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Elastic and Non-Elastic Response of Pile-Raft System Embedded in Soft Clay

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ABSTRACT: A pile-raft system is viable approach to carry heavy loads in clay soils. Very limited research work is available if a pile-raft system is used in soft clay. Present research aims to study the elastic and non-elastic response of integrated and non-integrated pile-raft system embedded in soft clay using a physical mod-elling approach. The pile-raft model system is fabricated using aluminium and piles employed had a slender-ness ratio, L/D, of 10. The behaviour was compared with responses of a flexible unpiled raft, single pile, and rigid pile groups. The effects of the numbers of piles on settlement, load sharing between pile and raft, load improvements ratio and settlement reduction ratio are some of the major issued that presented and discussed.

1 INTRODUCTION

For most piled raft foundation, the primary purpose of the piles is to act as settlement reducers. The proportion of load carried by the piles is considered as a secondary issue in the design. Over the past decades, extensive research work has been presented, aimed at improving the accuracy in the prediction of the behaviour of piled rafts. To carry the excessive loads that come from the superstructures like high-rise buildings, bridges, power plants or other civil structures and to prevent excessive settlements, piled foundations have been developed and widely used in recent decades. However, it is observed that the design of foundations considering only the pile or raft is not a feasible solution because of the load sharing mechanism of the pile-raft-soil. Therefore, the combination of two separate systems, namely "Piled Raft Foundations" has been developed (Clancy and Randolph (1993)).

The conventional approach of designing pile-raft foundation system generally results in the installation of more piles than that are necessary, which leads to uneconomical design practice. Different approaches, involving the use of piles as settlement reducers have been reported by Randolph (1994), Burland (1995), Sanctis et al. (2002), and Fioravante et al. (2008). The term 'settlement reducing piles' originates from Burland, Broms & de Mello (1977).

Bajad et al. (2008) conducted small scale model tests at 1 g-level to investigate the settlement behaviour of pile-raft system over soft clays having 4, 16, 36, 64 piles in group. Poulos 2001 gives the three stage progress to design the piled raft foundation system and compares his analysis with other analytical approaches available. Fioravate 2011 have studied the load transfer mechanisms between a pile and a raft with an interposed granular layer by means of centrifuge physical model tests.

2 EXPERIMENTAL WORK

A series of laboratory tests were performed on models of unpiled raft, single pile and central piled raft to examine the settlement behaviour of axially loaded pile-raft foundation system. Tests on 19 mm diameter aluminium piles with single pile has been carried out for centrally located pile and same thickness of raft. Details of piles configuration and model raft dimensions adopted in present research work is shown in Figure 1.

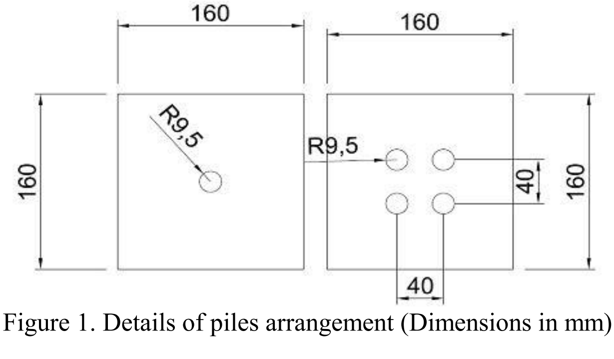


Figure 1. Details of piles arrangement (Dimensions in mm).

2.1 *Experimental set-up*

Tests were performed in a cylindrical mild steel vessel of 500 mm diameter and height of 500 mm. The mild steel base plate was also provided with four numbers of holes separated at 1200 angle and distanced at R/2, R/4, 2R/3 and at centre c/c for the drainage purpose. The loading frame consists of four vertical columns (C-Section) of 1 m height, two on each side and two horizontal beams (C-Section). The load was applied through a mechanical jack fixed at centre as shown in Figure 2. Two linear vertical displacement transducers (LVDTs) of 0.01 mm accuracy were located at the middle side of the raft, to measure vertical downward settlement.

