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Experimental Analysis of the Behaviour of Piled Raft Foundations in Loose Sand

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Abstract: This paper presents the experimental analysis that was conducted on small-scale 1g physical models of piled raft foundation structures with a group of 2 × 2 piles in loose sand. The purpose of the piles was to reduce the settlement of the raft. The test program included twelve experiments, three of which were conducted on a raft alone and nine on piled rafts at pile distances of 3d, 4d, and 5d and pile lengths of 10d, 20d, and 40d, where d is pile diameter. The test results show that the current conventional approach to design of piled raft foundations, at a high safety load factor in piles that assume to take the whole external applied load, is very conservative. Instead, it is more economical to apply a low bearing capacity factor for piles as settlement reducers and maximize use of raft bearing capacity to carry part of the external load.

Keywords: raft foundation; pile foundation; piled raft foundation; settlement; small-scale model; 1g model

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1. Introduction

1.1. Foreword

This research is motivated by the practical experience of the authors, that is, the need to reliably evaluate the interaction of the cap and piles that serve as settlement reducers. Namely, during construction of various structures within the coastal area of Danube River in Serbia, on a layer of very loose dredged sand up to 7 m thick, in order to reduce settling, deep foundation on piles is usually foreseen. Due to the relatively large thickness of the natural alluvion deposits near the riverbank, the piles predominantly demonstrated floating behaviour. To achieve a more economical solution, a proposal was made to determine the number of piles on the basis of a very low safety factor in relation to the ultimate load in the order of magnitude 1.2–1.3 to make as much use as possible of the bearing capacity of the caps with a reduction in settling due to the presence of the piles. Due to shortness in time, this idea was abandoned, but an interesting topic remained open, motivating this research, for which the authors of the paper conducted experiments on a small-scale 1g physical model. Bearing in mind that the piles are placed in fine-grained, loose Danube sand, it can be assumed that the shear strength resistance envelope of the sand is a linear function; that is, the angle of shear resistance is constant or independent of effective normal stress. As a result, the scale effects that mainly originate from the curved shear strength envelope, as in compacted sands, can be neglected. Having this in mind, it can be assumed that application of the small-scale 1g physical model as it is presented in this paper for pile bearing capacity estimation in loose sands is justified.

1.2. Introduction

In geotechnical engineering, a shallow foundation structure is not always applicable due to deformability of soil. One of the most significant aspects in foundation design is bearing capacity [1]. Accordingly, alternative foundation structure solutions are used, such

as deep foundations. Calculation of the pile group is based on the assumption that the entire load from the aboveground part of the structure is taken over by the piles, without taking into account the load bearing capacity of the raft. This approach to calculation is very conservative; the basic principle of calculation should be based on the fact that the foundation structure contains as many piles as would be required to reduce the settlement to an acceptable level. That way, the load from the aboveground structure is transferred to the ground partly through the raft and partly through piles. This calculation approach aims to contribute to optimization of the foundation structure, thus reducing the number of piles.

The mechanism and design theory considering utilization of soil below the raft to bear a part of the total applied load in piled raft foundation has been a research hotspot for more than half a century [2–4]. Assuming that the load is evenly distributed over the area of the raft, a deflection will occur in the middle of it, as schematically shown in Figure 1a. By adding a specific number of piles under the raft, settlement and differential settlement will be reduced (Figure 1b). Basuony El-Garhy et al. [5] have conducted tests with a limited number of piles beneath the central part of the raft, using piles as settlement reducers. Using piles to reduce settlement is an idea that originated earlier, in the 1970s [6]. There are many studies that deal with behaviour of raft foundations and piled raft foundations [7–19] and settlement of piled raft foundations [20–23]. In recent research [24–31], the response of piled raft foundations to static and cyclic loading was studied experimentally and numerically. Muhammad Rehan Hakro [32] investigated piled raft foundations in multilayer soil with different stiffness, exposed to different loads, by using software package Plaxis 2D. O. Reul and M. Randolph [33] dealt with the influences of certain parameters on the load distribution between the raft and the piles, such as the number and arrangement of piles, the piles' length, and the raft stiffness. They concluded that, when using longer piles, there may be less settlement than when using a larger number of piles, and bending moments in the raft cannot be reduced by supporting it with piles. Phung [34] concluded that the conventional practice of designing piled raft foundations is based on the assumption that external load is carried by piles and any raft contribution is neglected. Therefore, this approach is too conservative because the raft can carry a significant part of the load due to direct contact with the ground. Bayad and others [35] concluded that, in tests conducted on piled raft foundations 2 × 2, 3 × 3, and 4 × 4, when the raft settlement is 10 mm, which was the smallest lateral dimension of the raft, 60% of the total load was taken over by the pile group. Each pile group behaves as a raft with piles except those cases in which there is no contact between the raft and the soil [36].

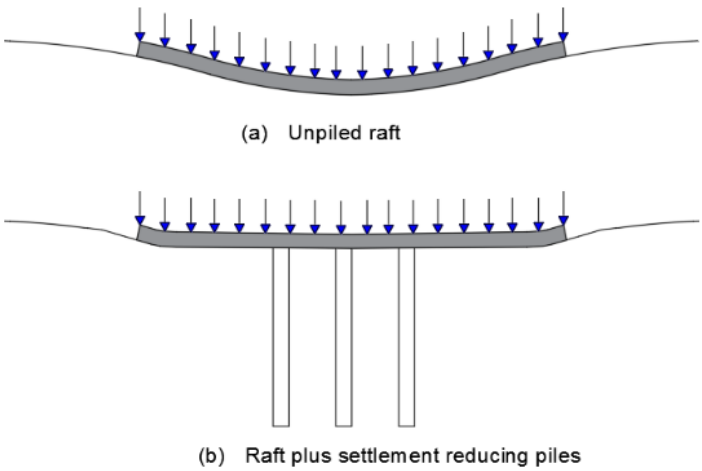


Figure 1. Piles required to reduce differential settlement.

Fleming [37] states that, when designing piled raft foundations, rafts have certain load bearing capacity. Due to not considering the contribution of the load bearing capacity of the raft, when designing piled raft foundations, more piles are required than actually

needed [38]. Assel Zhanabayeva et al. [39] compared designs of piled raft foundations by applying Eurocode 7 and Kazakhstan regulations. Thea concluded that Eurocode 7 shows more conservative results, with an increased level of safety [40–42]. Since the raft and the piles each contribute to the behaviour of the raft with piles system, the key component for the design is the portion of load carried by each element [36,43]. The piled raft foundation structure is a foundation structure that combines the effective bearing capacity of raft and piles while taking into account different interactions: pile–soil, pile–pile, raft–soil, pile–raft. The interaction between soil and structure has an impact on soil behaviour as well as the behaviour of piles subjected to load [44–46]. The behaviour of the pile–soil system is mostly nonlinear. The load in the horizontally loaded pile is resisted by the pile–ground interaction, which also depends on pile diameter and pile material [47]. Bourgeois [48] investigated the influence of the pile–soil interaction in a vertically loaded group of piles. Some previous studies have specified the ratio of load distribution as a function of the geometry of the foundation, stiffness, and compressibility of the soil [49–51]. For sandy soils, the pile–raft interaction effect is significant for the overall behaviour of the piled raft system [52–54]. Based on experimental results, Phung Duc Long and other [55] authors proposed a simplified method that can be used in design. The experiment shows that, at the beginning of the loading of the piled raft foundation, piles take over most of the load, and, after reaching the bearing capacity of the pile, the load is transferred to the raft. This method can provide effective results if used with the finite element method for estimating settlement of piled raft foundations. Some of the analytical and numerical studies conducted on this topic are described in [56–61]; however, experimental studies on piled raft systems are few, while verification of the analytical and numerical results can occur by conducting tests on physical models in the laboratory.

In this paper, the results of experimental analysis of the 1g model of the raft foundations, conducted for the purpose of doctoral thesis research of the first author, were used. The aim of the research was to point out that, when designing these types of foundation structures on loose sand, the load bearing capacity of the raft foundation should not be neglected. This will reduce the number of piles required to receive vertical force and thus lead to more efficient foundation structure design. In addition to raft and piles interaction, pile group effect was also investigated.

2. Materials and Methods

Laboratory tests were performed on a 1g model for a group of four piles, assembled in a 2 × 2 pile configuration. The test program consisted of twelve experiments, three of which were performed on piles of length L = 40d, 20d, 10d, with pile distances of 3d, 4d, 5d, and three experiments with a raft foundation system without piles. Pile arrangement, as well as raft dimensions, are shown in Figure 2.

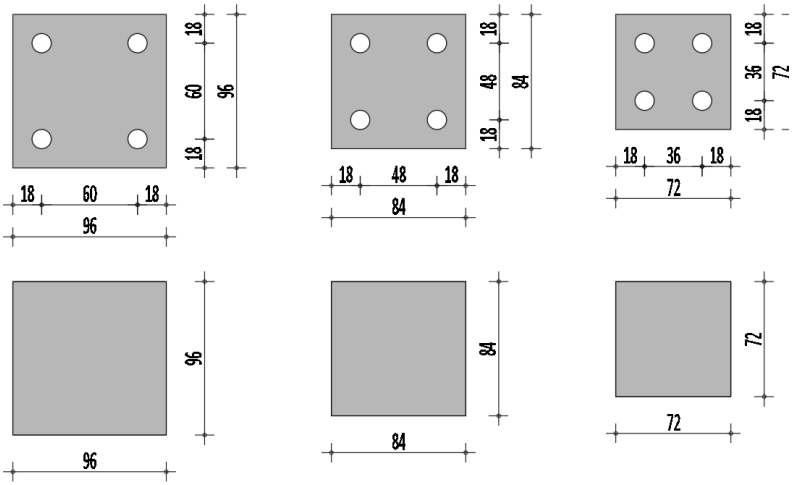


Figure 2. Pile arrangement and raft dimensions (in mm).

