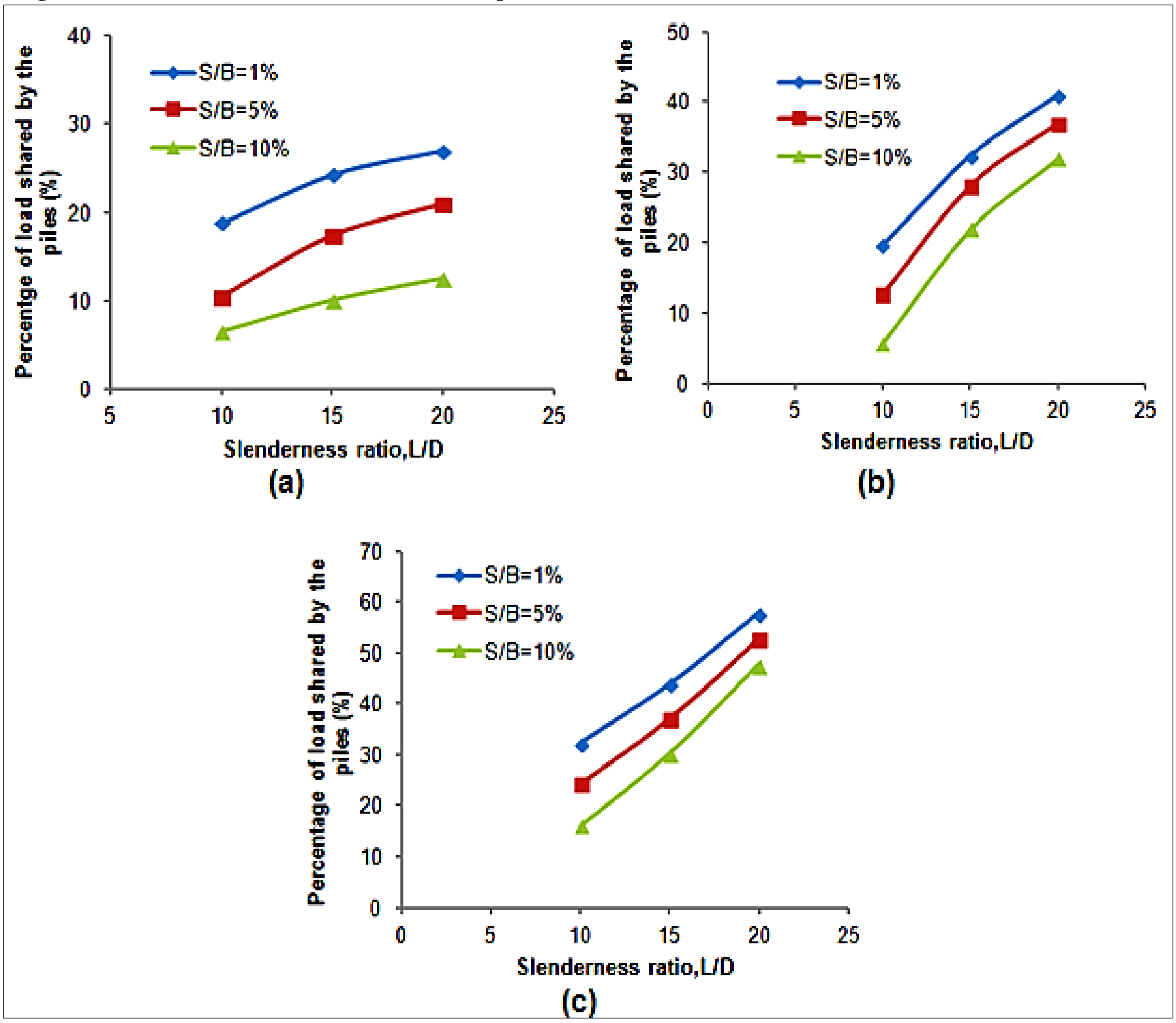

Fig. 7: *Influence of Pile Length on Load Sharing between Raft and Piles. Influence of Pile Number*

