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Experimental Study on Lateral and Vertical Capacity of Piled Raft and Pile Group System in Sandy Soil

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Abstract: In deep foundations, the pile group and the pile raft are generally used. To date, the contribution of the raft is not taken into account in the design, even when the raft is in contact with the soil and the whole system is therefore considered to work as a pile group foundation. In a combined pile raft system, the raft takes a considerable portion of the applied load, depending upon the number of piles, the spacing to diameter ratio of the piles, and the length to diameter ratio. In this paper, an experimental investigation is carried out to study the response of small-scale pile group and piled raft models with a varying number of piles subjected to both vertical and lateral loads. Additionally, the response mechanism of these models to both types of loads is also studied. A comparison was made between these models. It was found that, unlike the pile group, the piled raft provides considerably high stiffness to both types of loads, and the difference between the stiffness of both systems decreases as the number of piles increases. By comparing the response of the piled raft and the pile group with the same number of piles under the same vertical and lateral load, it was concluded that the piled raft response to the lateral and vertical loads was much stiffer than the pile group response. The lateral deflection and the vertical settlement of the piled raft were less than those of the pile group with the same pile configuration. This effective response of the piled raft to the vertical and lateral loads was due to the raft contribution in resisting the vertical and lateral loads. Moreover, with the increase in the number of piles, the vertical and lateral contribution of the raft decreases.

Keywords: pile group; piled raft; contact pressure; displacement; lateral load

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1. Introduction

The purpose of a foundation beneath structures is to transfer the superstructure load to the subsoil. For the proper functioning of the foundation, it is required to design it properly to satisfy the strength and serviceability requirements. The most common types of deep foundation are the pile raft and the pile group. In the piled raft, a raft is in contact with the soil surface, while in the pile group a raft is somewhat above the soil surface. The difference between the pile group and the piled raft response has been studied in the past by a few researchers [1–3]. The first attempt to use the combination of raft and piles was reported a half-century ago by the pioneer Leonardo Zeevaert [4,5] in Mexico City. They used piled rafts for "Tower Latino Americana" on the compressible volcanic clay of Mexico. In a piled raft foundation, the length of piles should be long enough to exceed the stress bulb caused by the raft.

The response of the pile group to lateral loading is significantly different from that of a single pile due to different interaction factors. The major interaction factors involved are the pile–pile interaction factor and the pile-to-raft factor. These factors are highly dependent on the distance between piles and reduce as the distance between the piles increases. McVay et al. [6] showed that the interaction effects reduce considerably when the pile-to-pile distance is equal to 5d, where "d" is the pile diameter. Moreover, Cox et al. [7] and Khari et al. [8] concluded that pile–pile interaction can be ignored when the distance between the piles is more than 6d. In this case, the pile behavior in the pile group is the same as that of a single isolated pile. Rollins et al. [9] conducted a study to find the effect of the interaction factors on the response of a single pile and a pile in a pile group. Feagin [10] performed a test on a pile group consisting of timber piles with a length of 32 ft installed in sand. The objective was to study the group effects on the timber and concrete piles under lateral loads. The author concluded that at a large deflection the group effects are significant and recommended that at a deflection of less than 6 cm the group effects do not affect the response of the piles in a pile group. Holloway et al. [11] conducted pile group tests under a lateral load at the same site as Feagin [10] used. The result was that the maximum lateral load was resisted by the front row as compared to the trailing row, which was due to shadowing effects. Zhang et al. [12] performed a numerical and experimental study on a single pile and a group of 3 × 3 and 7 × 3 piles in the sand under loose and medium dense conditions in lateral loading.

Many researchers [13–15] have worked on the vertical load analysis of the piled raft foundation. In the piled raft foundation system, the lateral loads are resisted by the piles, the passive resistance provided by the embedded structure, the frictional resistance along the embedded sides, and the frictional resistance of the raft base [16]. Some researchers have shown that the resistance offered by the embedded raft, the sides of the raft, and the base of the raft is substantial and even more than 50% of the total lateral load [9,17,18]. Beaty [17], in his work, conducted two tests on a 6-pile raft and considered only the passive resistance of the embedded pile cap. In this work, 50% of the applied horizontal load was resisted by an embedded pile cap or raft. In the same way, Rollin et al. [9] performed a test on a group of nine piles subjected to lateral loading and showed that the embedded pile cap lateral resistance was approximately equal to the lateral resistance of the piles. Horikoshi et al. [19] conducted experimental centrifuge ($50\times g$) tests on a piled raft and its components under horizontal load. The objective of the study was to examine the effects of the pile head connection on the response of the pile raft. The raft confining pressure causes an increase in the stiffness of a single pile rigidly connected to a raft in a piled raft compared to the stiffness of a single isolated pile. Ilyas et al. [20] performed centrifuge model tests on a pile group subjected to a lateral load in clay. The tests were conducted in the geotechnical centrifuge of the National University of Singapore at $70\times g$. The results of the tests showed that the average lateral load per pile decreases with the increase in the number of piles. It was concluded that at a pile spacing of 5d the group effect became less. Katzenbach and Turek [21] conducted a $1\times g$ lateral loading test on a model piled raft and pile group. They also tested isolated rafts of the same dimensions as those used for the model piled raft. The tests were performed under a lateral load of 1200 N with different vertical constant static loads of 1000 N, 3000 N, and 5000 N. The results showed that the lateral resistance of a piled raft under the vertical load of 1000 N was 2.5 times higher than that of the same pile group. The horizontal resistance under 3000 N and 5000 N vertical loads was even 4–6 times higher than the pile group, which is obviously because of the raft contribution. The bending moment measurements show that the maximum bending moment in the piles of the piled raft was four times lower than the maximum bending moment in the pile group piles. The latest research study included numerical and experimental approaches to examine the lateral behavior of the piled raft and the different factors affecting it [22–25]. To study the resistance of piles to dynamic torsion, Zhang et al. [26] postulated an analytical approach and also summed up that at the pile cross-section the resistance would vary radially. In recent research [27–29], the response of pile foundations to static and cyclic loading was studied experimentally and numerically.

The present study involves the comparison of the piled raft and the pile group behavior when subjected to lateral and vertical loads.

2. Experimental Setup

2.1. Soil Tests

Sieve analysis was performed on sand used in the model testing according to ASTM D422-0 [30]. The grain size distribution curve is plotted from the observed values of the percent passing through each sieve, as shown in Figure 1. ASTM D854-2005 [31] is used for calculating the specific gravity of sand, i.e., 2.6. The maximum and minimum unit weights of the dry sand were 17.6 and 14.5 kN/m^3, calculated according to ASTM D4253-00 [32] and D4254-00 [33], respectively.

