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Load Settlement Behaviour of Raft and Piled Raft on Granular Soil

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ABSTRACT: In recent decades, rising costs and scarcity of land have led to the construction of high-rise civil engineering facilities to meet the needs of a growing population. High-rise buildings are founded on deep foundations. The foundation system contributes significantly to the cost of the facility. Recently, the use of a Piled-Raft (PR) foundation has been advocated as a cost-effective solution to bear the loads from the superstructure of high-rise buildings. In this study, we investigate the load settlement response of model Raft and Piled-Raft foundation systems. Experiments were conducted using the scaled model of the Raft and Piled-Raft Foundation system. The influence of the relative density of soils, raft size, and foundation type (raft and piled-raft systems) on the load-settlement behaviour was investigated. With an increase in relative density from 30% to 70%, the load-carrying increased by 90%, 73 %, and 34% for the raft sizes of 200 mm, 300 mm, and 450 mm, respectively. For the piled-raft system, the increase in load-carrying capacity was found to be 70%. The results from the present study show that a piled-raft system is a cost-effective yet efficient and safe foundation system that could be used to sustain the heavy structural loads from high-rise buildings.

1 INTRODUCTION

Foundations are the sub-structural elements that safely transmit the structural load to the soil. The transfer of loads should be such that neither the soil fails in shear nor undergoes excessive settlements (Fang and Hsai-Yang, 2013). Shallow foundations often satisfy the shear criteria but fail to meet the permissible settlement. In that case, deep foundation is the obvious choice (Knappett and Jonathan, 2012). Still, the selection of a particular type of foundation is very much governed by the cost involved in constructing the foundation. From an economic point of view, a shallow foundation is always preferred over a deep foundation (Reese et al. ,2005). High-rise buildings require deep but costly foundation systems. A solution to reduce the cost is to use a piled-raft system; a combination of raft (shallow foundation) and pile (deep foundation) (Hemsley and John, 2000). In the conventional method of pile group design, the total applied load is carried by the piles alone, and the contribution of the raft is ignored. In the new design philosophy of the piled-raft system, the contribution of the raft is also taken into account, and the frictional piles act as a settlement reducer (Burland et al.,1977). Investigations reveal that small-scale tests are very effective and inexpensive for investigating the behaviour of rafts and piled rafts (Halder et al.,2022). A Physical model test can be used to perform sensitive studies (Baziar et al.,2009). Data collected during the tests can be analysed to examine the effects of various parameters, and data can be compared with theoretical results (Joseph et al.,1998). Several parameters like the relative density of soil, size of raft, length of piles, the diameter of the piles, and the configuration of the piles govern the load-sharing mechanism of the raft and piled raft. The effect of raft size and relative density of soil on the carrying capacity of raft and piled raft is not well understood yet. In the present experimental study, the effect of raft size and relative density on the ultimate load carrying capacity of raft and piled-raft under vertical load is investigated using a small-scale model in the laboratory.

2 METHODOLOGY AND TEST SETUP

2.1 Model raft and piled raft

The current study used a small-scale model of a raft and a piled raft. The pile and piled-raft models were fabricated using mild steel (Fig.1&2). Table 1 presents the geometric properties of the pile and piled-raft systems used in the present study.

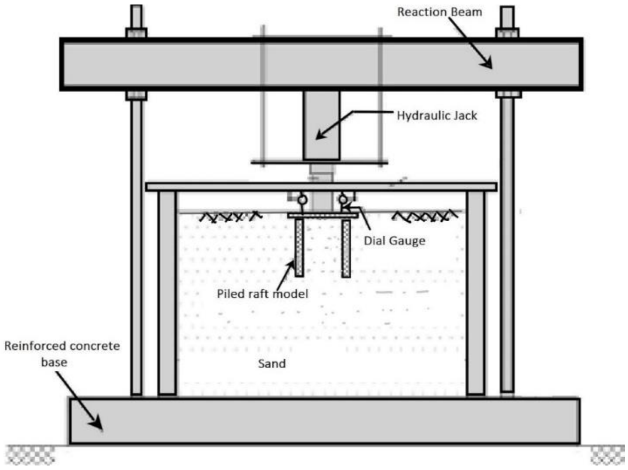

Fig 1 Schematic of Testing arrangement

Table 1 Geometric properties of various model foundations.