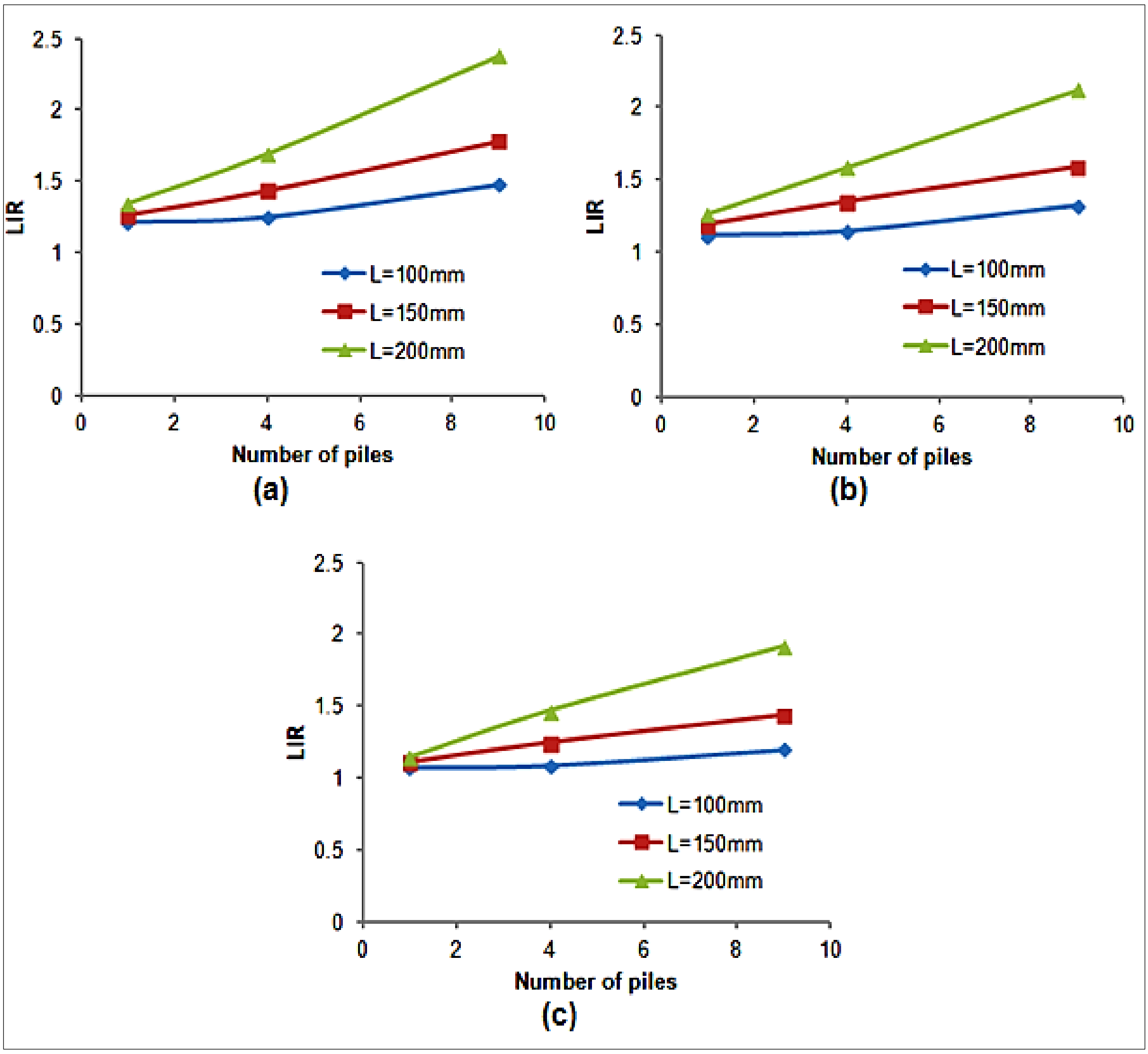

Fig. 8: *Variation of LIR with Number of Piles (a) S/B =1% (b) S/B =5% (c) S/B =10%.*

