An Experimental Study of the Piled Raft Foundation Subjected to Combined Vertical and Lateral Load

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Abstract: 1-g experimental tests have been carried out to investigate the behavior of piled raft foundation subjected to combined vertical and lateral load. The vertical load was applied till a constant settlement of test models and it was followed by the horizontal incremental load. The piled raft models including a single pile, unpiled raft and pile group models had been tested on cohesionless soil. The pile configurations of 2×2 and 3×3 with a constant spacing of 3.5 times diameter of a pile and constant pile length of 25 times diameter of a pile were adopted for the piled raft models in this study. The raft-soil contact was an important factor to reduce the horizontal displacement of the piled raft. There was a significant reduction found in the horizontal displacement of the piled raft foundation due to the presence of the vertical load.At an assumed horizontal load of 100 N, there was about 3.75 to 5.33 times reduction in the horizontal displacement of adopted piled raft models in the presence of vertical load till 10 mm settlement.

Keywords: Piled raft foundation, Horizontal incremental load, Horizontal displacement, Weight-pulley mechanism

1 Introduction

Piled raft foundation is aprogressive foundation concept to support high rise superstructures. It consists of three bearing elements, which are piles,raft and sub-soil.A new design philosophy of piled raft has been proposed to improve the loading capacity of conventional pile groups [1, 2]. The detailed study of average settlement and differential settlement of piled raft foundation and its implementation for the support of heavily loaded structures has been compiled by different authors [3, 4].

A number of experiments have been carried out to study the piled raftfoundation system by applying vertical load [5, 6]. The load-settlement relations of the piles,raft and the piled raft wereanalyzedand the improvement in the load-settlement curve due to the combined action of piles and raft was studied by authors [6, 7]. These experimental studies mostly describe the reduction in the settlement of piled raft and load sharing percentage of raft and piles.

Thebehavior of piled raft foundation subjected to static lateral load has been studied with 1-g experimental tests on piled raft models by different authors [8, 9, 10]. The confining stress of isolated pile and piles beneath the raft was different and so the lateral stiffness of piled raft was different from the piles. It was concluded that at a lower horizontal load, the horizontal load-displacement relation proposed linear relation. The experimentaltests on piled raft models subjected to horizontal load and moment load have been performed too [11]. As the height of the horizontal load point increased., the horizontal displacement and inclination of piled raft models also increased for a given horizontal load. It was also reported that the initial lateral stiffness of piled raft decreased with an increase in the height of the horizontal load point. To study the lateral load behavior of piled raft foundation, the centrifuge modelingtests have been carried out [12,13]. The effect of pile head connections has been also analyzed by the authors and a significant decrease was concluded at the moment at pile head of hinged connected piled rafts during lateral load analysis [14,15]. It was reported by the lateral load tests on the piled raft that most of the lateral force was carried by the friction of raft and soil because of thehigh contact pressure beneath the raft [16].

Since the horizontal displacement of the piled raft during lateral loading is essentially analyzed in the design practices. But, without a vertical load of the superstructure on the foundation, the lateral load analysis can lead to the overestimation of the design. A very few experiments have been reported on the combined effect of vertical and lateral load on the piled raft foundation system [17]. It was reported that the lateral displacement of the vertically loaded piled raft was reduced drastically.

A design concept based on the lateral load alone, may not be able to reveal the exact behaviour of the foundation system. The settlement of structure should be within permissible limit under vertical load and the lateral load analysis would be performed for vertically loaded foundation. In the present study, 1-g experimental tests have been carried out to study the response of the displacement behavior of vertically loaded piled raft foundation system, where, the vertical load was applied to the corresponding settlement of 10 mm and it was followed by a constant increase in horizontal load. A constant value of 10 mm settlement of each model has been considered which is less than 10% of the raft width.

2 Test Methodologies

In the first step, the test models in the experiment were subjected to a constant horizontal increment load. In the second step, these experimental models have been tested by applying vertical concentrated load till the settlement of 10 mm and followed by applying constant increment of the horizontal load to investigate the behavior of piled raft foundation system under the combined action of vertical and lateral load.

3 Test Materials

3.1 Sand

The river bed sand was taken to perform the experimental tests. It was free from organic materials and sieved with 2 mm sieve. The particle size distribution curve of the sand has been plotted and shown in figure 1 and the physical properties of the sand have been presented in table 1.