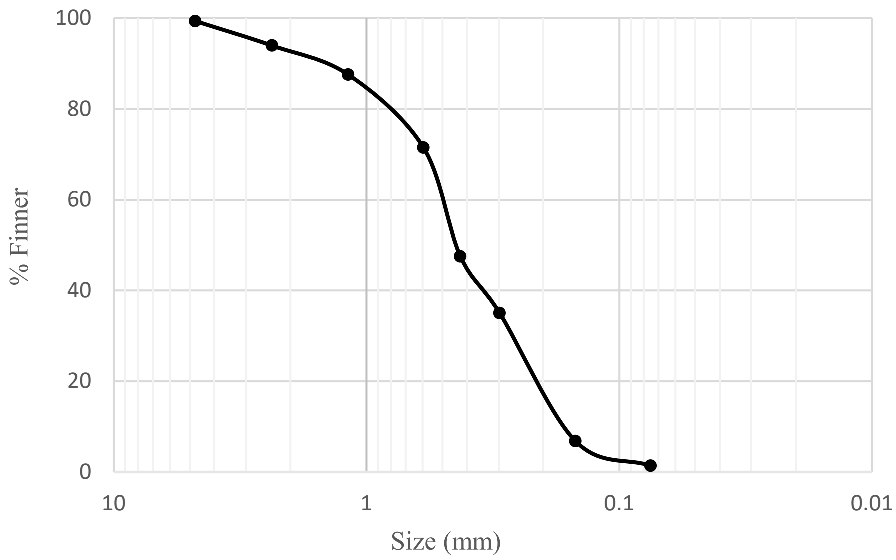
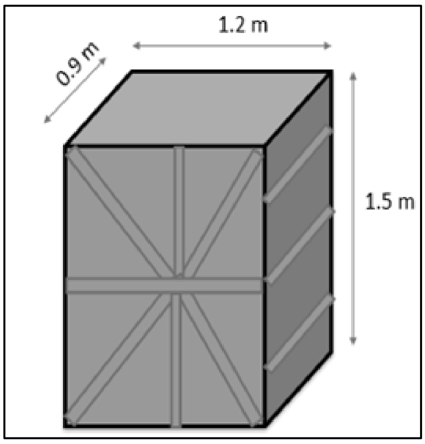


Figure 1. Gradation curve for dry sand.

2.2. Models

All model tests were conducted in a rectangular box made of steel and big enough to satisfy all the boundary conditions. To avoid the side effects of the boundary conditions, the dimensions of the soil box in comparison to the made piled raft model were large enough. The box was 1.5 m in height, 0.9 m wide, and 1.2 m in length, as shown in Figure 2a. The thickness of the steel plates was 6mm. For rigidity purposes, the diagonal as well as the vertical and horizontal stiffeners were also provided to strengthen the box to prevent lateral bulging of the soil during the application of loading, as shown in Figure 2b below.

Closed-end hollow galvanized circular iron pipes (E = 200 GPa) of length 457 mm were used as model piles, as shown in Figure 3 below. The outer and internal diameters of the model pile were taken as 19.05 mm and 16.7 mm, respectively. A plain bar of 19 mm diameter was welded at the top end of the piles, and threads were made for connecting to the raft through the bolts. The pile head was provided with a nut and bolt system. A nut and bolt system was provided to rigidly connect the pile to the raft and to ensure their fixity. To determine the influence of pile roughness on pile capacity, the friction angle between pile and soil was determined using a direct shear test [34], which was calculated as 21°. It was roughly 3/2 times the soil friction angle (i.e., 29°). The interface angle in a concrete pile is typically 3/4 times.



(**a**)

(**b**)

Figure 2. (**a**) Soil box; (**b**) stiffeners on each side.

Figure 3. Galvanized iron pipes used as a pile in model piled raft.

An aluminum plate of 25 mm thickness (E = 69 GPa), of dimensions 304.8 mm × 304.8 mm, was used as the raft shown in Figure 4. The raft was provided with 25 holes of 13 mm diameter, in which the pile head was passed and bolted. The Poisson ratio of the galvanized iron was 0.27, while that of the aluminum plate was 0.2. The purpose of selecting aluminum materials for the raft was that the elastic modulus of aluminum is 69 GPa, which is near to that of high-strength concrete, for which the elastic modulus varies in the range of 30–50 GPa. The Young modulus of the raft (aluminum) and the pile material (galvanized iron) was calculated according to ASTM E8 [35].

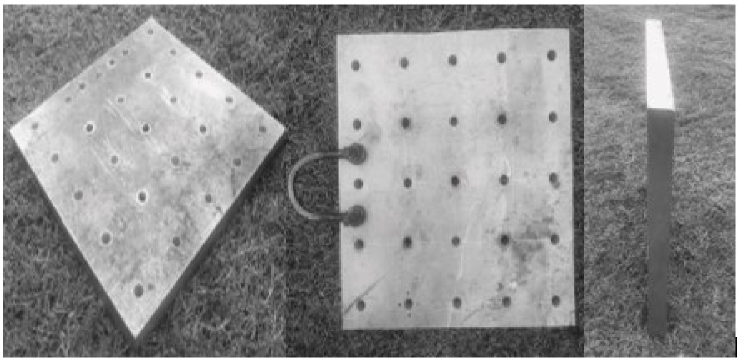


Figure 4. A 25 mm-thick aluminum raft.

2.3. Sand Raining Technique

Maintaining uniform and similar density for each trial test is very necessary; in the case of clays, it can be achieved easily, but in the case of sands, it needs great care. For this purpose, an air raining method [36] was used, where the soil was rained from a specific height with a specific discharge rate. A newly made device called a mobile pluviator, which works on the same principle as air raining, was fabricated; it covers a very large area as the system moves three-dimensionally. With this device, we can achieve a relative density from 10% to 98%. The full arrangement of the installation during the model piled raft testing is also shown in Figure 5. It was important to calibrate the mobile pluviator against a different rate of discharge and height of fall before using it in laboratory testing. For calibration of the mobile pluviator, the soil was poured against different falling heights and through different shutter sizes. The different shutter sizes are shown in Figure 6. In this research work, all the model piled raft tests were performed at a relative density of 60%. Corresponding to this relative density, a height of fall was determined which was 0.45 m for a 13 mm shutter. A dynamic cone penetrometer (DCP) was used to verify the relative density of 60% after filling the soil box with a mobile pluviator.

Figure 5. Mobile pluviator installed above the soil box.

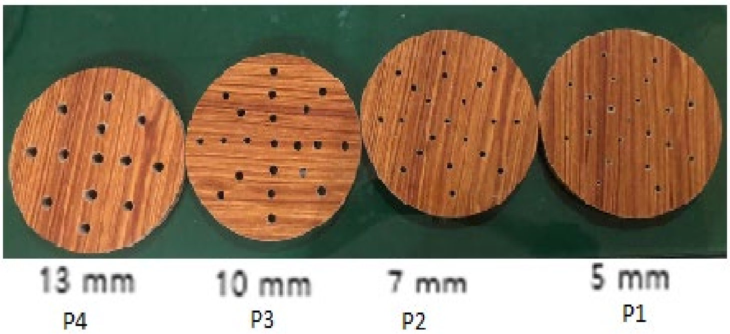


Figure 6. Shutters of different porosity.