2.1. Soil Parameters

Dry sand was used in the experiment. Granulometric analysis was performed in order to determine the granulometric curve of the soil used. The obtained granulometric curve parameters were: D_{10} = 0.11 mm, D_{30} = 0.15 mm, D_{60} = 0.23 mm, the uniformity coefficient is C_u = 2.1, and the curvature coefficient C_z = 0.8, Figure 3.

Based on the united soil classification (USCS), the tested soil sample is classified as poorly graded SP sand. By direct shear test, it is determined that the angle of internal friction is 30°.

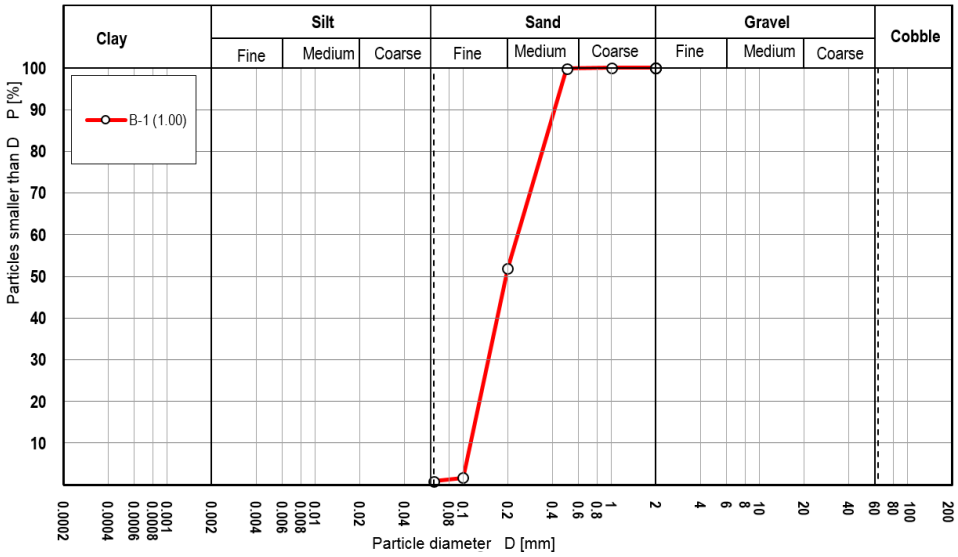


Figure 3. The granulometric curve.

2.2. Models of Piled Raft Foundations

The experimental model of the piled raft foundation is composed of the square raft and the piles. The raft is made of 10 mm thick steel S 235 plate, which represents an absolutely rigid body that is not susceptible to bending under forces that occur during the experiment.

Four 9 mm diameter holes were drilled in the raft, arranged in accordance with the configuration of the piles. Apart from the holes for the piles, additional small holes, 3 mm diameter, were prepared for placement of the miniature pressure sensors. The piles were installed so that their heads were slipped through the 9 mm holes, then the pile is fixed to the raft foundation by means of a thread that is incised at the top of the pile. That way, the piles could be tightened with a nut from the upper surface of the raft foundation, thus achieving a rigid connection between the raft and the piles (Figure 4). Piles are made of steel rods S 235 with a diameter of 12 mm. For easier and simpler installation, they are composed of three parts (Figure 5). Assembled piled raft model is shown in the Figure 6. The base of the pile is conical so that it reduces the base load bearing effects. On the upper section of the pile, an adapter was mounted that creates the connection between the raft and the pile. Within this adapter (Figure 7), the axial force in the pile head is measured with a miniature load cell. Figure 8 shows the actual piled raft model prior to driving it into the soil, while Figure 9 shows the model during its driving into the soil.

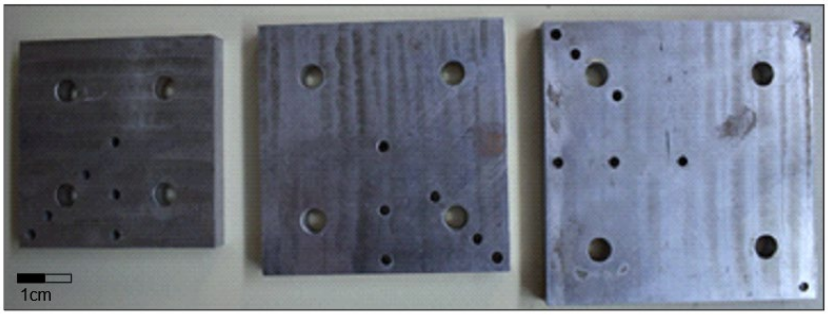


Figure 4. Raft models for groups of 2 × 2 piles.

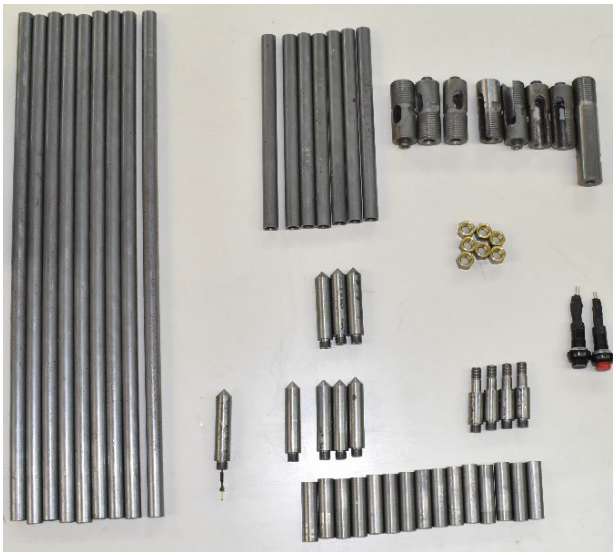


Figure 5. Assembly parts of the pile.



Figure 6. 3D drawing of the assembled piled raft model.

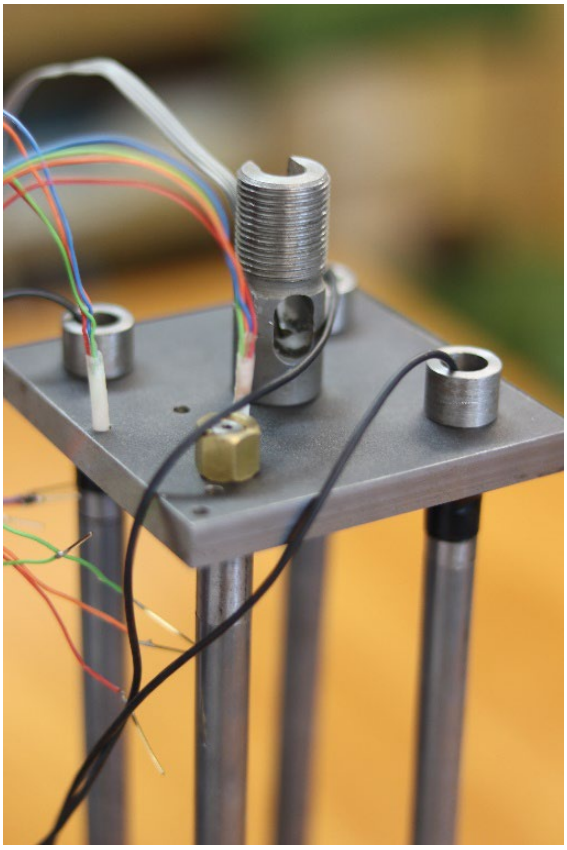


Figure 7. Piled raft model with installed measurement equipment.

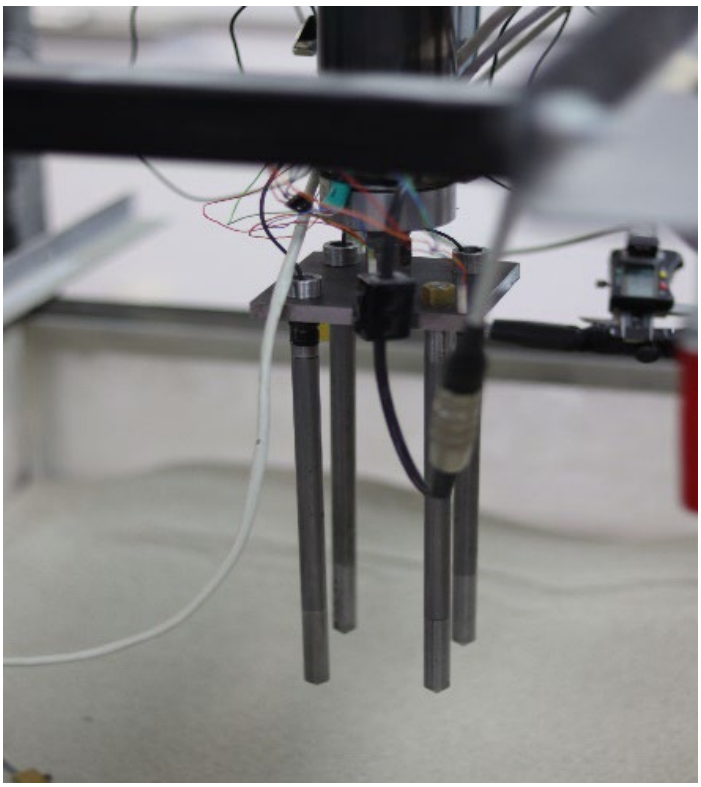


Figure 8. Piled raft model prior to driving it into the soil.