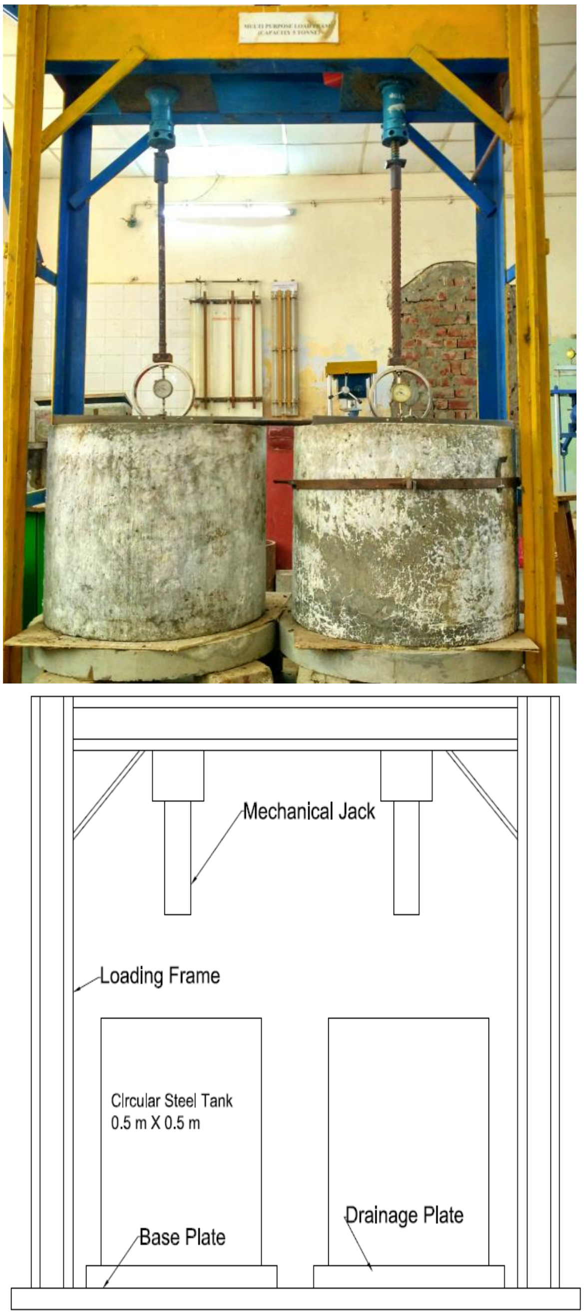


Figure 2. Schematic diagram and actual photograph of model test set-up.

2.2 *Properties of materials*

Marine soft clay is used to prepare soft clay bed. The index properties of soft clay are presented in Table 1

Table 1. Properties of soft marine clay

Index Property	Values
Specific gravity	2.47
Liquid limit	55
Plastic limit	21.31
Plasticity index	33.69
Shrinkage limit	17.16
Free swell index	30.77
Maximum dry density	16.7
Optimum water content	20.80

2.3 *Preparation of soft clay bed*

Soft marine clay available at Dahej, Gujarat having liquid limit and plastic limit as 55 % and 21.31 %, respectively was used in present research work. It was placed in the cylindrical vessel with water content equal to liquid limit and consolidated under the consolidation pressure of 80 kPa. After final consolidation, the water content of soil after model test was found to be between 35-40 %. Undrained shear strength of the consolidated clay as measured by unconfined compression tests after the model test was found to be 10 ±0.5 kPa. The angle of internal friction between pile and clay was found to be 11.910.

2.4 *Model of raft and piles*

Aluminium plates, with fixed thickness, served as model rafts. The dimensions of the raft was 160 mm ×160 mm × 4 mm. The modulus of elasticity and Poisson's ratio of aluminium plates were 70 GPa and 0.33, respectively. The model piles used in the experiments were aluminium hollow pipes of 19 mm in outside diameter and 1.5 mm in wall thickness. The modulus of elasticity and Poisson's ratio of the aluminium pipe were 70 GPa and 0.33, respectively. The embedded pile lengths of 200 mm was used in the experiments. The lengths represent L/D ratios of 10. Top head of each pile was provided with a bolt of 6 mm in diameter with a wooden piece of 20 mm length to connect the pile to the cap through two nuts to ensure a complete fixation between the pile and the cap as shown in Figure 3.