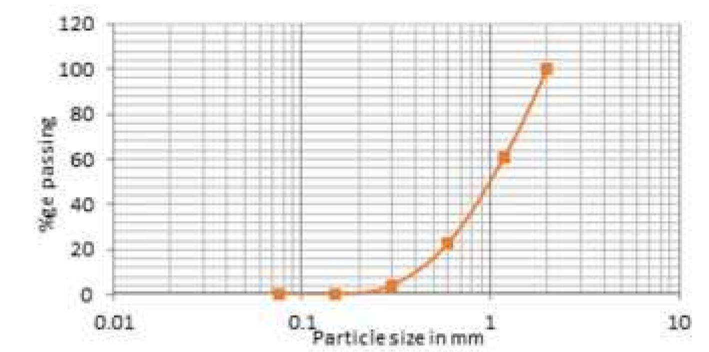


Fig. 1. Particle size distribution curve

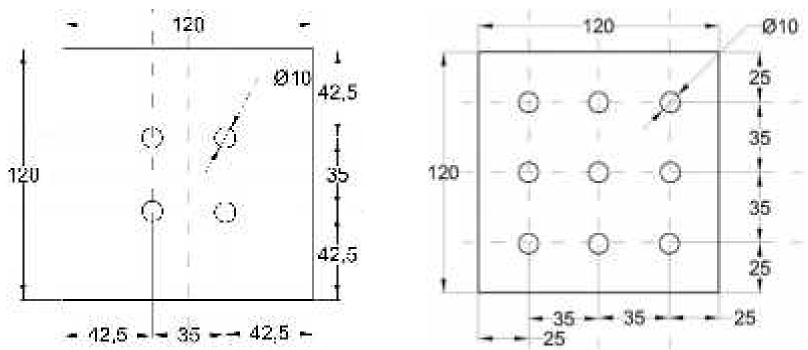


Fig. 2. Piled raft models layout of 2×2 and 3×3 configurations (All the dimensions are in mm)

3.2 Raft and pile models

The raft of dimension 120 mm × 120 mm × 10 mm was adopted throughout the experiment. The geometrical and material properties are represented in table 2.

The material properties of piles and raft models were similar. The pile of 10 mm diameter and 250 mm length was adopted throughout all the tests. The pile groups of configurations 2×2 and 3×3 were adopted for pile groups and piled raft system with a constant spacing of 3.5 times diameter of a pile. The layout of piled raft models has been shown in figure 2. Those piles were welded with each other in a group with thin plates to act monolithically during the load tests.

The length to diameter ratio of the pile, L/D=25, was referred to in the study, which lies between short to the long pile, as per IS 2911-Part-I (Section II).

Table 1. Physical properties of soil

Sr.no.	Physical properties	Values and Description
01	Specific gravity	2.63
02	Maximum dry density	16.20 kN/m^3
03	Minimum dry density	14.40kN/m3
04	Uniformity constant, Cu	2.60
05	Coefficient of curvature, Cc	0.90
06	Soil classification	SP
07	Secant modulus of soil at the density of 15.15 kN/m^3, E_{50}	3200 kN/m^2
08	Angle of internal friction by direct shear test, Φ	32.4^0

Table 2. Geometrical and Material properties of the raft and piles

Sr.no.	Description	Raft details	Pile details
01	Shape	Square	Solid circular
02	Dimension	120 mm× 120 mm× 10 mm	250 mm in length and 10 mm in diameter
03	Material	Mild steel	Mild steel
04	Modulus of elasticity	180×10^6 (kN/m^2)	180×10^6 (kN/m^2)

4 Test Procedures

4.1 Test set-up

The steel tank of dimension 850 mm × 850 mm × 600 mm was placed on the loading frame, which was fabricated for both vertical load and lateral load, shown in figure 3(a) with its descriptions.

The lateral load was applied with the help of hanging dead weight, which moves down with the help of non-extensible wire moving on the pulley mechanism to ease the constant increase in the horizontal load. This loading test facility has been shown in figure 3(b). The vertical load was applied with a constant strain rate of 1mm/min. The lateral load was similar to the dead weight, which increased with the constant addition of dead weight.

4.2 Installation of piles

The pile models were installed one-fifth length i.e. 50 mm first on the sand bed and then the soil was filled with the desired density up to the full length of pile i.e.250 mm length, without disturbing the pile. In the case of 3×3 configurations, the sequence of pile installation started with the inner pile, following by corner piles and edge piles at last. To assure the rigid pile head connection with the raft, 6 mm bolts were tightened to the threads of piles. On the account of the vertical load test, the free-standing single pile and pile groups were installed about 10mm above the sand surface.