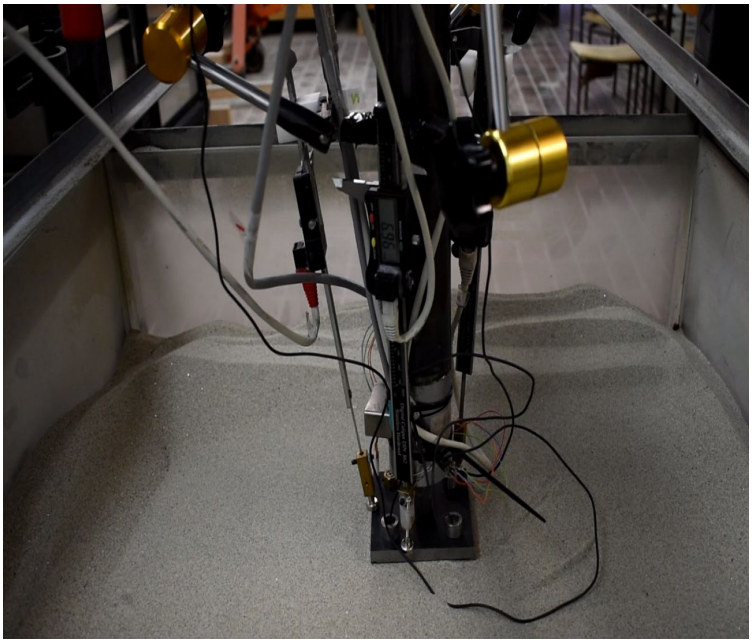


Figure 9. Piled raft model during its driving into the soil.

2.3. Measuring Instruments and Equipment

2.3.1. Test Box

Testing of the models was performed in specially designed mobile test boxes (Figure 10). The boxes, with dimensions of 75 × 75 × 100 cm, were made of steel L profiles, 35 × 35 × 2 mm. The corners are constructed with four columns, which are interconnected by horizontal profiles, welded on every 25 cm along the height of the columns. The profiles form a stable structure without lateral deformations of the box walls. The inside of the box is encased with 3 mm thick Plexiglass to make it easier to determine the height of the filled sand, as well as to eliminate friction between the sand and the walls of the box, as Mosa [62] and others have observed in their experiments.



Figure 10. Mobile test box.

2.3.2. Data Logger

Automatic digital data acquisition was conducted with use of a data logger that has 6 parallel and 64 serial channels (Figure 11).



Figure 11. Data logger.

2.3.3. Digital Callipers

To monitor the displacements of the raft due to load, digital callipers with an accuracy 1/100 mm were used. Three callipers (MIB Messzeuge GMBH, Spangenberg, Germany) with a maximum deflection range of 150 mm were attached to a special frame structure with flexible magnetic stands (Figure 12).



Figure 12. Digital callipers.

2.3.4. Load Cell

In order to measure the total vertical force acting on the raft foundation model, a load cell with measuring capacity of 350 kg and precision of 0.2% was used (Figure 13). Before commencement of the experiments, the load cell was calibrated with standard weights.

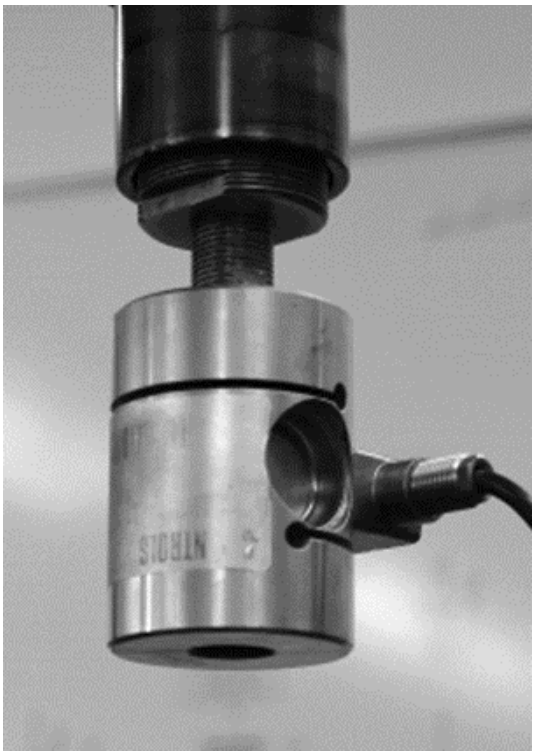


Figure 13. Load cell with a measuring capacity of 350 kg.

2.3.5. Sensor for Measuring the Force in the Pile

A miniature force sensor DYMH-106, with a total measuring capacity of 30 kg, was used to measure the force in the individual pile (Figure 14). The diameter of the sensor is Ø 12 mm, and it has connection necks with M6 threads. Force sensors were placed under the raft at the location of the connection adapter. Calibration was performed for the measuring range of the sensor, i.e., from 0 N to 300 N, where the load was gradually increased and maintained for a certain time interval, in order to clearly establish the step of changing the response with increasing load.



Figure 14. Miniature force sensor, "DYMH-106/30 kg".

2.3.6. Spreader

For the purpose of testing the piled raft 1g model, placed in loose sand, a self-propelled spreader, 70 cm wide, was made to fill the boxes with sand in the form of "sand rain" (Figures 15 and 16).

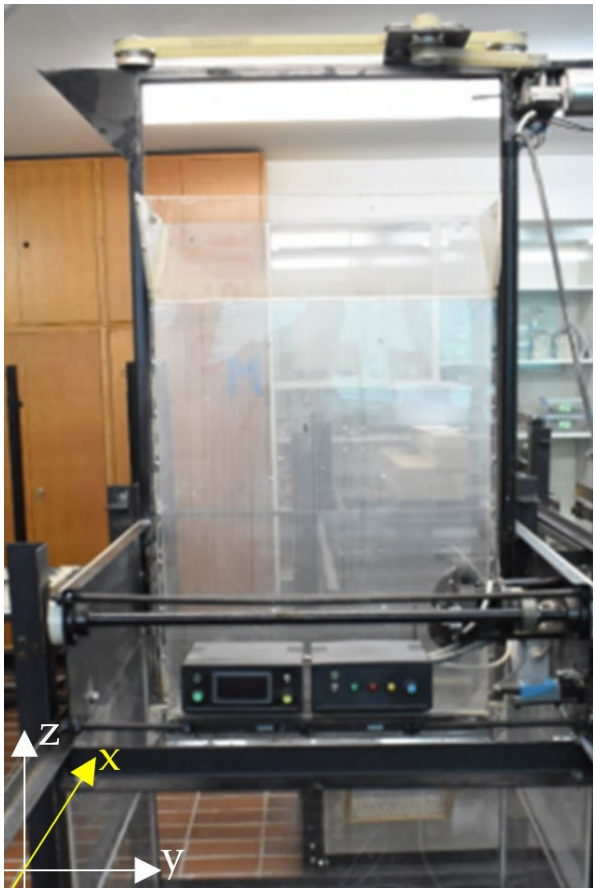


Figure 15. Spreader—front view.



Figure 16. Spreader—side view.

The spreader has two control panels. One control panel serves to control the movement of the support brace within the box, with a switch for adjusting the speed of movement.

The second control panel controls the support bracing box by adjusting the movement of the box in the z-direction, as well as the speed of box movement.

2.4. Testing Procedure

1. Prior to testing, the test box is filled with sand by means of a spreader, pouring sand in the form of sand rain from a height of 10 cm so that the sand remains loose after filling the box.

2. The filled sandbox is placed under previously installed test frame on which an engine with a mounted hydraulic piston is mounted. Load cell, which registers the vertical force on the system when pressing a group of piles into the sand, is mounted at the end of the piston.

3. The pre-assembled configuration of the piled raft is mounted on the load cell and the measuring equipment is connected to data logger (Figure 17).

4. Before applying the vertical compression force on the piled raft foundation model, spacers are placed between the piles at certain heights, ensuring that the piles remain vertical when pressed and are not skewed.

5. After the spacers are installed, the data logger is started, which is followed by final checking whether all measuring equipment is functional. The piles are driven in sand at a speed of 105 mm/min until the raft is at the height of 10 mm above the sand.

6. When the raft is at the height of 10 mm above the surface of the sand, the pressing speed is reduced to 1 mm/min and then the pressing continues until soil failure or until the raft is driven into the sand to a depth of 0.1B, where B is the width of the raft.