2.4. Test Procedure

First of all, the soil box was filled with the sand at a relative density of 60%, achieved through a mobile pluviator. The dried sand was then poured from the mobile pluviator hopper at a height of 0.45 m. The height of the fall was kept constant for a sand layer of 0.15 m by providing marks inside the soil box to ensure a relative density of 60%. In this way, the soil was rained into the soil box in 10 equal layers of 0.15 m thickness. During the air pluviation process, the hopper was constantly moved through the wheels in three dimensions to achieve a uniform sand surface. The model piled raft was placed exactly in the center of the soil box after the soil box was filled to a height of 1.2 m through air pluviation. Following the placement of the model piled rafts, air pluviation continued until the soil level reached a height equal to two-thirds of the pile length, as shown in Figure 7. The raft was then removed, and the remaining soil was poured into the soil box via air pluviation to the final depth. To avoid soil disturbance, the raft was installed above the piles again, with each pile held in place with a special type of wrench. The excess sand was removed and the leveling of the model piled raft was checked with the leveling tool. Pile load cells, vertical load cells, and transducers were connected to the computer-controlled data logger, as shown in Figure 8.

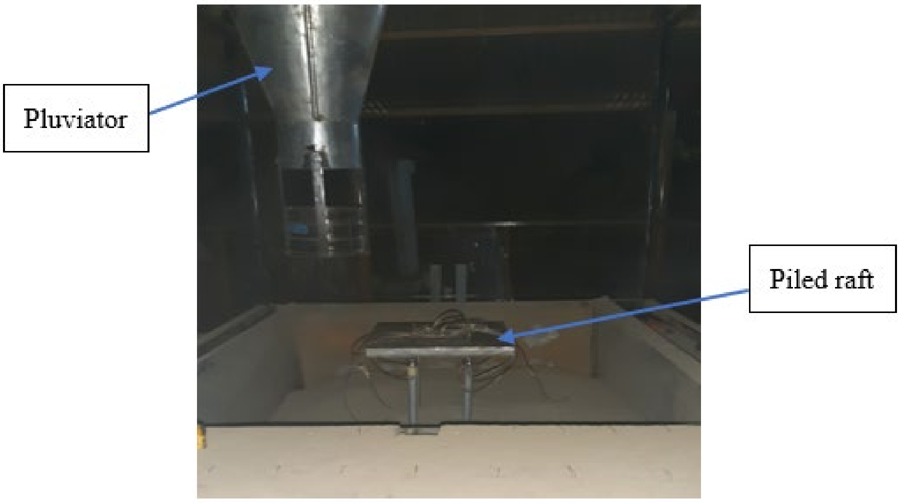


Figure 7. Piled raft model placement during air pluviation.

Figure 8. Experimental work arrangements in the field.

A vertical load cell of a 10 t capacity was installed for vertical load measurement. After checking all connections and arrangements, the model piled raft was then subjected to a vertical static load of 5250 N through the steel plates, and all data were stored in a MATLAB text file. A vertical static loading assembly was designed and fabricated out of steel plates and had the total load capacity of 5250 N, as shown in Figure 8. As for as our experimental testing, it involved the special arrangement of installing the LVDTs with the capacity of 25 mm on both sides of the raft for vertical settlement determination during the application of the vertical loads, as shown in Figure 9.

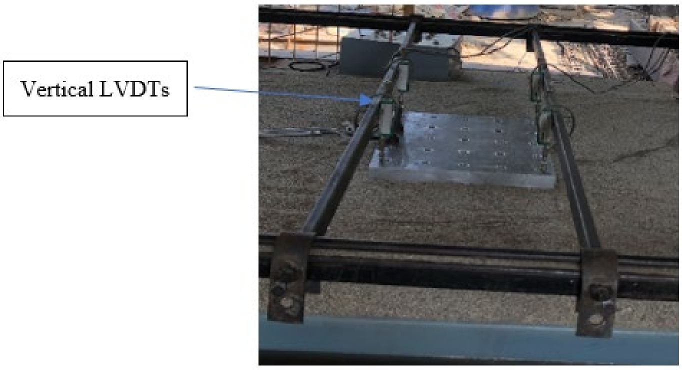


Figure 9. Arrangement for vertical LVDTs.

After the vertical static loading test, a connection for lateral load cells was made and connected with the data logger. The purpose of applying the vertical load first, then the lateral load, was to simulate the actual condition. As is commonly observed, the foundation is loaded with a superstructure load and then endangered with various types of lateral loads, such as wind load, earthquake, and water pressures, among others. The vertical transducers (LVDTs) were removed, and the lateral transducers were installed and connected to the side of the raft. The lateral load of 1500 N was applied through the hydraulic lateral load machine, and the load cell data were stored in the MATLAB text file. This type of loading machine, shown in Figure 10, is hydraulic and based on having two hydraulic motors equipped with chains. A load cell installed in this machine was of 50 KN capacity and installed at the front of the hydraulic jack, through which a lateral point load was applied by a 50 KN capacity lateral load hydraulic machine, which was fabricated especially for this purpose. The rate of application of the load by the hydraulic pumps was maintained at a very slow rate and was approximately equal to 4.9 N/s. The purpose of applying the load at this much slower rate was to capture the lateral load distribution with the increase in lateral load. As the model piled raft was very small, it needed special attention to data acquisition to obtain a clear insight into the model resistance.

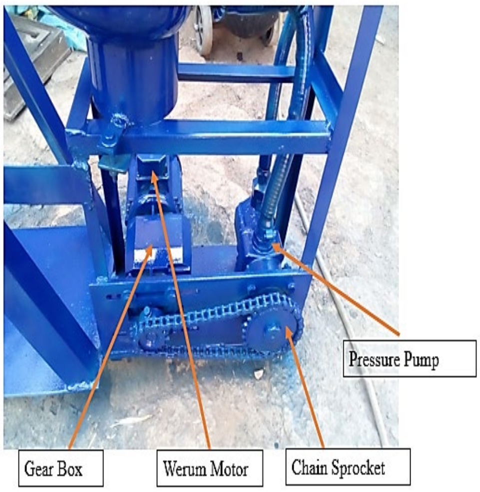


Figure 10. Components of hydraulic lateral load machine.

In the data acquisition system, a data logger was used, as shown in Figure 11. The data logger worked at the frequency of 10 readings per second and its was voltage controlled. It was locally fabricated with a total of 30 channels, in which 12 channels were used for transducers, 1 for load cells, and 17 channels for pile load cells. For all types of tests, the data were saved in a MATLAB program as a text file, and then, finally, those data were converted into an excel file for proper plotting work and analysis.