Figure 3. Connection between the pile and the raft.

2.5 *Test procedure*

– Each experiment started with placing the clayey soil in the cylindrical steel vessel in slurry state. The slurry was allowed to consolidate by its own for 24 hrs. Then artificial consolidation was carried out at 80 kPa.

– As the piles were driven, wooden templates were used to locate the piles in the correct positions, and then each pile was inserted vertically into the clay by driving with a steady succession of bellows on the top of the pile using a steel hammer weighting 2 kg. The sequence of piles installation started with the inner piles, then corner piles, and finally the edges piles.

– After the installation of piles to the required depth, the wooden templates were removed. Then, the raft model was placed on the clay 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.

– Two LVDTs were placed at the centre of the raft sides to measure the vertical downward settlement.

– A calibrated proving ring of 10 kN capacity was connected to mechanical 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 foundation system's settlement reaches 25 mm in case of unpiled raft, and piled raft. In case of pile group the test continued till the settlement reaches 20 mm.

3 RESULT AND DISCUSSION

The model tests results obtained from laboratory tests are analyzed and discussed in this section. The settlement equal to 10% of pile diameter or raft width is often adopted to define the ultimate load capacity in foundation design (Cerato et al. 2006, Lee et al. 1999, Lee et al.2005). In this model tests, loading was continued till the raft settlement reaches 25 mm and pile settlement reaches 20 mm.

3.1 *Effect of raft's thickness*

As seen in Fig. 4. the increase in raft's thickness improves load bearing capacity of unpiled raft. The thickness of raft is selected such as the stiffness varying from very flexible raft to rigid raft. The load carrying capacity of unpiled increases by 6% and 13% at 10mm settlement going from 2mm thick raft to 4mm and 8mm thick raft respectively. Similarly the increment was 9% and 20% for 4mm and 8mm thick raft at 25mm settlement.

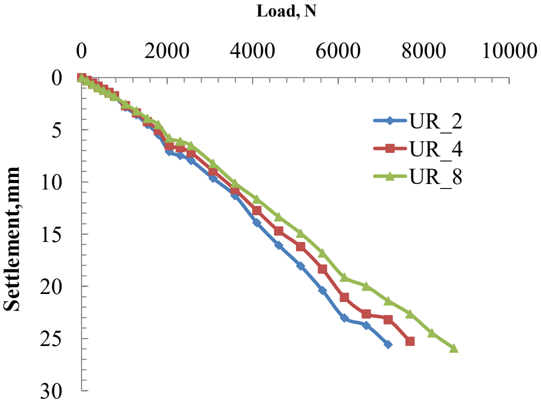


Figure 4. Load vs. Settlement for 2mm, 4mm and 8mm thickness of raft.

3.2 *Effect of number of pile*

Figure 5 shows the effect of number of piles in pile group and piled raft. The L/D ratio was 10, number of piles were 1 and 4 and raft of thickness 4 mm. It is seen that in case of pile group, increasing pile number from 1 to 4 increases load carrying capacity at 20 mm settlement by 6.45 %. While in case of piled raft system the load carrying capacity at 20 mm settlement increases by 39.57 % by replacing single pile by 4 piles. PG_1_10 means pile group with single pile of slenderness ratio 10, PR_4_1_10 means piled raft with 4mm thick raft and single pile of L/D 10.