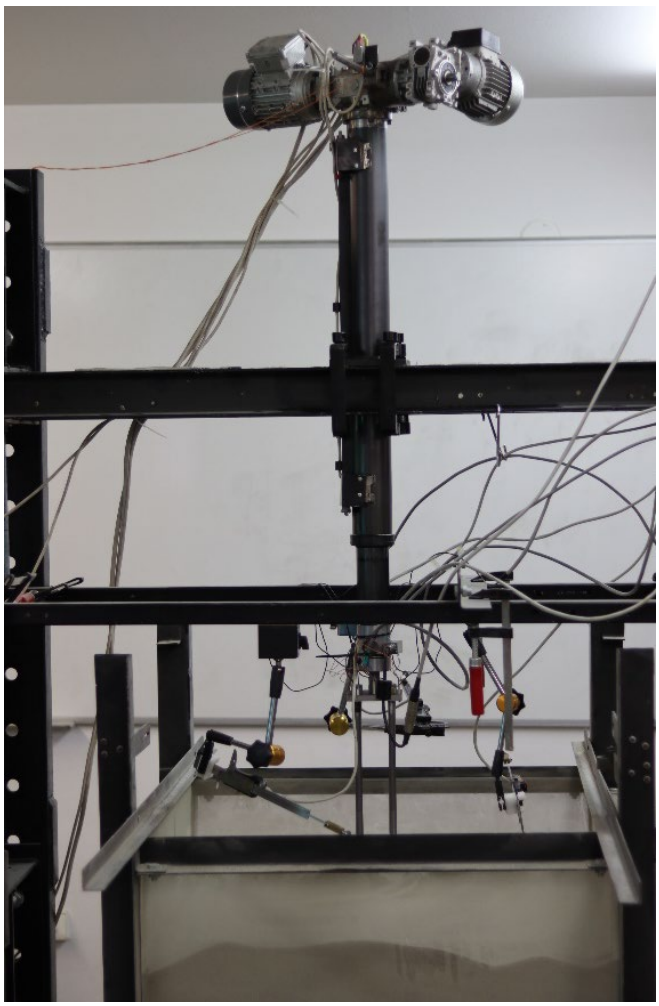


Figure 17. Photo showing the loading frame and measuring devices.

3. Results and Discussion

3.1. Rafts without Piles

Load bearing curves for rafts without piles, driven into the sand to a depth of 0.1B, where B is the raft width, for raft dimensions 72 × 72 × 10 mm, 84 × 84 × 10 mm (Figure 18), 96 × 96 × 10 mm, are shown in Figure 19.

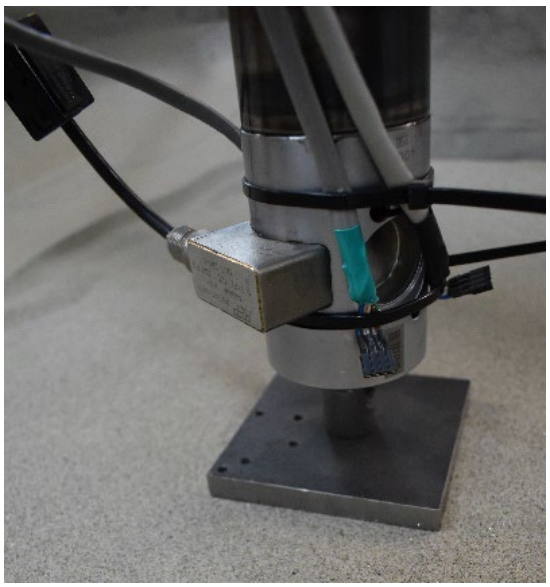


Figure 18. Raft model 84 × 84 × 10 mm prior to driving it into the soil.

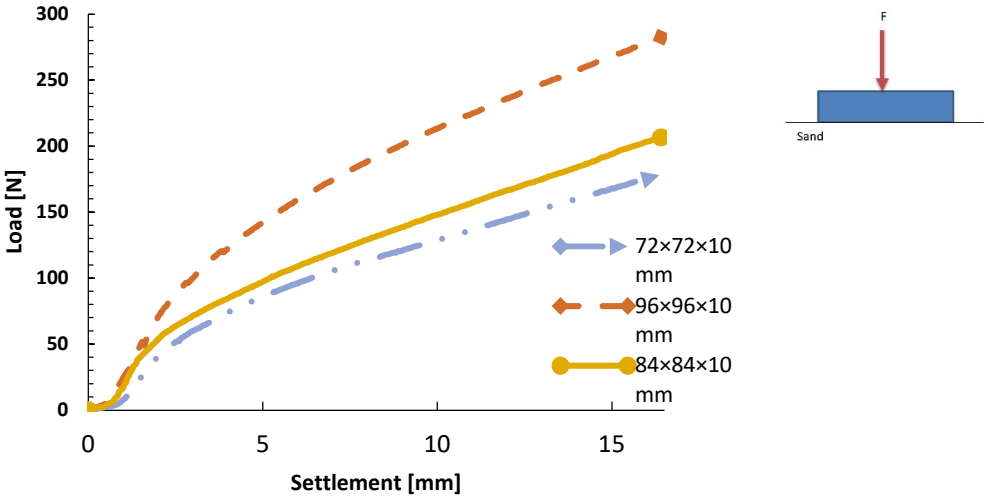


Figure 19. Load bearing curves for rafts without piles.

The results of the experiments show that, at the same external force, rafts with smaller contact area, i.e., smaller e/d ratio, have increased settlements, where "e" represents the distance between the pile axes and "d" is the pile diameter.

3.2. Piled Raft

Within this experiment, load distribution between raft and piles, when the model was driven into loose sand, was analysed. Figures 20–32 show "force–displacement" graphs of the piled raft for pile lengths of L/d = 40, 20, 10, which is often applicable in practice. The experiment was performed for pile distances of 3d, 4d, and 5d. The same layout was investigated by Marlapalle and others [63] in their experiments. From the graphs shown, it can be observed that, when settlement increases, the raft is activated, and, as the settlement

further increases, the part of the force carried by the raft also increases. The final settlement criterion was defined to be a settlement of 0.1B, measured from the moment when the raft makes contact with the sand. The graphs show the portion of the load taken by the raft.

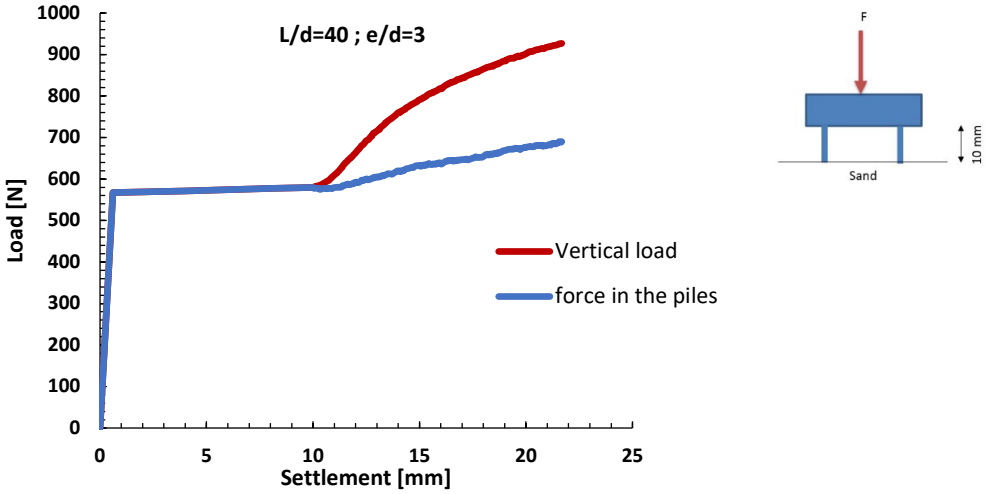


Figure 20. Diagram "force–displacement" of piled raft L/d = 40, e/d = 3.

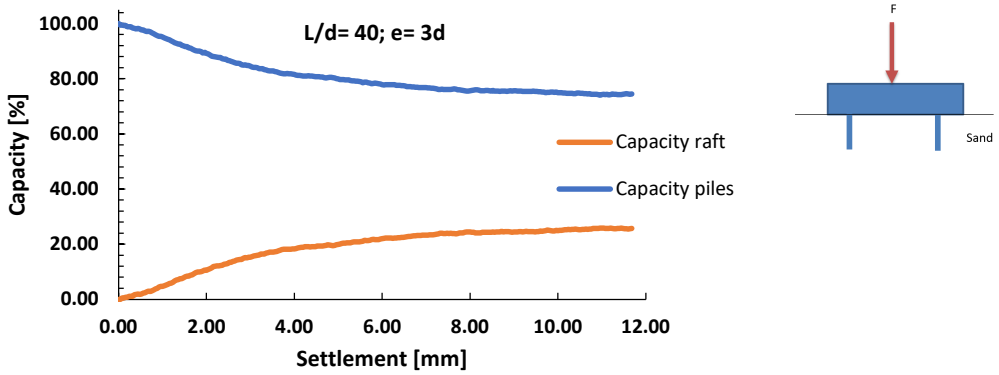


Figure 21. Load distribution graph for the group of 4 piles with 40d length at the distance of e = 3d.

Figures 20 and 21 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 40d at a distance of 3d. The results show that, if a value of 0.1B is chosen for limit settlement, measured from the moment the raft touches the soil (here, approximatively 7 mm), the piles carry 76% of the total load.