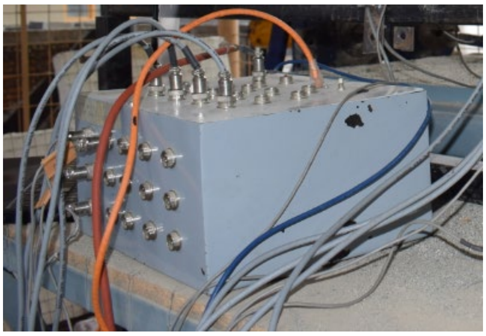


Figure 11. A 30-channel data logger.

2.5. Testing Models

A total of 7 piled raft and 7 pile group models were experimentally tested under both the lateral and the vertical loads. The plan view of the piles is shown in Figure 12 to specify the spacing between the piles. The spacing between the piles was provided based on a literature review, to take into account the interaction factors. The number of piles was varied between 4 and 25.

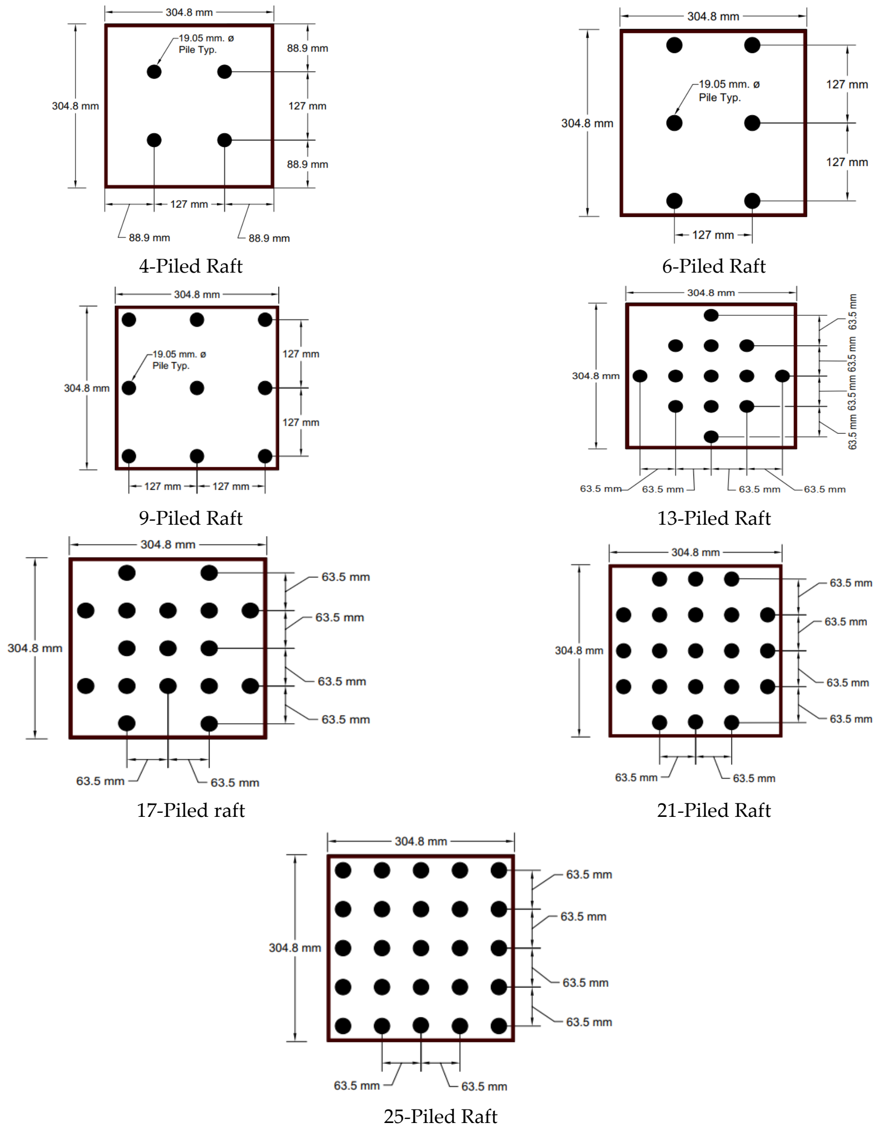


Figure 12. Plan view of piled raft.

3. Results and Discussions

3.1. Pile Group vs. Piled Raft under Vertical Loading

The pile group testing arrangement is shown in Figure 13. A clear space of 50.8 mm was provided between the raft and the soil top to prevent raft contact with the soil during the application of the loads. In this case, each pile group was subjected to a vertical load of 5250 N, except the 4-pile group, for which the vertical load was kept as 1920 N, and for the 6-pile group, this was taken as 2786 N. This decrease in loading is because of the lower capacity of these models to take vertical loads. The vertical load was applied with the same increment as in the piled raft, and the portion of the raft which was subjected to the vertical loads was kept as 203.2 mm × 203.2 mm. The settlement of the group piles was monitored at each incremental load application, and their behavior under vertical load was expressed by plotting a graph of the applied load versus the corresponding settlement and then comparing it with the piled raft.

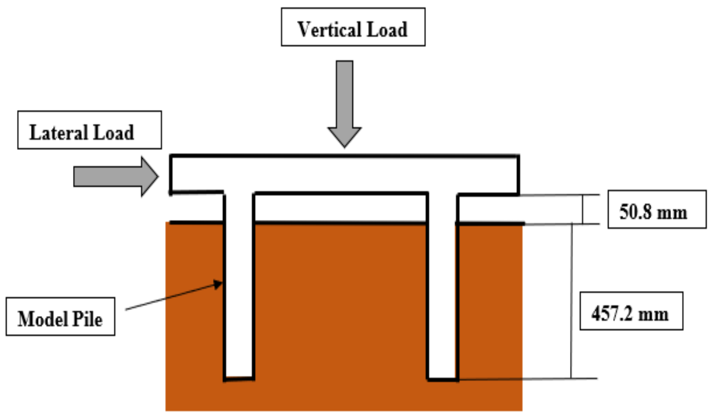


Figure 13. Pile group arrangement.

3.1.1. 4-Pile Group vs. 4-Piled Raft

The response of the 4-pile group was compared with the response of the 4-piled raft under a vertical load of 1920 N, as shown in Figure 14. In the case of the pile group, initially no settlement took place, but as the load increased, settlement started, and eventually at peak load, it gave a total settlement of 4.5 mm, but corresponding to this load, the settlement in the pile raft was 1.6 mm, which shows that the pile group experienced a settlement of 2.8 times that of the pile raft settlement at peak load. It is due to the raft contact with the soil in the case of the piled raft that the increase in the stiffness and capacity of the foundation occurred.