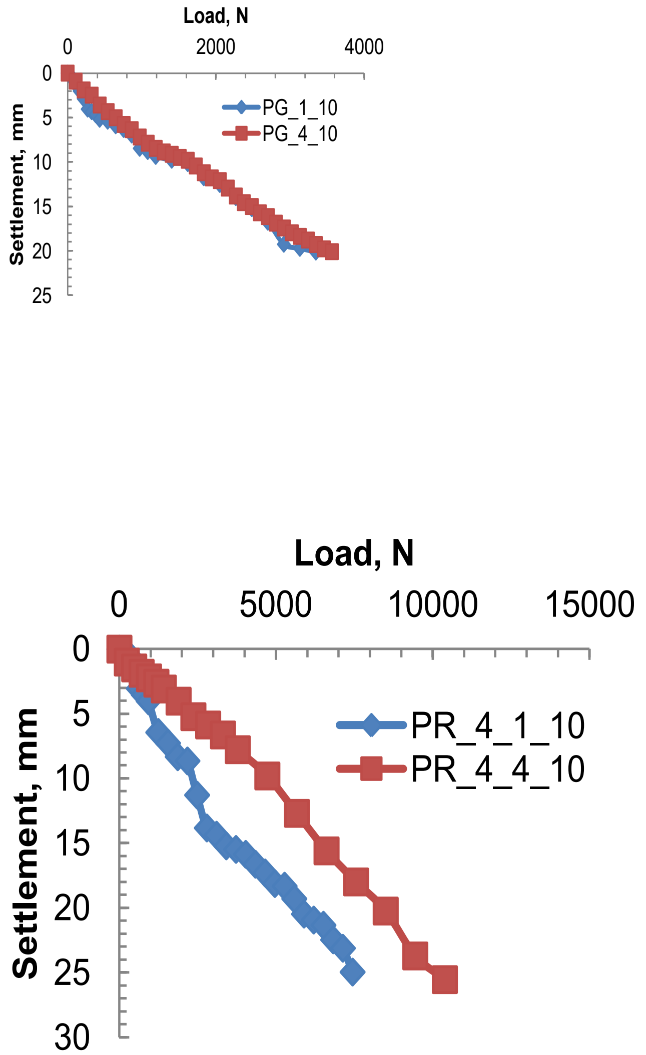
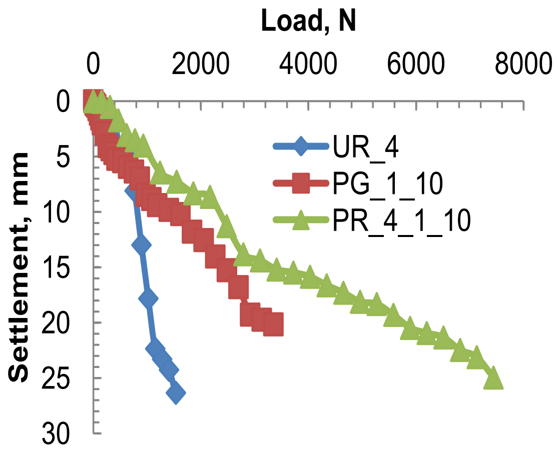


Figure 5. Load Vs Settlement for 1 and 4 numbers of piles in pile group and piled raft system .

3.3 *Piled raft system*

Figure 6 shows the load-settlement behaviour of piled raft foundation in soft clays compared to unpiled raft and pile group with 1 and 4 piles.



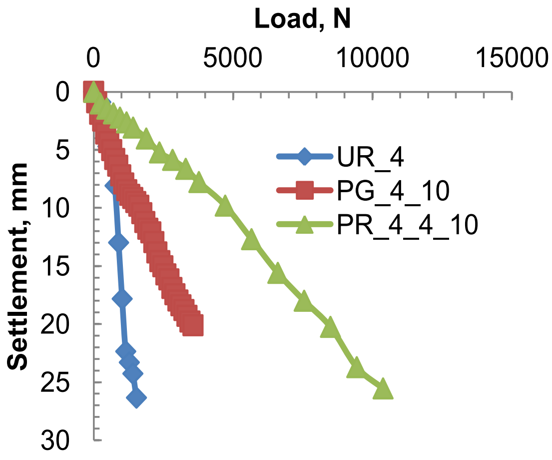


Figure 6. Load vs Settlement a) single pile b) four piles.

As seen in Figure 6a and Figure 6b the load carrying capacity of unpiled raft is higher than pile group for initial stage of loading but for at higher settlement the load carrying capacity of pile group is higher than unpiled raft. As seen in Figure 6a up to 7 mm settlement raft carries higher load than single pile then the single pile carries higher load. And in Figure 6b it has seen up to 5 mm settlement raft carries higher load after then pile carries higher load. The bearing capacity of piled raft is higher than both the unpiled raft and pile group.