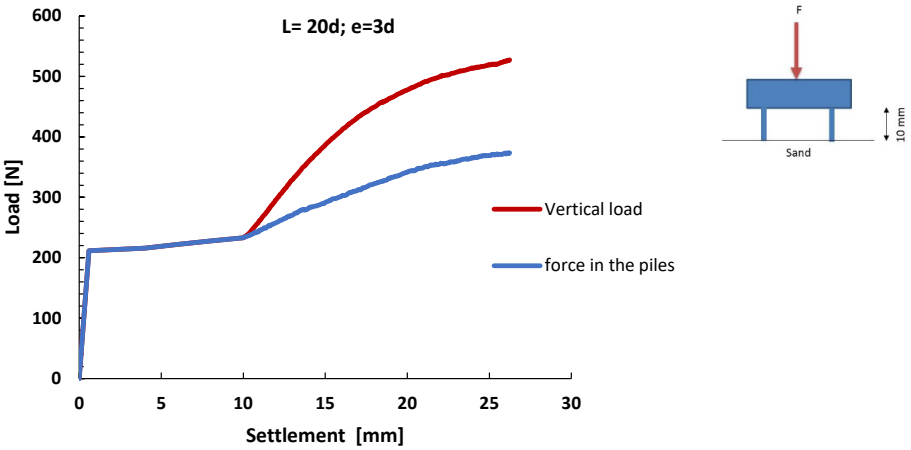


Figure 22. Diagram "force–displacement" of piled raft L/d = 20, e/d = 3.

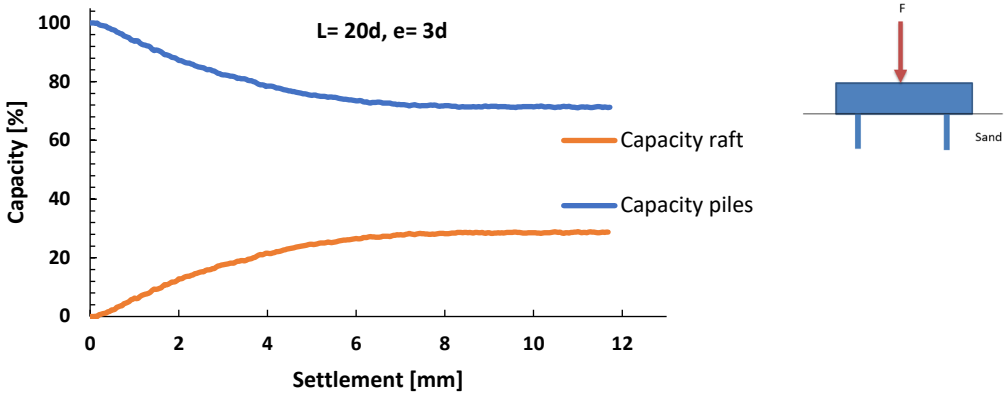


Figure 23. Load distribution graph for the group of 4 piles with 20d length at the distance of e = 3d.

Figures 22 and 23 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 20d at a distance of 3d. The results show that, if a value of 0.1B is chosen for limit settlement, measured from the moment the raft touches the soil (here, approximatively 7 mm), the piles carry 72% of the total load.

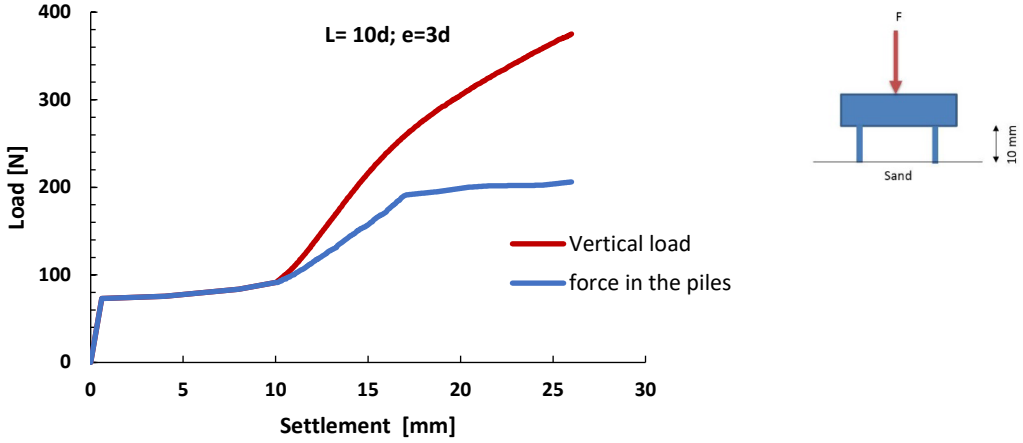


Figure 24. Diagram "force–displacement" of piled raft L/d = 10, e/d = 3.

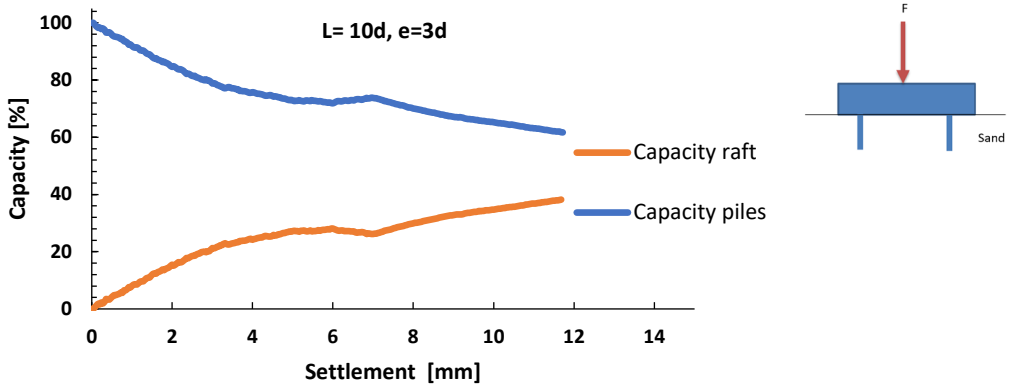


Figure 25. Load distribution graph for the group of 4 piles with 10d length at the distance of e= 3d.

Figures 24 and 25 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 10d at a distance of 3d. The results show that, if a value of 0.1B is chosen for limit settlement, measured from the moment the raft touches the soil (here, approximatively 7 mm), the piles carry 74% of the total load.

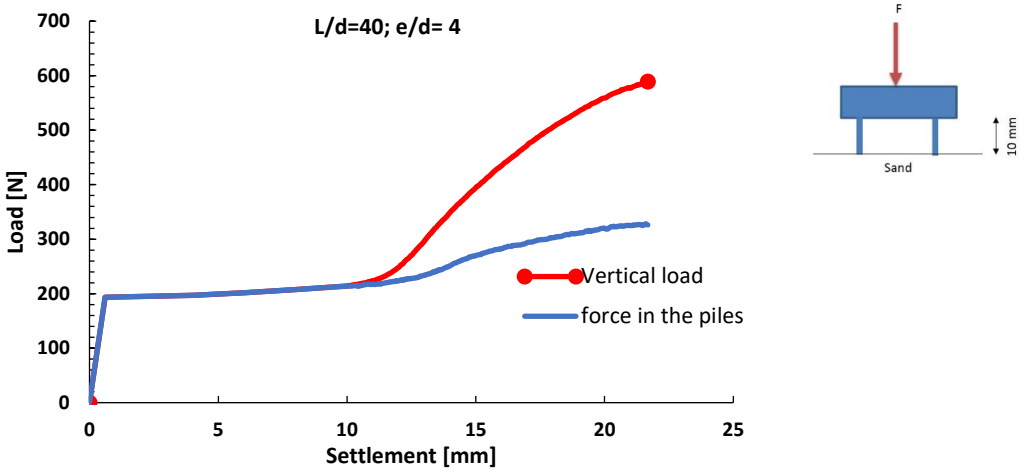


Figure 26. Diagram "force–displacement" of piled raft L/d = 40, e/d = 4.

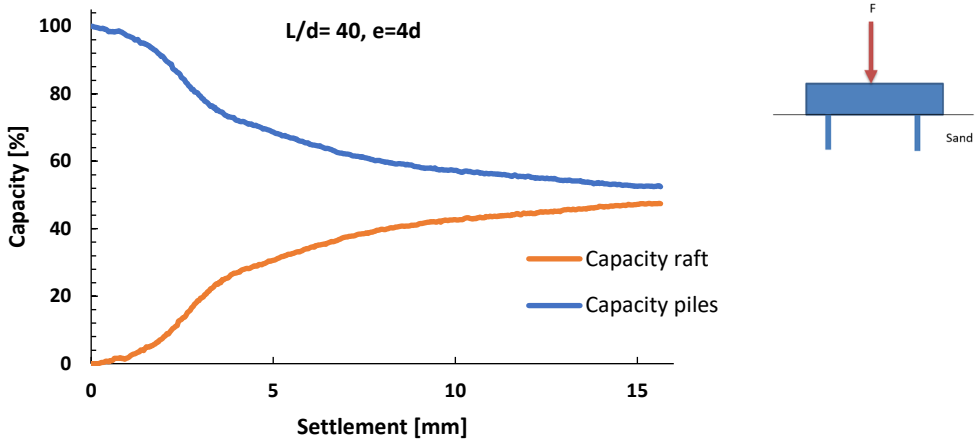


Figure 27. Load distribution graph for the group of 4 piles with 40d length at the distance of e = 4d.

Figures 26 and 27 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 40d at a distance of 4d. The results show that, if a value of 0.1B is chosen for limit settlement, measured from the moment the raft touches the soil (here, approximatively 7 mm), the piles carry 60% of the total load.