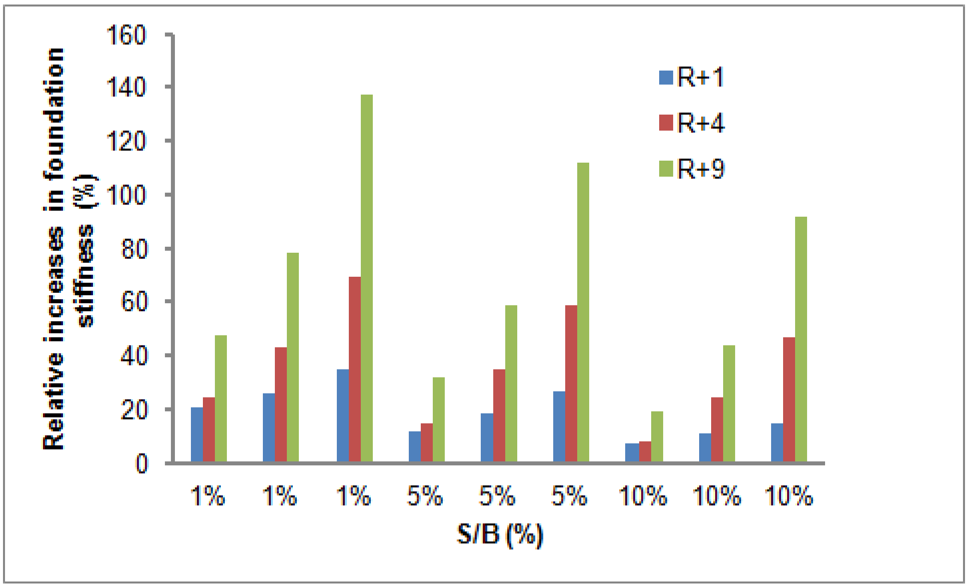

Fig. 9: *Relative Increase in Foundation Stiffness with Number of Piles.*

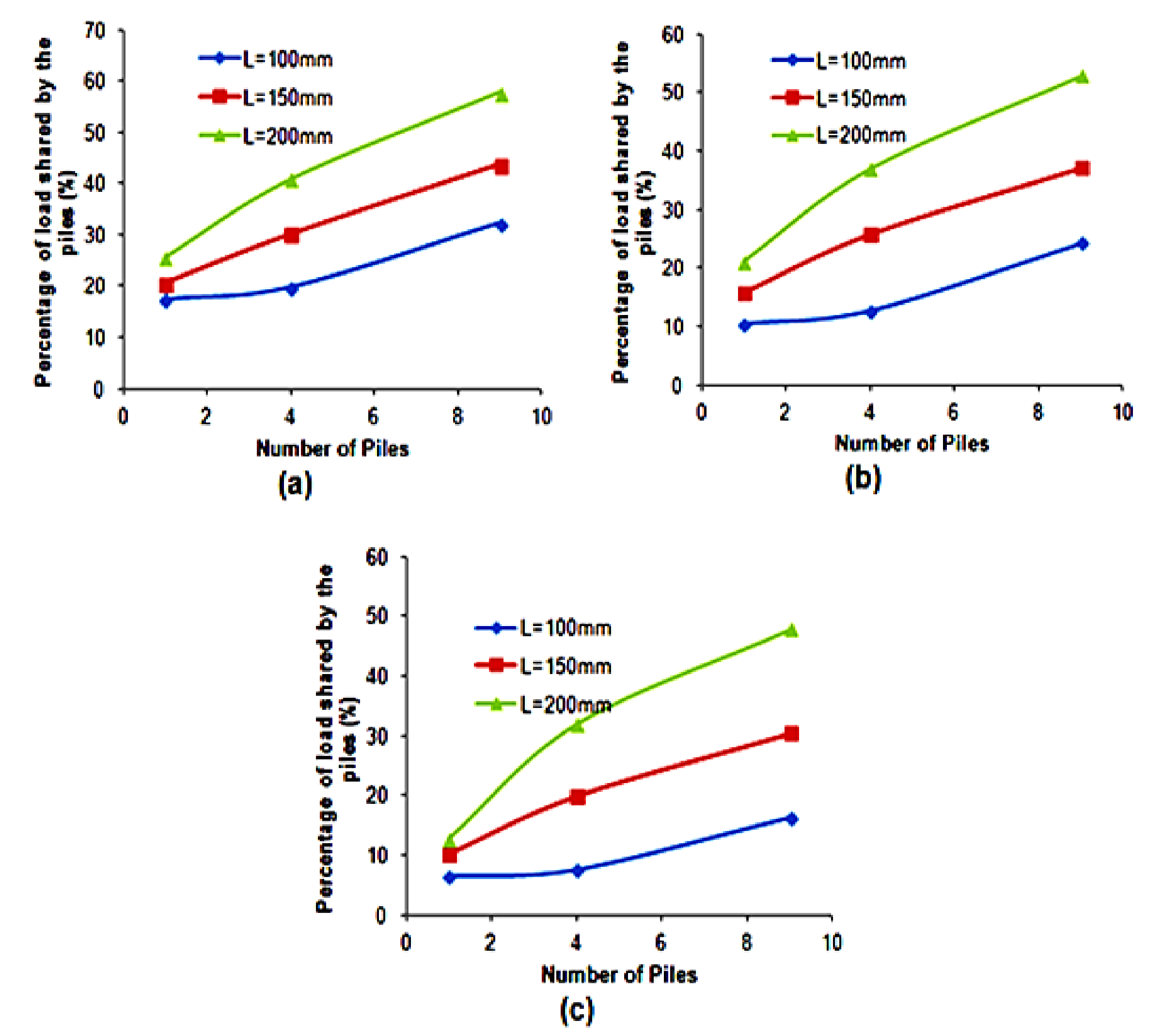

Fig. 10: *Influence of Pile number on Load Sharing between Raft and Piles.*

A comparison of the relative increase in foundation stiffness with varying pile numbers at settlement ratios, S/B of 1%, 5% and 10% as shown in Figure 9. It can be noted that with increase in pile numbers, stiffness of foundation system increases,e.g., at S/B =1%, foundation stiffness increases by 66% and 81%, while installing 1 central pile to 4 piles and 4 piles to 9 piles for pile length 150 mm. These results are in confirmation with the results reported in Reference [13].

Figure 10 shows the proportion of load carried by the piles with an increase in pile numbers. It can be observed that as the pile numbers increases the load carried by the pile increases. This is because of the more number of piles, more the load carried by the piles and load transfer takes place due to skin friction and end bearing.

CONCLUSIONS

This paper has presented experimental results of small scale laboratory model test on sand in order to investigate the load-settlement behaviour and load sharing between the piles and raft.

From the results of this study, the following conclusions can be drawn:

1. For a given piles underneath the raft, an increase in pile length was found to be effective for improving the stiffness of the piled raft system.
2. At initial loading stage, the load taken by the piles were found to increase rapidly, then to remain at a plateau in subsequent stages.
3. The load improvement ratio increases with increase in the pile length and pile numbers.

STM JOURNALS

4. The load shared by the piles increases with increase in the pile length and pile numbers.

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