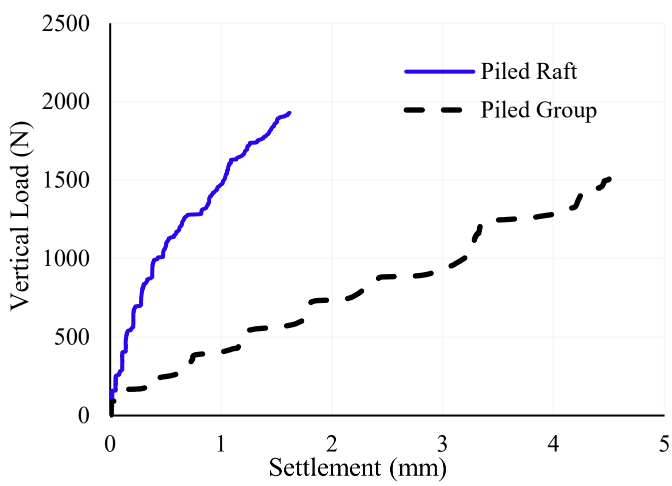


Figure 14. 4-pile group vs. 4-piled raft vertical response.

3.1.2. 6-Pile Group vs. 6-Piled Raft

The load settlement response of the 6-pile group vs. the 6-piled raft under the vertical load of 2786 N is shown in Figure 15. Throughout the application of the vertical load, the piled raft showed stiffer behavior than the pile group because of the raft contact in the piled raft. The pile group shows a settlement of 4.02 mm, and the piled raft shows a settlement of 3.01 mm at the peak applied load, which is 1.34 times less than the pile group. The difference between the displacement in the pile raft and the pile group decreased due to the increase in pile numbers which reduced the raft contact area with the soil. However, the overall settlement was reduced owing to the fact that the piles increased the foundation stiffness.

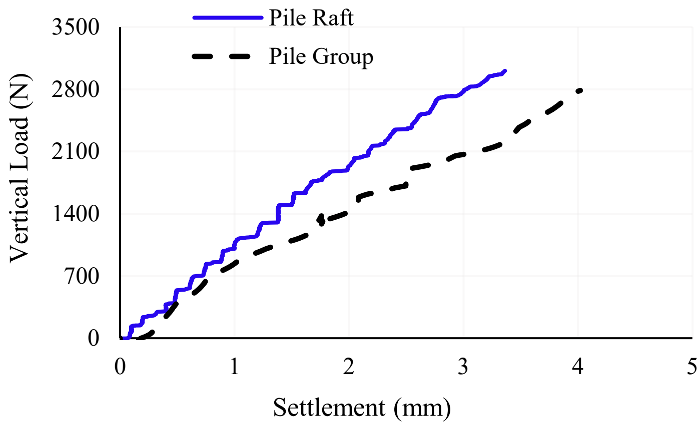


Figure 15. 6-pile group vs. 6-piled raft vertical response.

3.1.3. 9-Pile Group vs. 9-Piled Raft

With the increase in the number of piles, the stiffness of the system is going to increase, and hence, it can be seen in Figure 16 below which 9-pile group vs. 9-piled raft response under the vertical load of 5250 N is shown which is more than the previous cases. Corresponding to this maximum load, the settlement was reported as 12.97 mm in the pile group, and in comparison, the pile raft experienced a settlement of 5.14 mm at the same load, leading to it being 2.52 times less than the pile group.

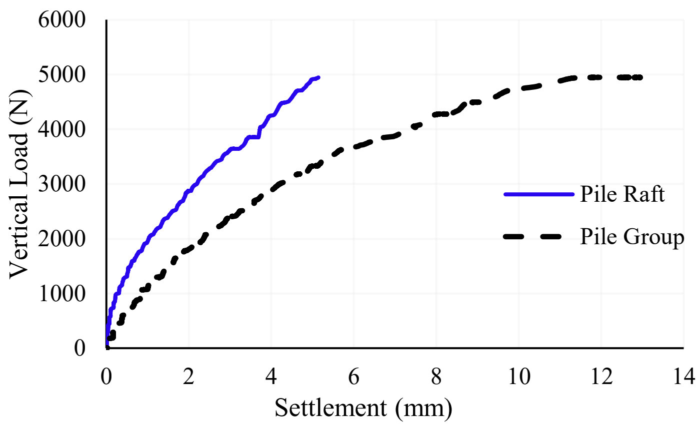


Figure 16. 9-pile group vs. 9-piled raft vertical response.

3.1.4. 13-Pile Group vs. 13-Piled Raft

The 13-pile group vs. the 13-piled raft response under the vertical load of 5250 N is shown in Figure 17. In this case, the piled raft behavior became somewhat similar to the pile group, for the reason that the contact area between the raft and soil reduced more.

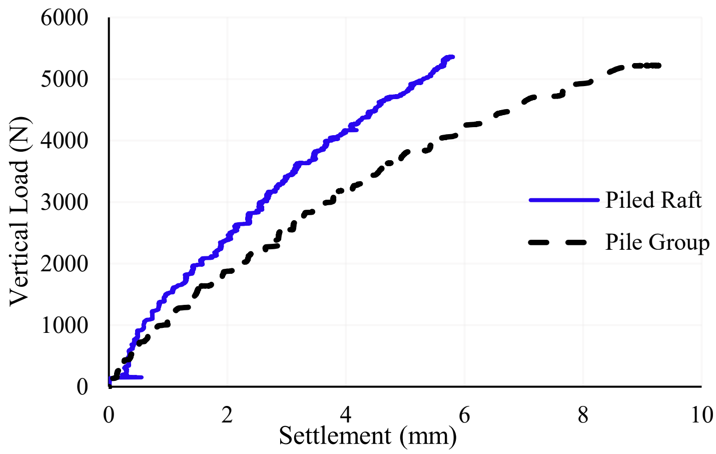


Figure 17. 13-pile group vs. 13-piled raft vertical response.

3.1.5. 17-Pile Group vs. 17-Piled Raft

The load settlement response of the 17-pile group vs. the 17-piled raft under vertical load is shown in Figure 18. In this case, the stiffness of the piled raft is also more than that of the pile group throughout the application of vertical load. At the peak applied load, the vertical settlement of pile group is 6.45 mm, and the piled raft settlement is 4.60 mm, which is 1.40 times less than the pile group.

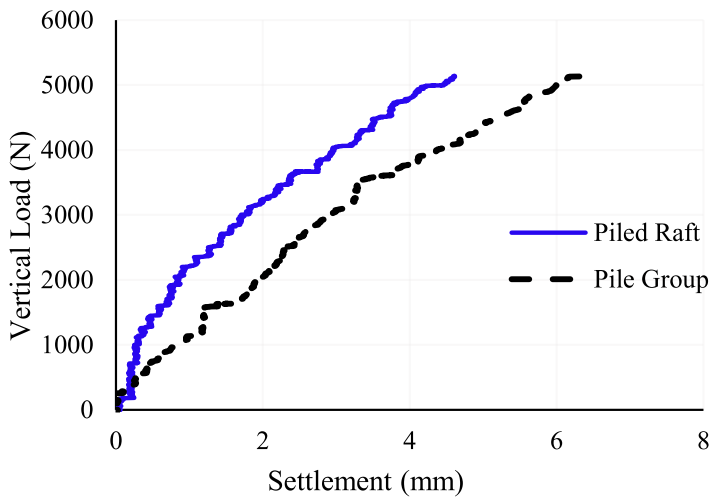


Figure 18. 17-pile group vs. 17-piled raft vertical response.