Model	Raft length (mm)	Pile length (mm)	Pile diameter (mm)	Spacing c/c (mm)
	200	-	-	-
Square-raft	300	-	-	-
	450	-	-	-
Piled-Raft	300	300	25	125

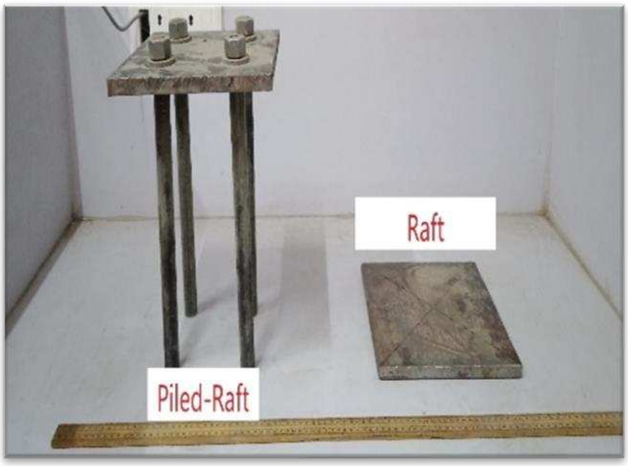

Fig 2 Model raft and piled raft

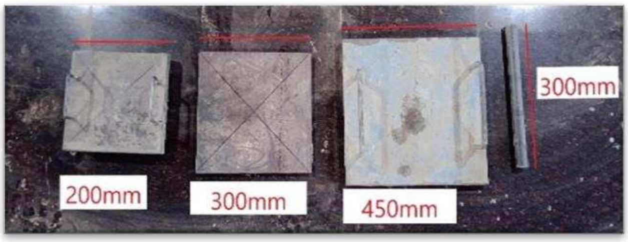

Fig 3 Model Rafts

2.2 Tank and Loading Frame

A rigid steel tank of dimensions 1m x 1m x 1m was used in the current study (Fig.3). To maintain the rigidity of the tank, all four sides were reinforced with a diagonal bracing. The size of the tank was determined by taking the size of the raft and pile into account and to minimize the boundary effects. Concrete cubes were provided at the bottom of the tank for a depth of 15 cm. These cubes act as cushion and ensure the rigidity of bottom. A hydraulic jack was mounted on a reaction beam.

Fig 4 Steel Tank

2.3 Data Acquisition System

A digital data logger manufactured by Tokyo Measuring Instrument Lab was used in the current study. This data logger is capable of recording deformation, strain, and stress. The number of input channels is expandable by suitable switches and provides channel to channel isolation for more security. The calibrated Proving ring of 100 kN capacity with a least count of 0.1225 kN was used to measure the load on the foundation systems.

Fig 5 Loading Frame

2.4 Sand Properties

The sand used during the experimental study was obtained from the Jhelum River bed in India. Basic geotechnical properties like particle size distribution, specific gravity, and minimum and maximum void ratio were determined following Indian Standards (IS 2720). Table 2 presents the basic geotechnical properties of Jhelum sand obtained from the testing.

Table 2 Basic Properties of Jhelum sand

Soil Property	Jhelum Sand
D_{10} (mm)	0.33
D_{30} (mm)	0.52
D_{50} (mm)	0.79
D_{60} (mm)	0.95
Coefficient of uniformity (C_u)	2.86
Coefficient of curvature (C_c)	0.87
Maximum dry unit weight (kN/m^3)	19.42
Minimum dry unit weight (kN/m^3)	15.88
Maximum void ratio (e_{max})	0.62
Minimum void ratio (e_{min})	0.33
Specific gravity (G_s)	2.62
Classification (ISSCS)	SP

2.5 Sand Bed Preparation

The Jhelum River bed sand was filled in the test tank in eight layers with a thickness of 100 mm each. The sand was poured using buckets from a relatively low height. Each layer's compaction was done using a 300mm x 300mm compaction plate with a 2.5kg hammer. The mass of sand filled in each layer was calculated using equation (1) as 185 kg and 172 kg to achieve target relative densities of 70% and 30 % (dense and loose states) respectively. The relative density of the tank was checked by placing a no. of small canes in the tank.

$$D_r = \left[\left(\frac{\rho_d - \rho_{dmin}}{\rho_{dmax} - \rho_{dmin}}\right) * \frac{\rho_{dmax}}{\rho_d}\right] * 100 \qquad (1)$$

Table 3 Void ratio, friction angle, and unit weight of Jhelum sand at different densities

D_r (%)	e (Void ratio)	Φ (Degree)	γ (kN/m^3)
30	0.52	34	16.86
70	0.41	40	18.14

2.6 Test Procedure

After filling the tank at the desired relative density, model foundation systems were placed on the levelled surface of the sand. Two LVDTs were attached to the model foundation in two perpendicular directions. The load was applied manually by rotating the arm of the hydraulic jack mounted on the reaction beam, the corresponding settlement was recorded using the data logger.