(b)

3.4 *Settlement of pile-raft*

The theoretical settlement of pile-raft foundation was calculated using Burland's approach (1995).

$$s_{pr} = s_r * K_r / K_{pr} \quad (1)$$

Table 2. Theoretical and measured settlement

Theoretical Settlement, mm	10
Measured settlement for piledraft with 1 pile, mm	7
Measured settlement for piledraft with 1 pile, mm	3.15

Its seen that the measured settlement is lesser than the theoretical value of settlement. And it reduces as the number of pile increases.

3.5 *Load sharing behaviour*

The load sharing behaviour can be expressed using the load sharing ratio αp that represent the ratio of load carried by piles to the total load imposed on piled raft.

$$\alpha_p = Q_p / Q_{pr} = 1 - Q_r / Q_{pr} \quad (2)$$

Q_{pr} = load imposed on piled raft, Q_r and Q_p = load carried by piles and raft.

Clancy and Randolph proposed an equation of αp in terms of pile and raft stiffness as :

$$\alpha_p = 1 - [\{ (1 - i_{rp})(K_r / K_p) \} / \{ 1 + (1 - 2i_{rp}) (K_r / K_p) \}] \quad (3)$$

where K_r and K_p = raft and pile stiffness on load-settlement curves; i_{rp} = raft-pile interaction factor.

Using both the equations it is determined that in case of pile-raft system with single pile and four piles the load shared by pile is 45 % of total imposed load on pile-raft and raft is carrying is 55 % of it.

Figure 7a shows the variation of the proportions of loads carried by piles and raft with the number of settlement reducing piles for raft of relative stiffness 0.36. As seen from the graph, by adding four piles the load sharing ratio of raft reduces by 23.52 % and by same amount the load sharing ratio of pile increases for 4 number of piles. It can be noted from Figure 7b that at the same raft relative stiffness (0.36) and L/D ratio (10), the value of L/R increases as the number of piles increases. At 25 mm settlement, for 0.36 relative stiffness of raft, installing 4 settlement reducing piles with L/D=10 causes an increases in the raft load by 35.74 %.

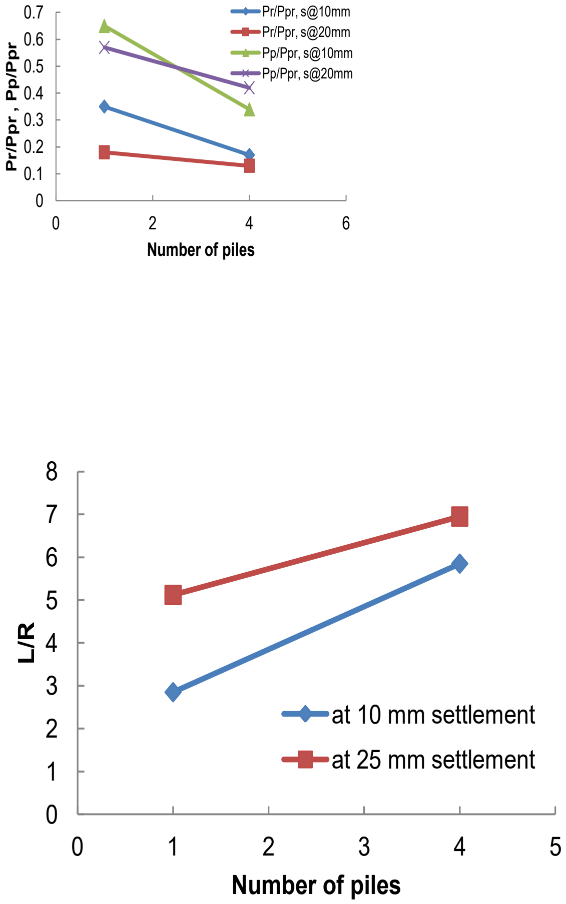


Figure 7. a) Load sharing between raft and piles for central piled raft, b) Load improvement ratio with number of piles at 10mm and 25mm settlement