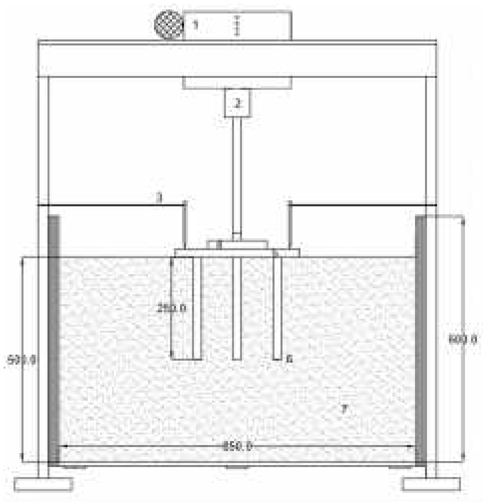
4.3 Soil distribution

The sand bed was prepared with each layer of 50 mm up to 500 mm with a relative density of 47%. To achieve a density of 15.15 kN/m^3 corresponding to 47% relative density, the rainfall technique was used from a height of fall of sand 300 mm. The pre-calculated volume of each layer was maintained and levelled with its desired density to the full test height of the tank during the entire experiment.

4.4 Loading test procedure

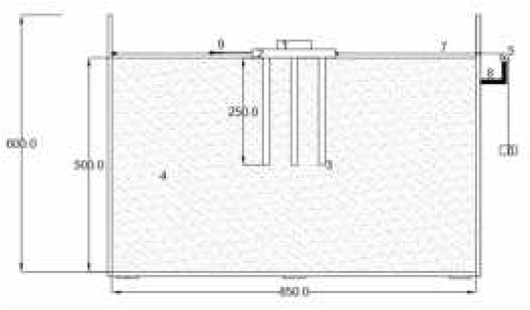
1. The sand bed was prepared with the desired density of each 50 mm layer.
2. In the first phase of the experiment, the purely lateral load was applied to the piled raft models along with a raft and piles. The horizontal load was increased with a constant load of 10 N placing the dead weight on the weight assembly, which was moving freely over the frictionless pulley with non-extensible steel wire. The displacement of these models was measured with the help of a linear variable differential transducer (LVDT), which was installed horizontally to the foundation system. It was waited till a constant value of settlement by LVDTs before placing another load on the weight assembly. In the second phase of the experiment, the vertical concentrated load was applied to each test model with a constant strain rate of 1 mm/minute till the constant settlement of 10 mm, which was followed by the lateral load with the help of wire-pulley mechanism.
3. The calibrated load cell was used to perform the vertical load test and LVDTs were placed vertically in the middle of sides of a raft to measure the corresponding settlement. The channel box was able to display the load and corresponding displacement.
4. The soil was replaced for each test in the loading tank.

A number of model tests in the experimental program were carried out to investigate the behavior of piled raft foundation in the present study and presented in table 3.



1. Motorized strain-controlled loading machine
2. Load cell, capacity 10 kN
3. LVDTs
4. Loading plate
5. Raft
6. Piles
7. Sand up to 500 mm

(a)



1. Loading plate
2. Raft model
3. Piles of 3×3 configuration
4. Sand
5. Frictionless pulley
6. Deadweight
7. Non-extensible wire
8. Angle section to support pulley mechanism
9. LVDT

(b)

Fig. 3. Experimental set-up with descriptions: a) Vertical load facility & b) Lateral load facility (All dimensions are in mm)

Table 3. Experimental program

Models	Purely Lateral load test	Combined load test (Vertical load applied till 10mm settlement and followed by Lateral load)
Unpiled raft	Yes	Yes
Single pile	Yes	Only vertical load was applied
Pile group and piled raft (2×2 and 3×3)	Yes	Yes

5 Results and Discussions

The results of the lateral load test and combined vertical and lateral load tests have been discussed with horizontal load vs. horizontal displacement of the test models. The vertical load tests were also discussed with the vertical load vs. average settlement.

5.1 Horizontal load test results

The horizontal load-displacement behavior of a single pile and pile groups has been shown in figure 4 (a). The horizontal stiffness of 2×2 and 3×3 configurations of pile groups were found higher than the single pile. It justified that with an increase in the number of piles in a group, there was an increase in the lateral stiffness of pile groups.