3 RESULTS AND DISCUSSION

The tests were performed as per the procedure described in the previous section. The results obtained from tests were presented in the form of load-settlement curves and the ultimate capacities of the model foundation are summarised in Table 4. The model foundation is said to have failed when the settlement reached a value of 10 mm (allowable settlement = 10 mm).

3.1 Raft on loose sand (Dr=30%)

R 200-30: The load settlement curve of Raft 200mm x 200 mm is shown in Fig.5. From the figure, it is clear that the foundation experienced local shear failure. The ultimate load at allowable settlement was found to be 5.51 kN.

R 300-30: Comparing the performance of Raft 300mm x 300mm at a relative density of 30% with Raft 200mm x 200mm (Fig.5)., it is clear that increasing the raft width increases the ultimate load carrying capacity to 7.84 kN and reduces the settlement without changing the failure mechanism.

R 450-30: Fig. 5 shows the load settlement curve of a 450mm x 450 mm raft. The curve shows that the ultimate capacity increases further due to the increase in width. At maximum allowable settlement, the ultimate load is 21.7 kN.

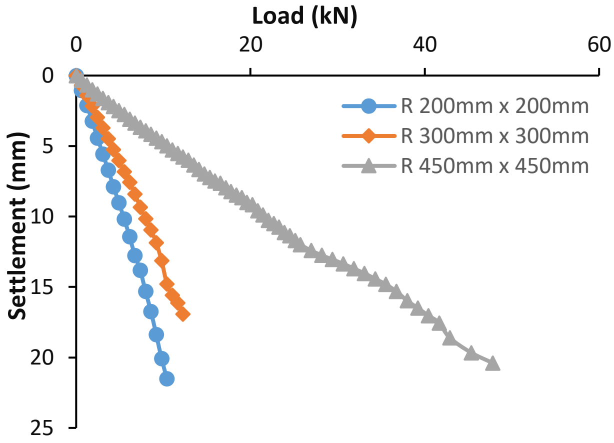

Fig 6 Load-settlement curve of different raft sizes on loose sand (D_r=30%)

3.2 Raft on Dense sand (Dr=70%)

R 200-70: Fig. 6 shows a significant change in the slope of the load-settlement curve. The curve clearly shows that the foundation experienced general shear failure. The ultimate bearing capacity was found to be 10.50 kN.

R 300-70: The raft of size 300mm x 300mm on dense (D_r=70%) sand experienced general shear failure similar to a raft of size 200mm x 200mm, and the ultimate capacity obtained from the load settlement curve (Fig.6) was found to be 13.6 kN. Which is twice the value found for loose sand (D_r=30%)

R 450-70: The load settlement curve of a 450mm x 450 mm raft shows an ultimate load of 29.1 kN.

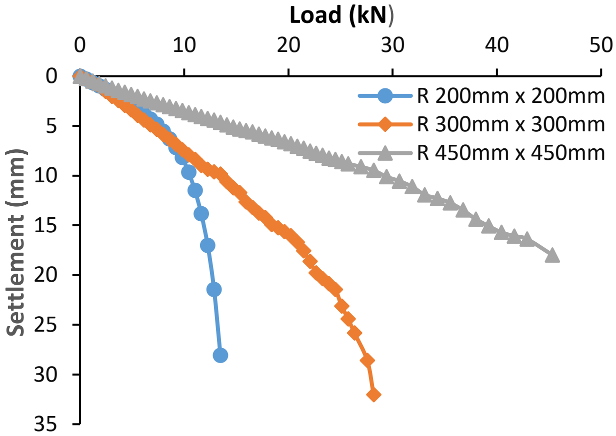

Fig 7 Load-settlement curve of different raft sizes on dense sand (D_r=70%)

3.3 Piled raft on loose and dense sand (Dr =30% & 70%)

PR 300-30: The load-settlement curve of the piled raft at relative density Dr=30% is shown in Fig. 7. The failure load was found to be 10.86 kN.

PR 300-70: The piled raft in dense sand experienced general shear failure (Fig.7), and the ultimate load was found to be 19.25 kN.

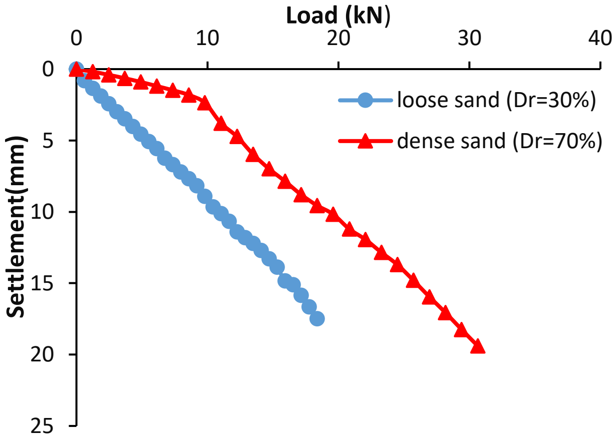

Fig 8 Load-settlement curve of the Piled raft on loose and dense sand

3.4 Test Results

Table 4. Various Tests results

Test name	Relative Density (Dr %)	Raft width (mm)	Ultimate load (kN)
R 200-30	30%	200	5.51
R 300-30	30%	300	7.84
R 450-30	30%	450	21.70
PR 300-30	30%	300	10.86
R 200-70	70%	200	10.50
R 300-70	70%	300	13.60
R 450-70	70%	450	29.10
PR 300-70	70%	300	19.25