3.1.6. 21-Pile Group vs. 21-Piled Raft

The vertical load response of the 21-pile group vs. the 21-piled raft is shown in Figure 19 under a load of 5250 N. Initially, the stiffness difference is small, but as the loading increases, the difference becomes larger. This is because, in the case of the vertical loads, the piles resist the load at first, making their response less differentiable, but at large loads, the raft begins to take the load, and the difference increases significantly. The pile group settlement was recorded as 6.28 mm, while the piled raft settlement was recorded as 4 mm, showing 1.57 times less settlement than the pile group.

3.1.7. 25-Pile Group vs. 25-Piled Raft

The vertical response of the 25-pile group vs. the 25-piled raft is shown in Figure 20, which shows the same response as the previous test. The settlement of the 25-pile group is 4.60 mm, while the piled raft settlement is 3.61 mm under the same vertical load of 5250 N, which is 1.27 times less than that of the pile group.

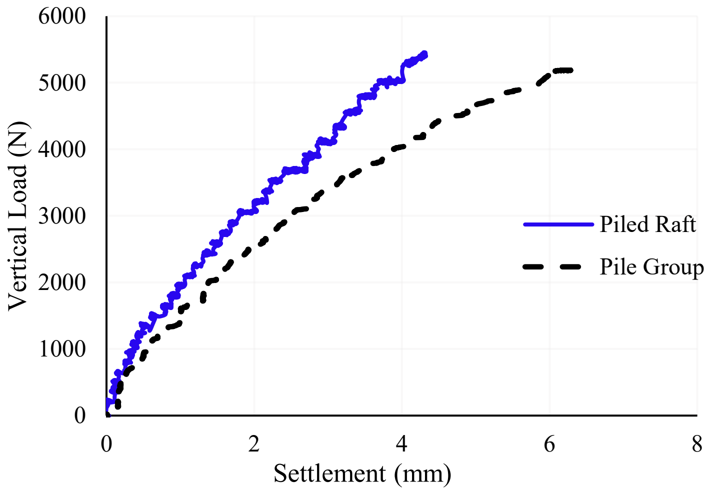


Figure 19. 21-pile group vs. 21-piled raft vertical response.

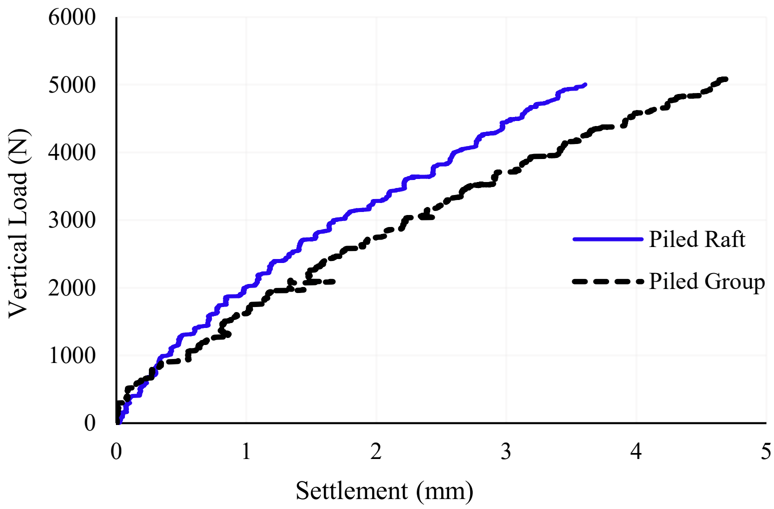


Figure 20. 25-pile group vs. 25-piled raft vertical response.

3.2. Summary of Pile Group Vertical Response

The pile group response was compared with the pile raft response under a vertical load with the same number of piles and the same configuration. In all the tests, the stiffness of the piled raft was more than that of the pile group under the same vertical load, which is because of the raft load resisting potential in the piled raft.

3.3. Pile Raft vs. Pile Group under Lateral Load

The load displacement behavior of the pile raft and the pile group was compared under the same vertical and lateral load. The purpose of this comparison is to show the beneficial effects of the raft contact in a piled raft foundation. The vertical and lateral capacity of the 4- and 6-pile group is less, and it cannot sustain a vertical load of 5250 N; that is why the lateral load tests were conducted under less vertical and lateral load. For comparison purposes, the 4- and 9-piled raft tests were also conducted under the same vertical and lateral load. A lateral load of 460 N was applied on the 6-pile group subjected to a constant vertical load of 1920 N. Similarly, the 6-pile group was subjected to a lateral load of 600 N under the vertical load of 3030 N. For both these cases, the piled raft tests were also conducted under the same load condition. All the other pile group tests were conducted under a vertical load of 5250 N, which was the same as the piled raft load.

3.3.1. 4-Pile Raft vs. 4-Pile Group

Both the 4-piled raft and the 4-pile group tests were conducted under a constant vertical load of 1920 N and subjected to an incremental lateral load of 460 N. The lateral response comparison of both models is shown in Figure 21. It can be observed that at the displacement of 4.73 mm, the lateral load resistance of the pile group is 460 N, while in the pile raft case, it resists the same load at a lateral displacement of 0.12 mm, which is very small compared to the pile group.

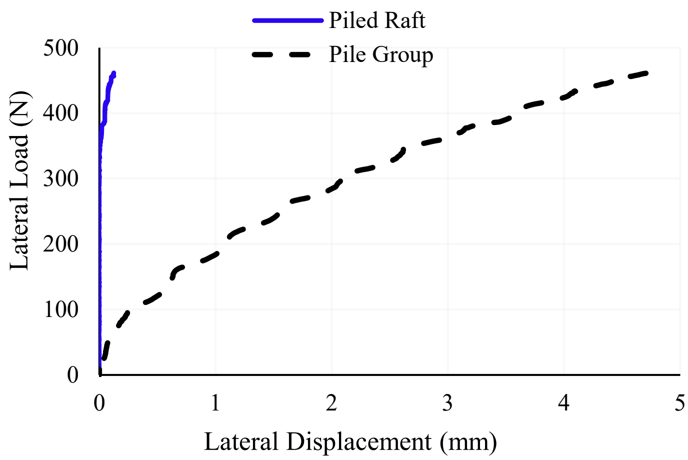


Figure 21. 4-piled raft vs. 4-pile group response under lateral Load.