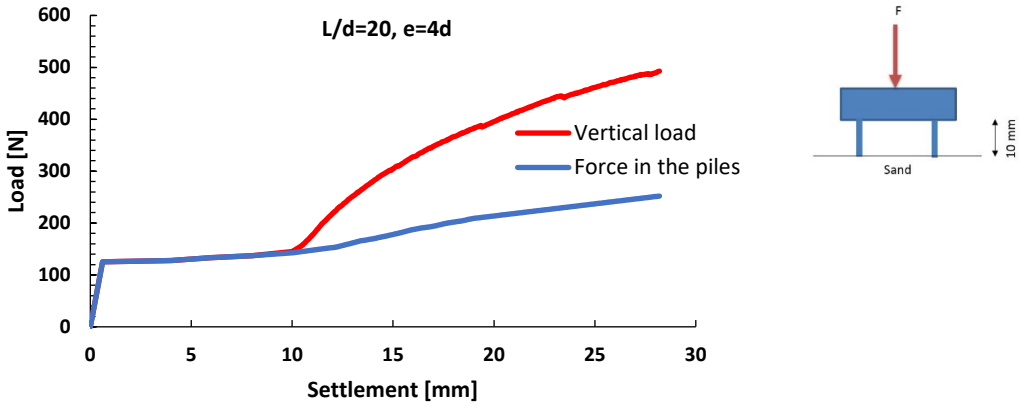


Figure 28. Diagram "force–displacement" of piled raft L/d = 20, e/d = 4.

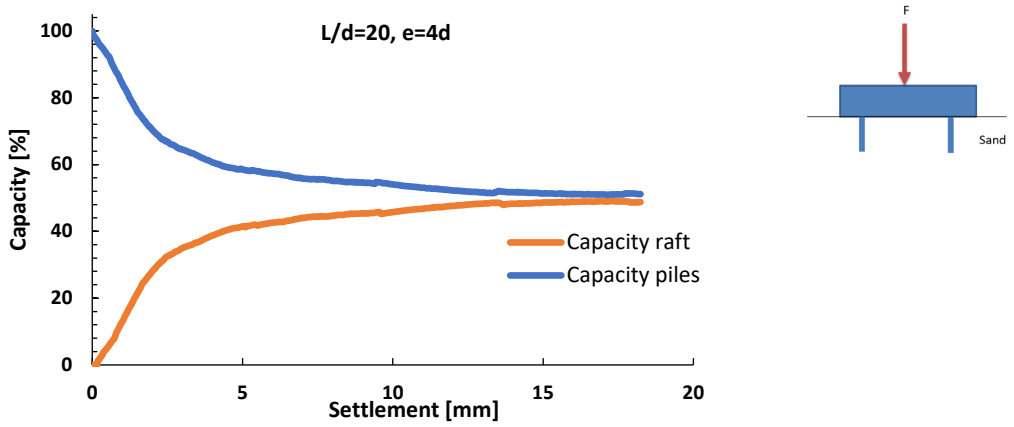


Figure 29. Load distribution graph for the group of 4 piles with 20d length at the distance of e = 4d.

Figures 28 and 29 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 20d at a distance of 4d. The results show that, if a value approximatively 8 mm is chosen for limit settlement, the piles carry 55% of the total load.

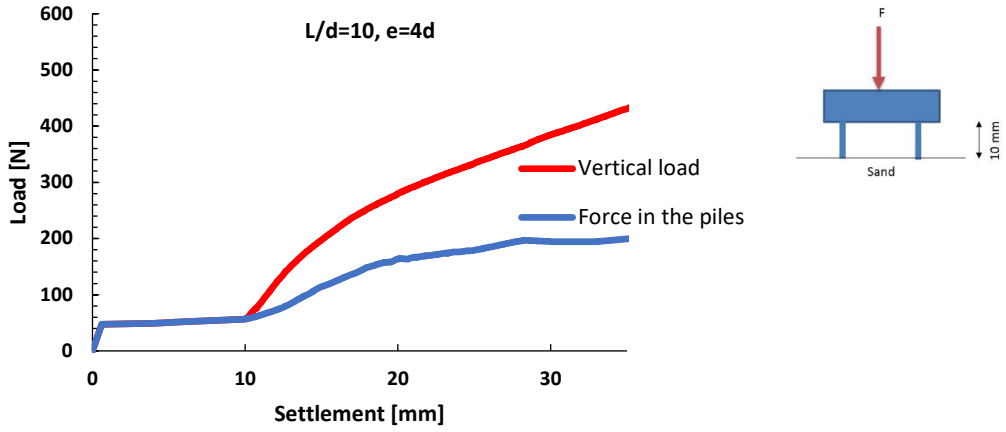


Figure 30. Diagram "force–displacement" of piled raft L/d = 10, e/d = 4.

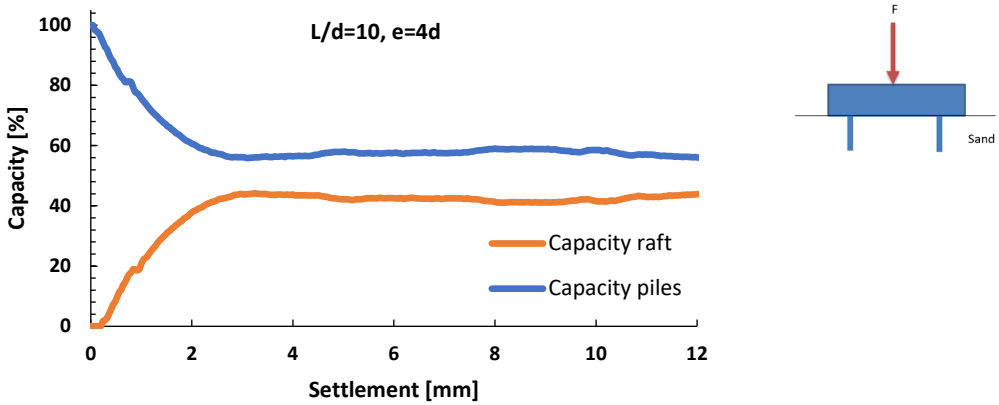


Figure 31. Load distribution graph for the group of 4 piles with 10d length at the distance of e = 4d.

Figures 30 and 31 show the "force–displacement" graphs, i.e., "load bearing capacity–settlement", for piles with a length of 10d at a distance of 4d. The results show that, if a value approximatively 8 mm is chosen for limit settlement, the piles carry 58% of the total load.

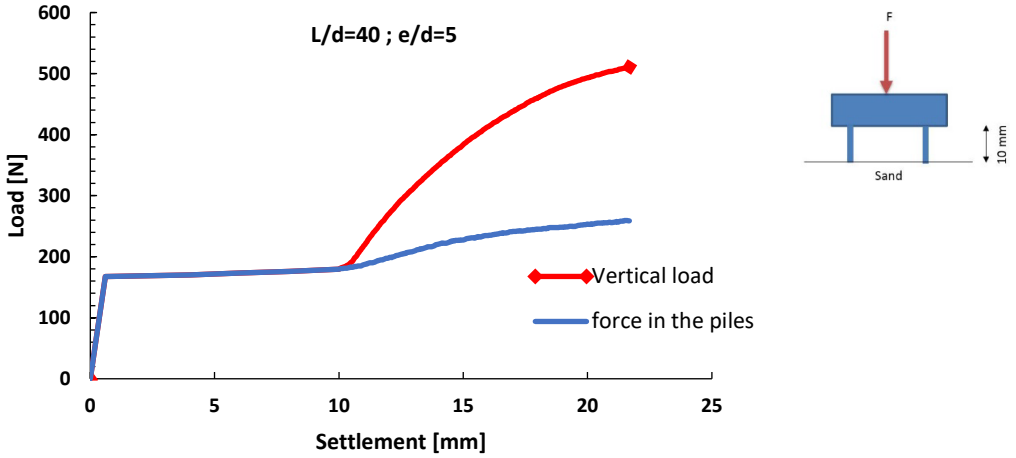


Figure 32. Load distribution graph for the piled raft L/d = 40, e/d = 5.

Figure 32 shows the "force–displacement" graphs for piles with a length of 40d at a distance of 5d. The results show that, if a value of approximatively 9 mm is chosen for limit settlement, the piles carry 53% of the total load.

Previous diagrams show that, when designing piled raft foundations, the calculation should not be based on the required number of piles that should accept the entire load but on the number of piles needed to reduce the settlement to the allowable limits.

Long Phung [34] presented the measurement results of a load distribution mechanism for the Messe-Torhaus building in Frankfurt, 30 floors high and 130 m high. The building has a piled raft foundation, with raft dimensions of 24.5 × 17.5 m and pile spacing of about 3d. The established load distribution was such that about 25% of the total load was taken over by the raft, which corresponds to measurements obtained in this paper for the pile spacing of 3d. Long Phung [64] analysed the foundations of the ICC shopping centre in Hong Kong, one of the ten tallest buildings in the world, by means of numerical analysis with PLAXIS software and obtained that 30% of the total load is carried by the raft, which also corresponds to the range of measured results obtained by this experiment.

3.3. Influence of Pile Distance—Group Effect

Within the experiment, the influence of pile spacing on the relationship between load and settlement in a piled raft foundation system was investigated, as well as the distribution of forces between piles and raft.

The diagram in Figure 33 shows that pile spacing has an effect on the relationship between load and settlement of this combined foundation system. This influence is much more pronounced when the spacing is e/d = 3 or smaller when compared to models with pile spacing of e/d = 4 and 5. Smaller pile spacing provides significant improvement in the performance of the piled raft foundation, and, accordingly, increased spacing of the piles leads to increased settlement of the foundation. Pile spacing also affects the distribution of forces between the piles and the raft.