3.5 Discussion

The effect of the introduction of piles below the raft can be seen clearly from the load settlement curve of the raft and piled raft. At the same allowable settlement, a piled raft carries a higher load than the raft, and at the same ultimate load, there is less settlement in the case of a piled raft. Piles increase the stiffness of the piled-raft foundation system thus acting as a settlement reducer. The load-settlement curves of raft and piled raft at different densities are compared in Fig.8 and Fig.9. As expected, the ultimate bearing capacity of the model foundation increases with an increase in the relative density. The increase in ultimate load can be attributed to the change in failure mechanism from local shear failure in the case of loose sand to general shear failure in the case of dense sand. The effect of raft size on the ultimate bearing capacity of the raft is studied by comparing the test results of various rafts. This comparison reveals that with an increase in raft size, the ultimate load-carrying capacity increases. This increase in ultimate load is observed for both the loose and dense sands.

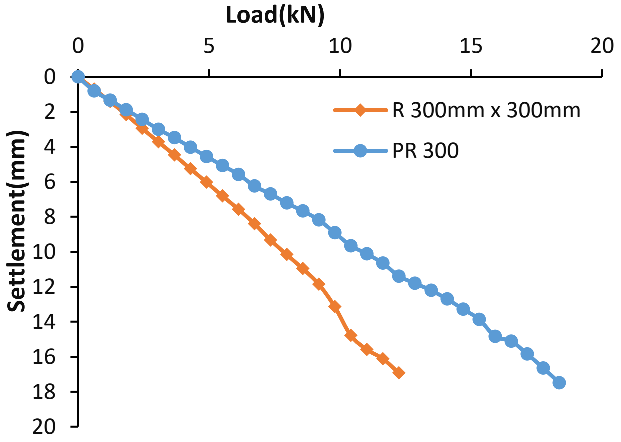

Fig 9 Comparison of raft and piled raft on loose sand (Dr=30%)

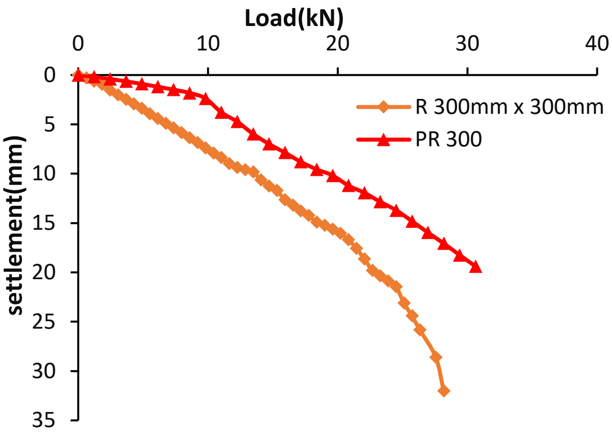

Fig 10 Comparison of raft and piled raft on dense sand (Dr=70%)

4 CONCLUSIONS

In the present work, the effect of the raft size and the relative density on the load settlement behaviour of the raft foundation was investigated. Model and piled rafts of different sizes were founded on Jhelum sand compacted at different relative densities. The results from the experiments gave insight into the load-sharing mechanism of rafts and piled rafts on the sand. the following conclusion can be drawn from the current study:

(1) For the piled raft size of 300 mm square and pile length of 300 mm, an increase of relative density from 30% to 70 % increased the load-bearing capacity by 70%.

(2) By changing the raft size by 100 mm, the load-carrying capacity increased by 40% and 30% for loose and dense sand, respectively.

(3) By increasing the raft size by 150 mm, the load-carrying capacity increased by 290% and 170% for loose and dense sand, respectively.

(4) The piled raft's load-carrying capacity was found to be greater than that of a raft of similar size. In the case of loose sand and dense sand, the piled raft carried 40% and 75 % more load than the raft, respectively.

(5) At the same ultimate load (Q_{ult}=4.9kN), the settlement of the piled raft is 24% less than that of the raft foundation in loose sand and 72% less in dense sand.

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