It was seen in figure 4(b) and 4(c), the lateral loading capacity of piled raft foundation was higher than pile groups at a given displacement because the horizontal load of the piled raft was carried by both the piles and raft-soil friction. The combined stiffness of raft and piles increased the horizontal load capability of piled raft foundation, where the raft-soil contact was an important factor to increase the horizontal stiffness of piled raft. Before yielding up to the elastic stage, the lateral stiffness of both the configurations of the piled raft was almost the same as shown in figure 4(d). The lateral stiffness of configuration 3×3 of piled raft foundation was found about 1.2 times to the configuration 2×2 of piled raft foundation at a given displacement of 0.1D, where D is the diameter of a pile.

5.2 Vertical load test results

Figure 5 (a) shows the load-settlement behavior of single pile and pile groups of 2×2 and 3×3 configurations. The single pile was yielded earlier than pile groups. The stiffness of pile groups was increased with an increase in the number of piles in a group and the average settlement was also reduced.

The load-settlement curve of the unpiled raft and piled rafts are shown in figure 5 (b). The average settlement of the piled raft foundation was found remarkably less than the unpiled raft. There was a considerable improvement in load-settlement behavior of piled raft foundation over free-standing pile groups, as shown in figure 5(c) and (d).

The vertical loading capacity of piled raft foundation of configurations 2×2 and 3×3 was found increased 1.32 times and 1.20 times to a pile group of 2×2 and 3×3 configurations respectively at a considered settlement of 10 mm due to combined stiffness of both raft and piles.

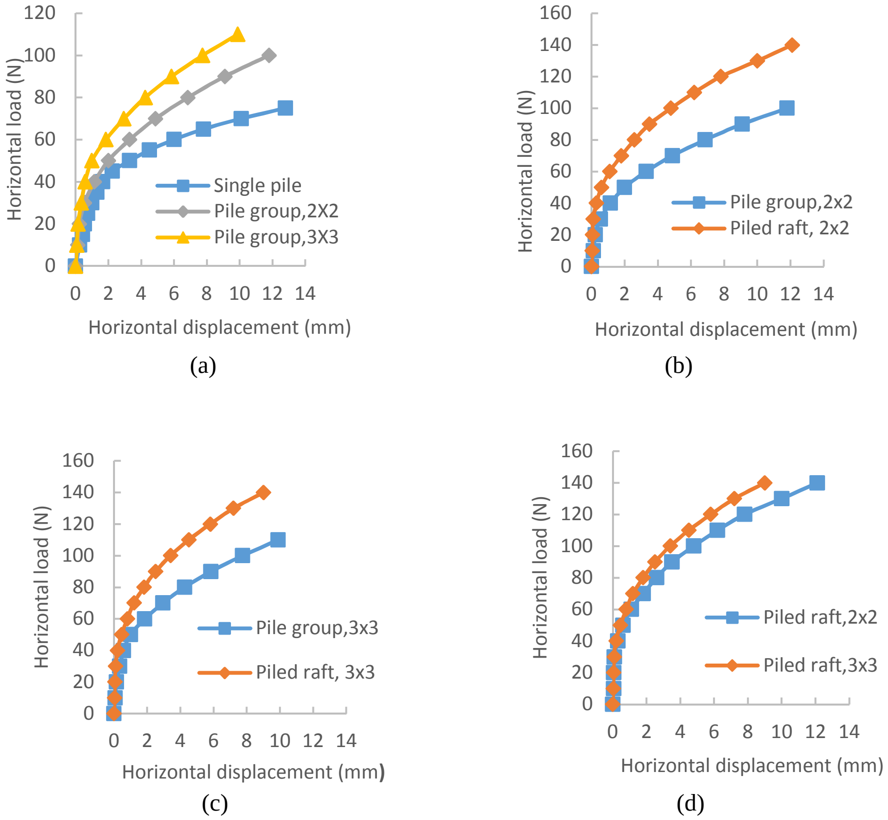
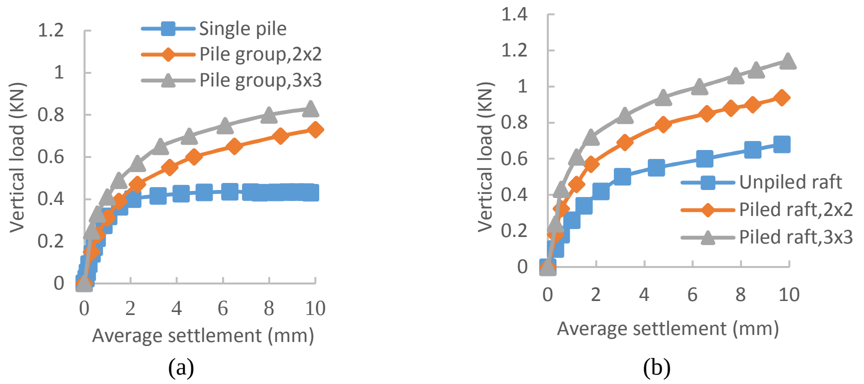
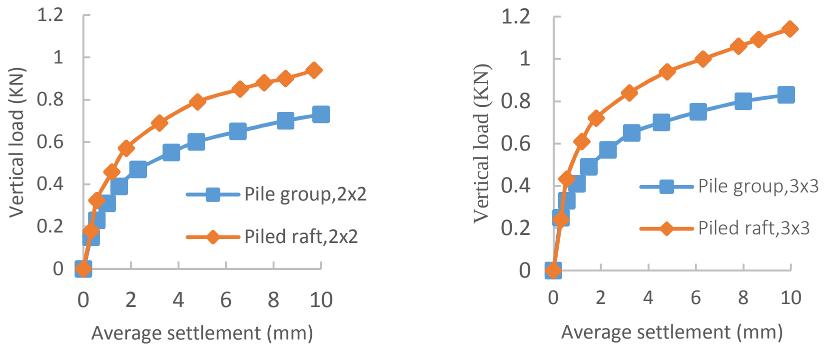