Figure 34 shows the effect of a group of piles. It can be observed that the shape of the curve is approximately the same for pile lengths of 10d and 20d, while the curve for pile length of 40d has a slightly different shape. Moreover, the effect of the pile group at a pile distance of 3d is much more pronounced, about 2.72 times larger, when compared to the pile distance of 4d. For piles of lengths 20d and 10d, the effect of the pile group at a distance of 3d is, in relation to a pile distance of 4d, about 1.55 times greater for a length of 20d and about 1.45 times greater for a length of 10d. It was also observed that, with a pile length of 40d at distances greater than 5d, the group effect is lost and the piles start to behave as individual piles, while, for piles of 10d and 20d length, the group effect can still be observed. Similar conclusions were reached by Sharafkhah et al. in their work [65].

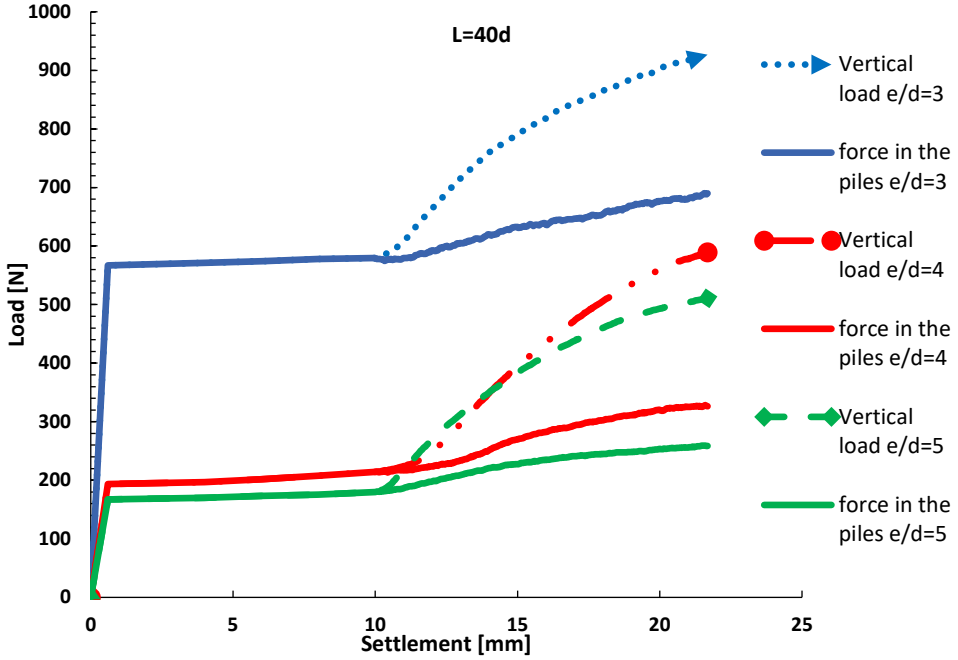


Figure 33. Diagram "force–displacement" for the piled raft L = 40d, e/d = 3;4;5.

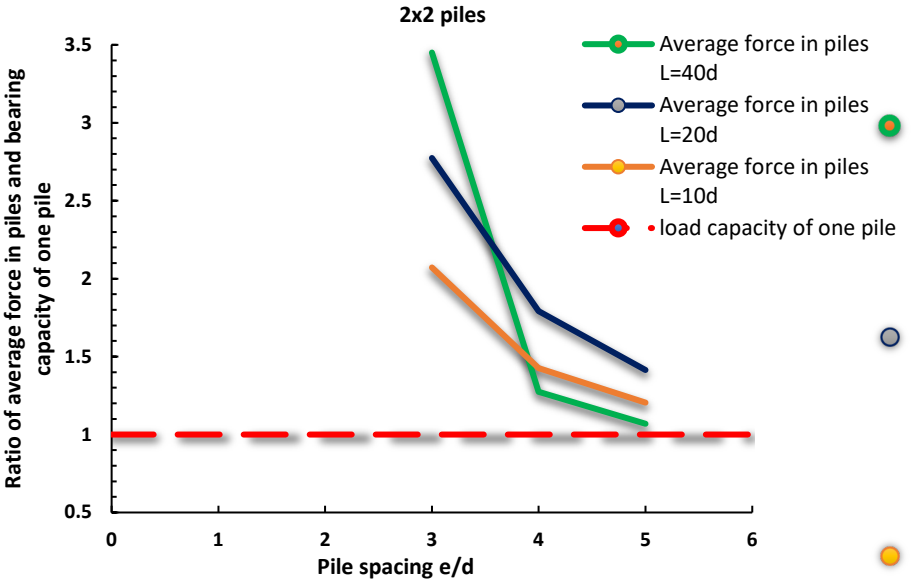


Figure 34. The effect of the group of 2 × 2 piles for piles length L = 40d.

Figures 35–37 show the value of settlement of the raft for the same pile lengths at a mutual distance of 3d, 4d, and 5d. It can be observed that, in all three cases, the settlement is greater at the same force for rafts with a greater distance between piles and the shapes of the curves for lengths of 40d and 20d are similar, while, for a length of 10d, the settlement increases linearly with increasing distance between piles.

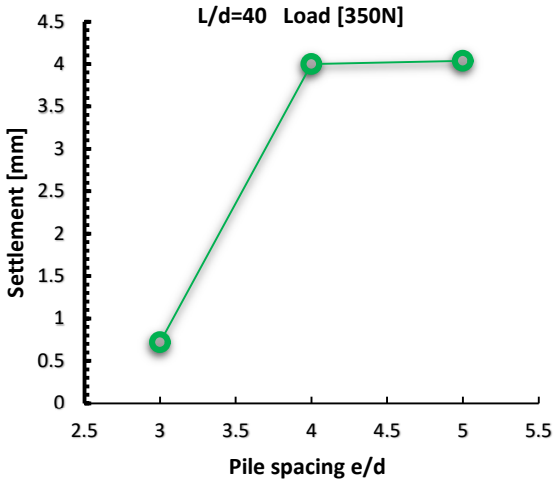


Figure 35. Settlements of pile groups with length of L = 40d in relation to pile distances at the load of 350 N.

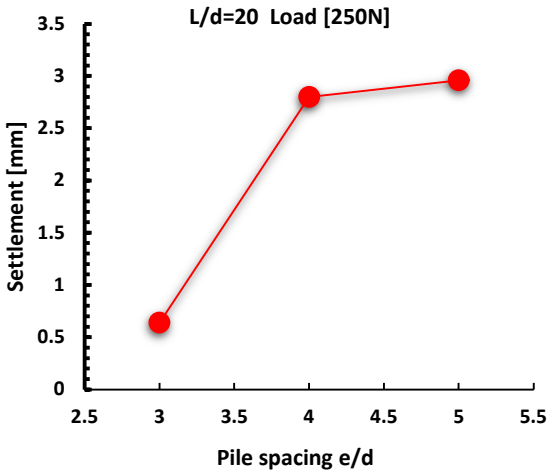


Figure 36. Settlements of pile groups with length of L = 40d in relation to pile distances at the load of 250 N.

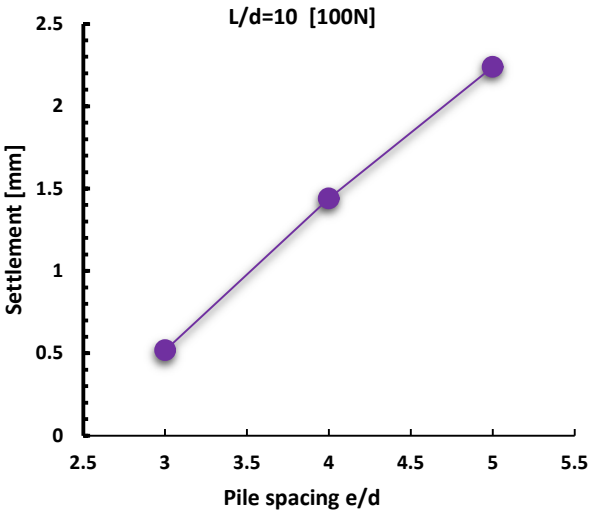


Figure 37. Settlements of pile groups with length of L = 10d in relation to pile distances at the load of 100 N.

3.4. The Effect of Length

The experimental analysis found that the length of the piles has no particular effect on the load distribution between the raft and the piles, as shown in the following figure.

It was observed that, after the yield point of the foundation system, the stiffness of the raft is not affected by the change in the length of the piles, which can be concluded from Figure 38. On the other hand, the bearing capacity of the foundation increases significantly with an increase in the length of the piles before and after the yield point. Similar observations were made in the studies by Omekan [66] and El Sawwaf [67].

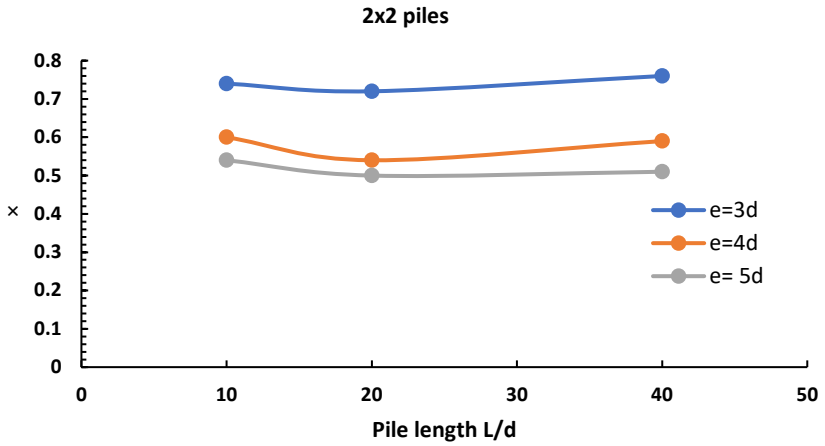


Figure 38. Total portion of the load carried by the piles for same distances and different pile lengths.