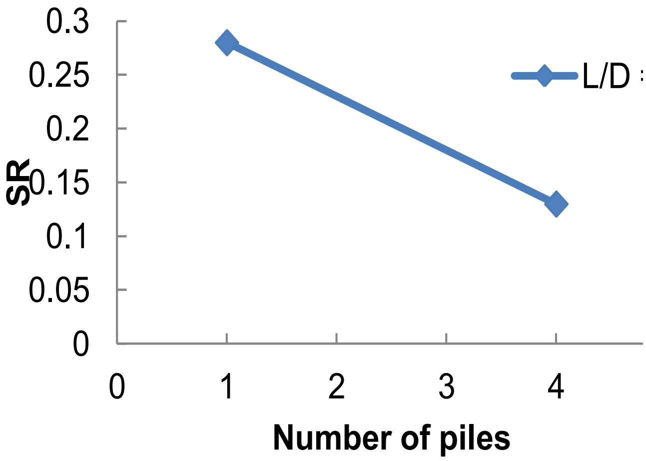


Figure 8. Settlement ratio, SR, with number of piles.

Figure 8 shows the variation of settlement ratio, SR, with the number of piles for raft with relative stiffness of 0.36. It is observed that the settlement ratio decreases as the number of piles increases i.e. installing 4 piles causes a decrease in the settlement of the raft by 53.57 %.

4 CONCLUSIONS

The paper has presented experimental results of load tests on model unpiled raft, pile group, and piled raft embedded in soft clays. The research work focuses on the load-settlement behaviour and load sharing between the pile and raft. From the result of this study following conclusion can be drawn:
From the result of this study, the following conclusions can be drawn:

- Increase in raft thickness shows higher increment in the load carrying capacity of unpiled raft for large settlment compared to small settlement.
- The addition of piles beneath the raft causes increase in raft's load bearing capacity. Addition of 1 and 4 piles causes 4 and 6 times increament in load carring capacity of unpiled raft.
- At 10 mm and 25 mm settlements, L/R, load improvement ratio increases as number of piles increases. There is 18.8 % increament in L/R for 4 numbers of piles from 10 mm to 25 mm settlement.
- Its also observed that as the number of piles increases the load shared by raft reduces and load shared by pile increases.
- There is also considerable amount of decrement in settlement ratio by going from 1 to 4 number of piles.
- The rate of increase of settlement reduction ratio decreases as the thickness of raft increases.With either increase in length of pile or number of piles the ultimate load carrying capacity of pile-raft system decreases.

- The influence of number of pile over settlement analysis shows that as the number of pile increases the % settlement reduction increases for the same load.
- In case of length of pile, the increase in pile length causes an increment in % settlement reduction of pile-raft system.
- It is observed from the research study that the amount of compressive load resisted by unpile raft is more than that of pile group with mono pile for the same settlement.
- It is also observed that even if there is increment in the length of the pile its resistance to compressive load is less than unpiled raft.
- In case of group piles it is observed that the compressive load resisted by pile group with four piles is more than that of unpiled raft for higher settlement.
- Initially the compressive load carried by raft is higher than that pile group but gradually as the compressive load increases the compressive load carried by pile group increases.

A raft may be adequate in terms of bearing capacity but calculated settlements may exceed the tolerable values. In such cases, piles may be introduced under the raft foundation. These piles are limited in number so that they are continuously at the limit state with factor of safety of one. This concept is known as settlement reducing piles. It is also concluded that pile-raft system flexible and rigid raft and 4 number of piles is efficient both in terms of compressive load capacity and settlement when embedded in soft clay. Out of many factors which affect the pile-raft system behaviour and its load transferring mechanism, the slenderness ratio (L/D), number of piles, thickness of raft, soil-pile interface angle (δ), stiffness of pile-raft system, moisture content of soil bed, joint between pile and raft are major factors which play a major role in estimating load capacity and settlement under axial compressive.

If a raft behaves as a flexible member with a pile the flexible approach of uniform compressibility under raft will govern the design or load carrying capacity. While assuming raft to be rigid like a pile cap, the design will be governed by type of pile and pile length. Thus from the above study the pile-raft system can be used successfully in clays with selection of suitable approach.

5 ACKNOWLEDGEMENT

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