Fig. 4. Horizontal load-displacement graphs: a) Single pile and pile groups b) Pile group and piled raft of configuration 2×2 c) Pile group and piled raft of configuration 3×3 d) Piled rafts of configuration 2×2 & 3×3





(c) (d)

Fig. 5. Vertical load-displacement curve of (a) Single pile and pile groups (b) Unpiled raft and piled rafts (c) Pile group and piled raft of 2×2 configuration (d) Pile group and piled raft of configuration 3×3

For both the vertical and horizontal load tests, the linear trend on the graphs presents that during the first stage both the pile-soil & raft-soil system of piled raft foundation behaves elastic & then after yielding it shows the elastic-plastic behavior and the similar response of piled raft experimental models have been reported by the author [1].

5.3 Combined vertical & horizontal load test results

The constant increase in horizontal load & corresponding displacement of test models with influence of the vertical load & without vertical load is presented in figure 6. The horizontal displacement reduced rapidly with the influence of the applied vertical load. The greatest influence of vertical load on horizontal displacement was recorded by piled raft foundation models. The horizontal load capacity of the unpiled raft was increased 1.2 times by applying a vertical load of 488 N, corresponding to a 10 mm settlement at a given displacement of 10% of the diameter of a pile as shown in figure 6(a). The horizontal loading capacity of pile groups of 2×2 and 3×3 configurations was increased by about 1.2 and 1.4 times respectively with applying vertical load till 10 mm of corresponding settlement presented in figure 6 (b) and (c). At a given settlement of 0.1 D, the horizontal loading capacity increased to 1.67 & 2.4 times of configurations 2×2 and 3×3 of piled raft foundations respectively as shown in figure 6 (d) and (e).

At a horizontal load of 100 N, there were about 3.75 times and 5.33 times reduction in the displacement of a piled raft of configurations 2×2 and 3×3 respectively in presence of vertical load corresponding to 10 mm settlement.