3.5. Load Bearing Capacity of the Raft with and without Rafts

Figure 39 shows the bearing capacity of piled rafts and rafts without piles for pile spacing of 3d and pile lengths of 40d, 20d, and 10d. For a raft settlement of 0.1B, which is approximately 7 mm, the bearing capacity of the piled raft foundation system with piles of length 10d is about 2.43 times higher than for the raft without piles. The bearing capacity of the piled raft on piles with a length of 20d is greater by about 1.67 times than for the piled raft with piles of 10d length, while the bearing capacity of the piled raft with piles of 40d length is greater by about 1.15 times than the piled raft with piles of 20d length.

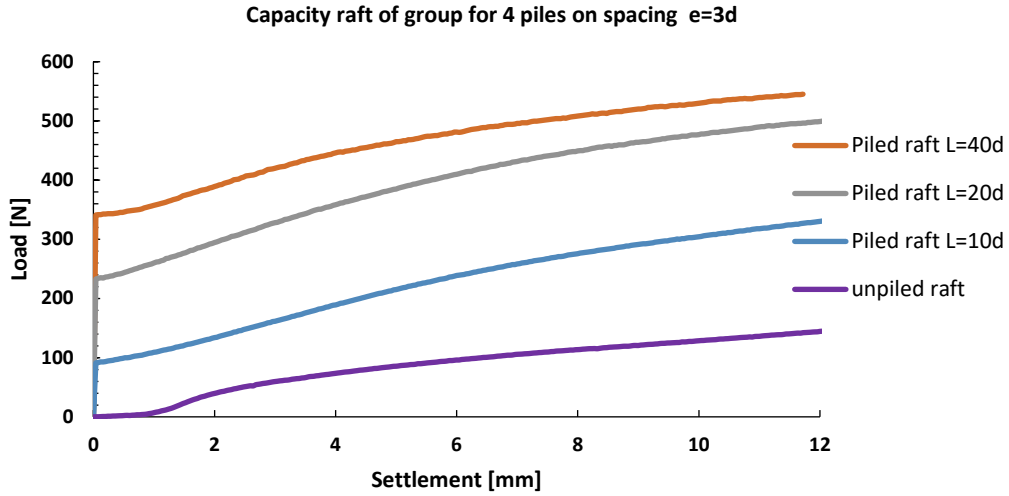


Figure 39. Bearing capacity of piled rafts and rafts without piles for different pile lengths and piles at a distance of 3d.

Figure 40 shows the bearing capacity of piled rafts and rafts without piles for pile spacing of 4d and pile lengths of 40d, 20d, and 10d. For a raft settlement of 0.1B, which is approximately 8 mm, the bearing capacity of the piled raft foundation system with piles of

length 10d is about 1.95 times higher than for the raft without piles. The bearing capacity of the piled raft on piles with a length of 20d is greater by about 1.45 times than for the piled raft with piles of 10d length, while the bearing capacity of the piled raft with piles of 40d length is greater by about 1.38 times than the piled raft with piles of 20d length.

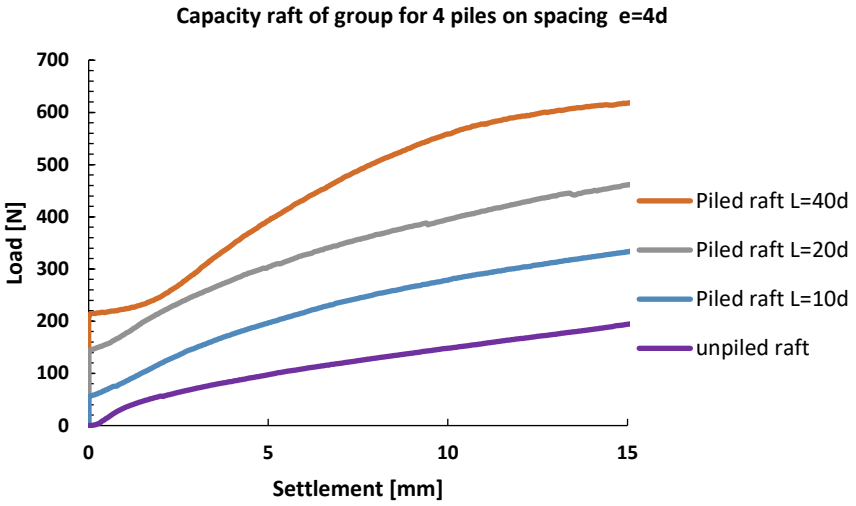


Figure 40. Load bearing capacity of piled rafts and rafts without piles for different pile lengths and piles at a distance of 4d.

Figure 41 shows the bearing capacity of piled rafts and rafts without piles for pile spacing of 5d and pile lengths of 40d, 20d, and 10d. For a raft settlement of 0.1B, which is approximately 9 mm, the bearing capacity of the piled raft foundation system with piles of length 10d is about 1.15 times higher than for the raft without piles. The bearing capacity of the piled raft on piles with a length of 20d is greater by about 1.79 times than for the piled raft with piles of 10d length, while the bearing capacity of the piled raft with piles of 40d length is greater by about 1.16 times than the piled raft with piles of 20d length.

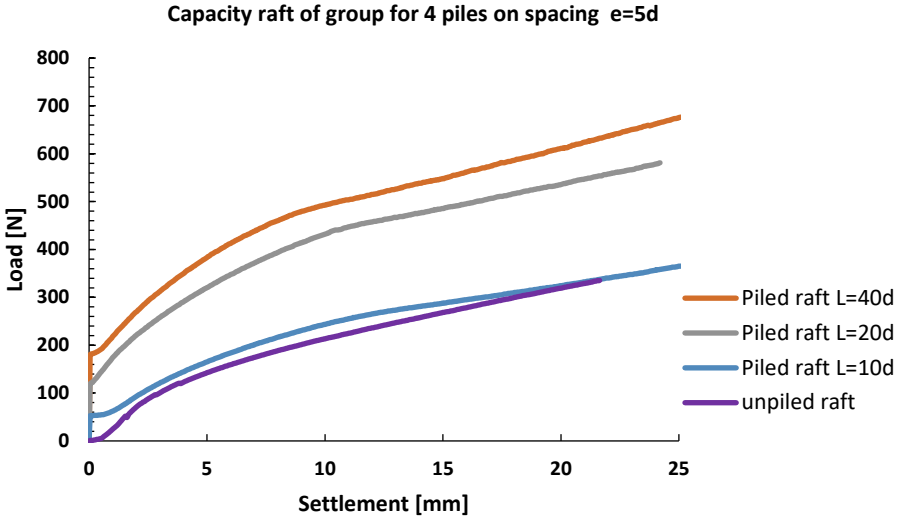


Figure 41. Load bearing capacity of piled rafts and rafts without piles for different pile lengths and piles at a distance of 5d.

4. Conclusions

Based on experimental results, the following conclusions were reached:

1. Application of small-scale 1g models for pile bearing capacity estimation in loose sand is justified for this research because there is no significant scale effect that could originate from the curved strength envelope for dense sand.

2. For the same external force, a raft with smaller contact area, i.e., smaller e/d ratio, and smaller pile slenderness (L/d) has higher settlements.
3. For the same external force and same e/d ratio, an increase in pile slenderness ratio L/d reduces settlement of the raft.
4. The scientific contribution of this paper is showing that the influence of scale effect on estimation of pile bearing capacity in loose sand that has a constant value of the angle of shearing resistance is negligible. In other words, application of 1g models on assessment of the bearing capacity of piles in loose sand is not essentially related to the size of the model. By contrast, in dense sand, the shear resistance envelope is curved. This means that the mobilized angle of shearing resistance at smaller pile dimensions is smaller; i.e., the average normal stress is lower and vice versa, or, in other words, the scale effects become significant.
5. Piled raft foundation systems with smaller contact surfaces at the same load levels have higher settlements than systems with larger contact surfaces; the increase in the raft contact surface improves the load bearing capacity of the piled raft foundation system at the same settlement values. This improvement in performance is caused by the horizontal pressures in the soil beneath the raft, which increase the friction between the soil and the pile surface, therefore increasing the load bearing capacity of the whole piled raft foundation system.
6. When driving in a group of piles, as soon as the raft makes contact with the sand, the raft is activated, and its load bearing contribution increases as settlement increases.
7. For the case of raft settlement at a value of 0.1B, where B is the width of the pile, depending on the distance between the piles, the pile carries about 24% to 50% of the total load acting on the foundation system.
8. The length of the piles does not play a significant role in the distribution of the load between the raft and the piles.
9. For the pile spacing of 3d, the pile group effect is very pronounced, while, as the spacing increases, the pile group effect decreases. It was concluded that the pile spacing of 5d represents the upper boundary value, after which the pile group effect contribution to the load bearing capacity is lost.

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