3.3.2. 6-Pile Raft vs. 6-Pile Group

Both tests were conducted under a vertical constant load of 3030 N and subjected to a lateral incremental load of 660 N. The lateral load response is plotted against the lateral deflection for the 6-piled raft and the pile group and is shown in Figure 22. The graph shows that the pile raft system resists loads up to 300 N with zero displacement, and a 600 N load corresponds to a 0.39 mm displacement. In comparison, the behavior of the pile group shows that it can withstand loads of up to 60 N with zero displacement and a lateral displacement of 2 mm at 600 N, which is considered very large when compared to the piled raft case.

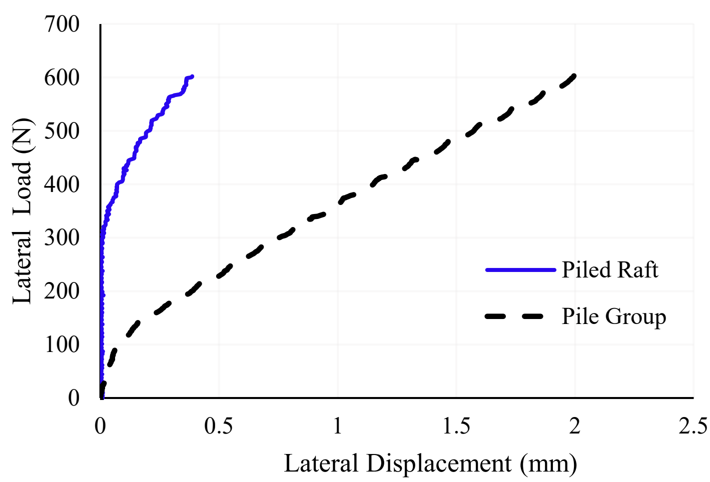


Figure 22. 6-piled raft vs. 6-pile group response under lateral load.

3.3.3. 9-Pile Raft vs. 9-Pile Group

These tests were conducted under a vertical load of 5250 N and subjected to a lateral load of 578 N. The lateral response of the 9-piled raft and the 9-pile group is shown in Figure 23. The graph depicts that the pile raft resists loads up to 400 N with zero displacements, while in the 6-pile raft model, this value is 300 N, showing that the 9-pile raft model is stiffer than the 6-pile raft system. In this case, the lateral displacement of the piled raft is 0.25 mm, while the pile group displacement is 1.45 mm, corresponding to a lateral load of 578 N.

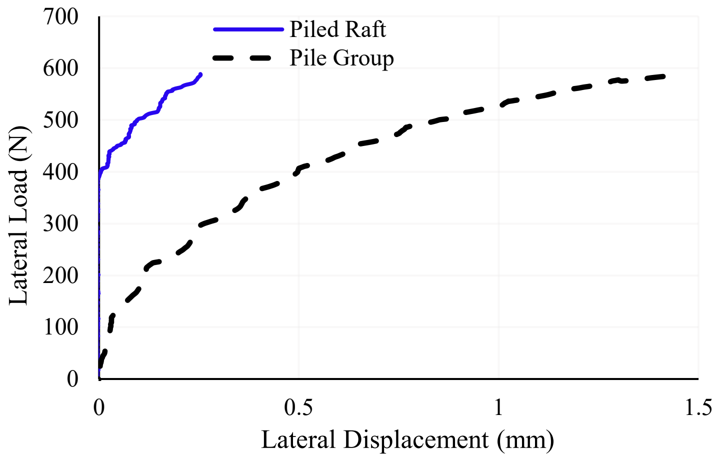


Figure 23. 9-piled raft vs. 9-pile group response under lateral load.

3.3.4. 13-Pile Raft vs. 13-Pile Group

These tests were conducted under a constant vertical load of 5250 N and subjected to a lateral incremental load of 693 N. The lateral load response comparison curves for the 13-piled raft and the pile group are shown in Figure 24, which shows that the piled raft response is much stiffer than the pile group. The 13-piled raft shows a lateral displacement of 0.42 mm, while the 13-pile group shows displacement of 2.60 mm, corresponding to a lateral load of 693 N.

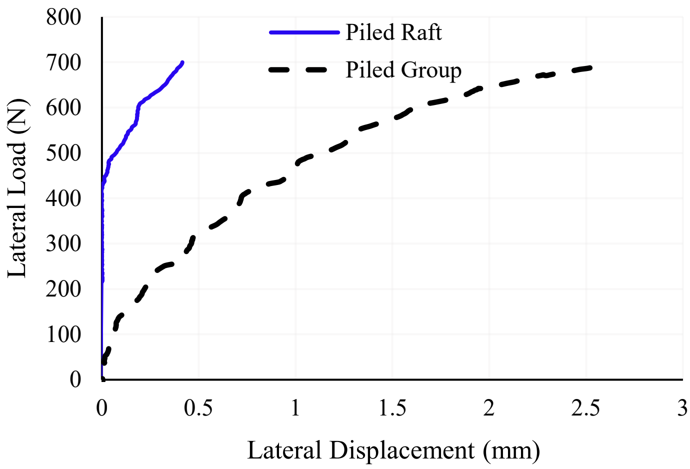


Figure 24. 13-piled raft vs. 13-pile group response under lateral load.

3.3.5. 17-Pile Raft vs. 17-Pile Group

Both tests were conducted under a vertical constant load of 5250 N and subjected to incremental lateral loading of 1500 N. The response of both models is shown in Figure 25, which shows that the piled raft response is stiffer than the pile group lateral response through the application of the lateral load. Under the same lateral load of 1500 N, the pile group shows a lateral displacement of 6.13 mm, while the piled raft shows 2.68 mm, showing the beneficial effects of raft contact in a piled raft system.

3.3.6. 21-Pile Raft vs. 21-Pile Group

The lateral response curves for the 21-piled raft and the pile group are shown in Figure 26. These tests were conducted under the vertical load of 5250 N and a lateral load of 1500 N. The lateral displacement of the piled raft is reduced significantly. One reason is that the raft showed a contribution to the lateral load and another reason is that the vertical load on the raft also influenced the displacement. Therefore, the lateral stiffness of the piled raft is larger than that of the pile group.

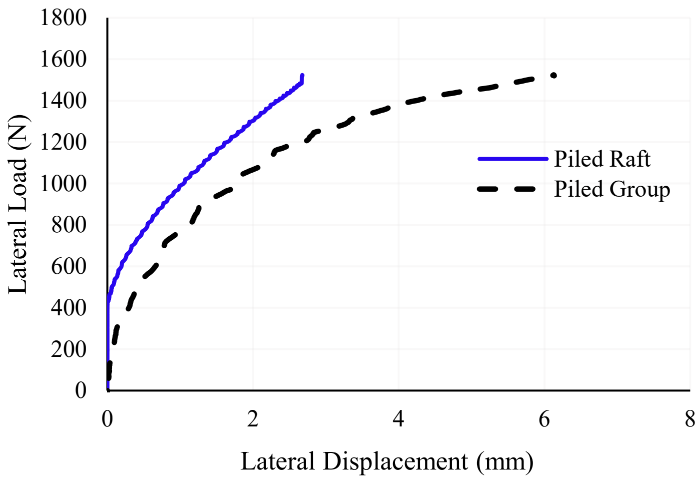


Figure 25. 17-piled raft vs. 17-pile group response under lateral load.