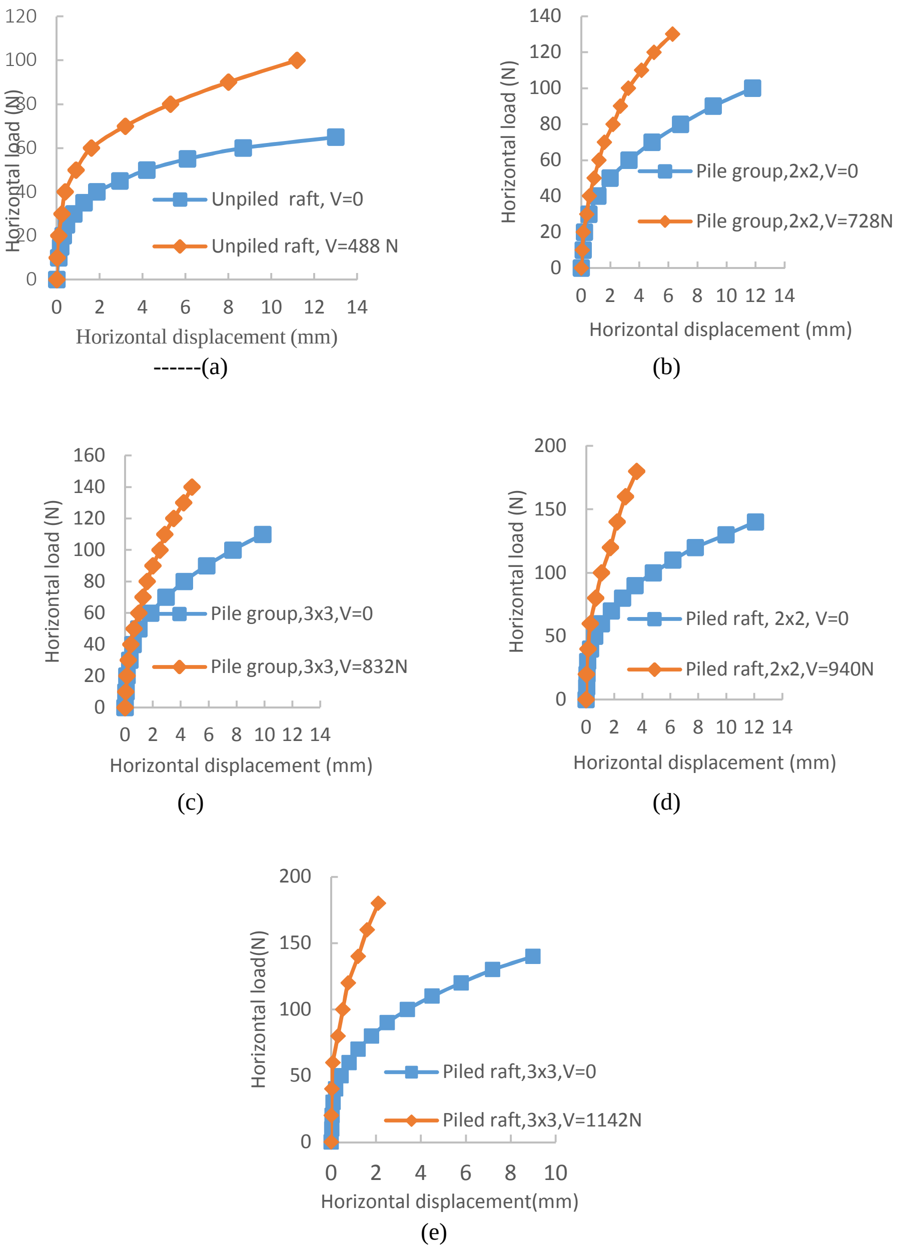


Fig. 6. Horizontal load-displacement behavior of a) Un-piled raft b) Pile group of 2×2 configuration c) Pile group of 3×3 configuration d) Piled raft of 2×2 configuration e) Piled raft of 3×3 configuration in presence of vertical load

There was a significant effect on horizontal displacement of unpiled raft, piles and piled raft foundation on applying vertical load on medium dense sand. The strongest influence was recorded for the piled raft foundation.On applying the vertical load, the horizontal loading behavior of the piled raft foundation shows a similar behaviour published by the author [17].

6. Conclusion

The 1-g experimental tests on piles, raft and piled raft have been carried out to investigate the behavior of piled raft foundation system subjected to combined vertical and lateral load. These experimental model tests were conducted on a dry sand bed of density 15.15 kN/m^3. As per the material and geometrical properties of 1-g model test conditions in the study, the following conclusions were drawn:

1. The raft contact with soil was found very effective to reduce the horizontal displacement and the vertical settlement of the piled raft foundation system.
2. The initial horizontal stiffness of the piled raft was higher than the piles and unpiled raft. At a lower lateral load level, the horizontal stiffness contributes a linear relation between the horizontal load and displacement, but with an increase in horizontal load, there was a non-linear trend observed.
3. The horizontal load-displacement behavior of piles, raft and the piled raft was found dependent on vertical load. In the presence of vertical load, there was a significant reduction of horizontal displacement during the lateral load test. The horizontal displacement was reduced by about 3.7 to 5.33 times of the vertically loaded piled raft of adopted configurations and geometrical properties in the study at a considered horizontal force of about 100 N. The maximum reduction in horizontal displacement recorded in piled raft foundation among piles, unpiled raft and piled raft foundations in the presence of vertical load.

   It was very clear that neglecting the vertical load on a piled raft, the horizontal displacement of piles is very high during the lateral load test and it may lead to overestimation in design.

References

1. Poulos, H.G.: Piled raft foundations: design and applications, Geotechnique 51, No.2, 95-113 (2001).
2. Randolph, M.F.: Design methods for pile groups and piled rafts, Proc. 13th ICSMFE, 61-82 (1994).
3. Hemsley, J. A.: Design applications of raft foundations, Thomas Telford, England, London (2000).

4. Poulos, H.G.: Method of analysis of piled raft foundations, ISSMGE TC-18, Report (2001).
5. Balakumar, V., Kalaiarasi, V.,Ilamparuthi K.: Experimental and Analytical Study on the Behaviorof Circular Piled Raft on Sand. Proc. 16th Intl Conf. on Soil Mechanics and Geotechnical Engineering, Osaka, Japan, pp. 1943-1947 (2005).
6. Patil, J, Vasanwala, S., Solanki, C H.: An experimental study on behavior of piled raft foundation. Indian Geotechnical Journal.Volume 46, Issue1, pp 16-24 (2016).
7. Kumar, V, Kumar, A.: An experimental study to analyze the behavior of piled-raft foundation model under the application of vertical load, Innovative infrastructure solutions (2018).
8. Hashizume, Y., Matsumoto, T.: Lateral load tests on model pile groups and piled raft foundations in sand. Int. Conf. on Physical Modelling in Geotechnics, St. John's, Canada, 709-714 (2002).
9. Horikoshi, K., Matsumoto, T., Hashizume, Y., Watanabe, T., Fukuyama, H.: Performance of piled raft foundations subjected to static horizontal loads. IJPMG – Int. Journal of Physical Modelling in Geotechnics, Vol. 2, 37-50 (2003a).
10. Pastsakorn, K., Hashizume, Y., Matsumoto, T.: Lateral load tests on model pile groups and piled raft foundations in sand. Int. Conf. on Physical Modelling in Geotechnics, St. John's, Canada, 709-714 (2002).
11. Matsumoto, T., Fukumura, K., Kitiyodom,P., Horikoshi, K., Oki, A.: Experimental and analytical study on behaviour of model piled rafts in sand subjected to horizontal and moment loading, International Journal of Physical Modeling in Geotechnics, 4(3), 1-19 (2004a).
12. Horikoshi, K., Matsumoto, T., Hashizume, Y., Watanabe, T., Fukuyama, H.: Performance of piled raft foundations subjected to dynamic loading. Int. Jour. Of physical modeling in Geotechnics, Vol. 2, 51-62 (2003b).
13. Matsumoto, T., Fukumura, K., Horikoshi, K., Oki, A.: Shaking Table tests on model piled rafts in sand considering the influence of superstructures, International Journal of Physical Modeling in Geotechnics, 4(3), 21-38 (2004b).
14. Kumar, A, Chaudhary, D., Katzenbach, R.: Behaviour of the combined piled-raft foundation under static and Pseudo-static conditions using Pla×is 3D, 6th international conference on earthquake geotechnical engineering.Christchurch, New Zealand (2015).
15. Matsumoto, T., Nemoto, H., Mikami, H., Yaegashi, K., Arai, T.,Kitiyodom, P.: Load tests of piled raft models with different pile head connection conditions and their analyses, Soils, and Foundations, Vol.50, No.50, 63-81 (2010).
16. Hamada, J., Tsuchiya, T., Tanikawa, T., Yamashita, K.: Lateral Loading Tests on Piled Rafts and Simplified Method to Evaluate Sectional Forces of Piles. Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol. 46, No.2 (2015).
17. Katzenbach, R, Turek, J.: Combined pile-raft foundation subjected to lateral loads. Proceeding of the 16th international conference on soil mechanics and geotechnical engineering (2006).
18. Indian standard 2911 (Part I/Sec II): Design and construction of pile foundations. Bureau of Indian Standards, New Delhi (2010).