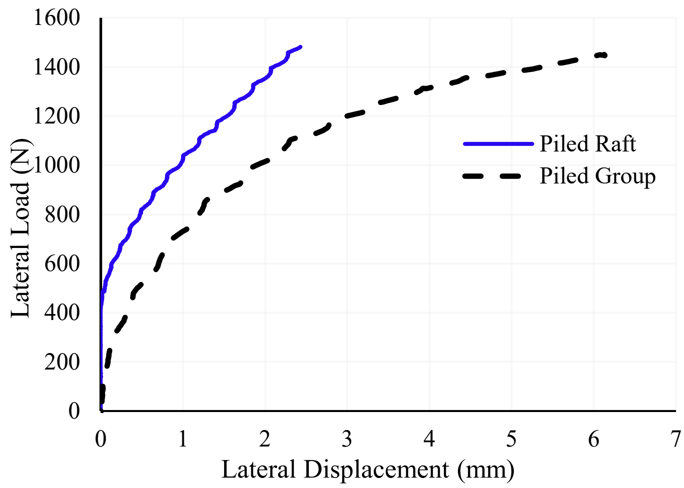


Figure 26. 21-piled raft vs. 21-pile group response under lateral load.

3.4. Stiffness Difference in Pile Group vs. Pile Raft

The pile group response was compared with the pile raft response under a vertical load with the same number of piles with the same configuration. In all the tests, the stiffness of the piled raft was more than that of the pile group under the same vertical and lateral load; this is because of the raft load resisting potential in a piled raft. The summary of the performed tests is shown in Tables 1 and 2.

3.5. Effect of Number of Piles on the Contribution of Raft to Lateral Loads in Piled Raft System

It is observed from Figure 27 that an increase in the number of piles causes a decrease in the lateral contribution of the raft in a piled raft under approximately the same lateral load. The same behavior is also exhibited under vertical load. This is because an increase in the number of piles causes a decrease in the vertical contribution, which causes less mobilization of the raft capacity due to less vertical settlement.

Table 1. Stiffness difference in pile Group vs. pile raft under vertical load.

Type	Stiffness Difference	Piled Raft Settlement (mm)	Pile Group Settlement (mm)	Maximum Vertical Load (N)
4-Piled raft vs. 4-Pile group	4.50/1.60 = 2.81	1.60	4.50	1920
6-Piled raft vs. 6-Pile group	1.34	3.01	4.02	2786
9-Piled raft vs. 9-Pile group	2.52	5.14	12.97	5250
13-Piled raft vs. 13-Pile group	1.65	5.62	9.28	5250
17-Piled raft vs. 17-Pile group	1.40	4.60	6.45	5250
21-Piled raft vs. 21-Pile group	1.57	4.00	6.28	5250
25-Piled raft vs. 25-Pile group	1.27	3.61	4.60	5250

Table 2. Stiffness difference in pile group vs. pile raft under lateral load.

Type	Stiffness Difference	Piled Raft Displacement (mm)	Pile Group Displacement (mm)	Maximum Lateral Load (N)
4-Piled raft vs. 4-Pile group	39.16	0.12	4.70	462
6-Piled raft vs. 6-Pile group	5.13	0.39	2.00	600
9-Piled raft vs. 9-Pile group	5.80	0.25	1.45	600
13-Piled raft vs. 13-Pile group	6.20	0.42	2.60	693
17-Piled raft vs. 17-Pile group	2.29	2.67	6.11	1520
21-Piled raft vs. 21-Pile group	2.51	2.43	6.09	1448

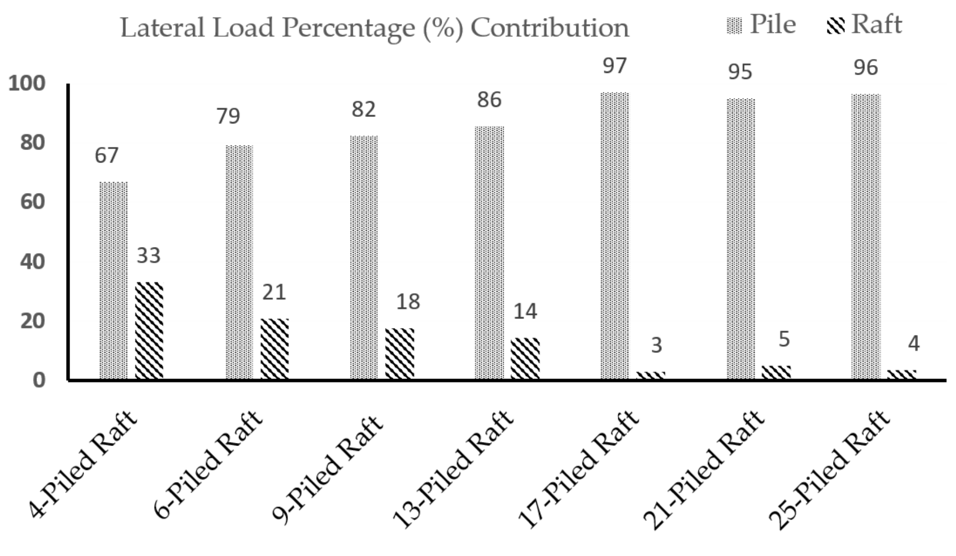


Figure 27. Effect of number of piles on contribution of raft to lateral loads in piled raft system.

4. Conclusions

The following are the main conclusions of the study:

- Comparing the pile group and pile raft responses under the same vertical and lateral load with the same pile configuration, it is evident that the piled raft stiffness is more in all cases because of the raft contribution in addition to the piles.
- By comparing the responses of the piled raft and the pile group with the same number of piles under the same vertical and lateral load, it was concluded that the piled raft response to the lateral and vertical load was much stiffer than the pile group response. The lateral deflection and vertical settlement of the piled raft were less than those of the pile group with the same pile configuration. This effective response of the piled raft to the vertical and lateral loads was due to the raft contribution in resisting

the vertical and lateral loads. It was found that, unlike the pile group, the piled raft provides considerably high stiffness to both types of loads, and the difference between the stiffness of both systems decreases as the number of piles increases. Moreover, with the increase in the number of piles, the vertical and lateral contribution of the raft decreases. It was observed from the results of the piled raft tests under the vertical and lateral load that an increase in the number of piles causes a decrease in the vertical and lateral contribution of the raft. The increased vertical contribution causes an increase in the stiffness of the soil beneath the raft, which leads to an increase in the lateral contribution of the raft.

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