The behaviour of piled raft foundation in loose sandy soil

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Abstract. The conducts of pile raft basis depend on piles, raft, as well as soil. When designing a pile group, it is expected that only the piles carry out the applied loading. No contribution is given to soils underneath the raft because of the complicated interacting amid the piles and their cap with soils. When the soil under the raft foundation shares carrying the applied loads, this interaction will increment the piled raft system's bearing capability as well as decrease the settlements. To comprehend the piled raft system's complicated conduct, testing for twenty-seven experimental models was done within loose sands with a load applied to the piled raft foundation via a compressing jack then the measurement was done using a loading cell. Wide parametrical examinations had been executed with the variables number of piles, pile length, raft dimension ratio. The soil under the raft contributed a certain percentage in carrying the applied weights in the piled raft foundation. Similarly, there is an increase in the loading taken via piles to the overall load executed on pile raft with the growth of the number of piles in the series, and there is a decrease in the share of the soil under the raft for the applied loads when there is increasing within the piles' amounts. The increment within the piles' lengths causes an increase in the soil’s share underneath the raft, and the maximum settlement of the piled raft system does not exceed 5% of the raft width in all cases.

1. Introduction
The piled raft bases were utilized more common for reducing the total and settlement of footing. It is a novel concept in that the complete loading which comes from the superstructure is partially shared through piles, while the remain loading is shared through raft contacting with soil. The Pile foundations' concept was proposed first by Poulos and Davis in 1972 [1], now used widely in Europe, and in particular to support the load of the high-rise towers or building. The piled raft favourable application happens once the rafts have sufficient load limit, yet the settlements or the differentiation settlements surpass the permissible values in the case that the main objective of the piles is to serve as the reduced settling [2]. This paper will illustrate the piled rafts system using an experimental model.

2. Soil model
Within the current work, the sand is relatively poorly graded fine clean sands of grain-size between (0.075 mm and 2.36 mm). Sand is taken from a region in Karbala-city at a depth of 10 m to 15 m and utilized
within the current work. Table (1) illustrates the characteristics of sands utilized within the current work. According to the ASTM standard, laboratory tests include grain-size distributing, precise gravity, minimum and maximum dry unit weights, and direct shear test. It was executed the Sieve analysis according to the ASTM D 422- 2000 (Standardized Testing Methods for Particle Size Analysing for Soil) [3], as shown in Figure (1).

3. Model setup formulation
A novel load scheme was fabricated to apply the pile raft load testing. Such scheme consists of the next segments:
Steel Structuring of Casing Model, Steel Tank Container, Steel Movable Beam Load Scheme, Steel Movable Axial Load Scheme, Compressing Loading Cell Kind (s), Mechanic Jack, Electronic Weighing Indicator, PS (universal power system), Rain scheme, Dial gaging pointer, Pile drive installing scheme. Steel Pile Cap and Reading Board.

Table 1. Physic features for the loose sand utilized within the present testing.

| Index property                  | Value  | Specification          |
|---------------------------------|--------|------------------------|
| Grain size analysing            |        | ASTM D 422-2007        |
| D10(mm)                         | 0.16   |                        |
| D30(mm)                         | 0.28   |                        |
| D50 (mm)                        | 0.35   |                        |
| D60 (mm)                        | 0.4    |                        |
| Coefficient of uniformity (Cu)  | 2.5    |                        |
| Coefficient of curvature (Cc)   | 1.225  | USCS*                  |
| Soil classification             | SP     | USCS*                  |
| Specific gravity (Gs)           | 2.63   | ASTM D 854-2014        |
| Maxi dry unit weight (kN/m3)    | 17.4   | ASTM D 4253-2014       |
| Mini dry unit weight (kN/m3)    | 15.46  | ASTM D 4254-2000       |
| Dry unit weight adopted (kN/m3) | 15.91  |                        |
| Relative Density (Dr%)          | 25.5   |                        |
| Void ratios                     |        |                        |
| Maximum void ratio              | 0.667  |                        |
| Minimum void ratio              | 0.482  |                        |
4. Sand deposit preparing

The sand rain approach was used for the preparation of sands within the current work, as shown in figure (2). It was executed six times of trial for the purpose of controlling the sand's density. It was utilized various dropping heights for pouring the sands (10, 20, 30, 40, 50 and 60) cm to achieve similar volume. The outcomes indicate that there is an increase in the sand's weight needed to block up the measured volume when dropping height increases; in conclusion, there is a straight relationship between the sand’s density with the height of the drop at certain limits. Figure (2) shows the influence of drop height on the measured density, once the sand preparing process is complete as well as levelled for the last layer, after that scraping by a well edge ruler for the purpose of making a possible level surface. The height of the fall is about (200 mm), this signifies a seat unit weight of (15.91) kN/m3, voids’ rate of (0.62) with a relative density about 25.5%. Table (1) illustrates the properties of sands utilized in the testing.
5. Testing procedure
The procedure that is used to study the tested piles was organized in the subsequent steps:
- Sand deposits formation
- Execution of the pile models.
- Carrying out the vertical load

Hydraulic jack with a ten-ton capacity used to put on vertical downward compress loading, with a hydraulic constant ratio motion- Jack. The applied load can be determined using the load cell that used to connect between the hydraulic jack and the pile head by a steel shaft; also, the load cell is linked with the electronic reading indicator to allow reading the utilized load. The perpendicular deformation of soil beneath pile raft tip (pile raft displacement) is scaled by a dial gauge with 0.01 mm sensitivity ASTM D1143[4].

6. Testing program
Twenty-Seven model of piled raft system were made as driven piles throughout the fourth stages:
The first stage includes 3 models of the piled raft (2x1,2x2 and 2x3) with different lengths (40, 50 and 60 cm) installed by driving in loose sand and tested under compression load statically to examine the participation ratio for each of the piles and the soil below the raft and its impact on the bearing capacity of the piled raft foundation and for study the effective of piles' length, piles amount plus size of piled with raft foundation upon the conduct of piled with raft scheme in loose sand soils.

7. Results and discussion
The prime objective of a parametrical investigation is to examine the piled raft system performing below various dimensions' geometry. Hence, the cases to the parametrical survey should match with the dimensions of piled raft geometry, precisely, the piles’ number, the diameters of piles, the lengths of piles for pile groups and raft dimension rate (L/B) (B, L: the width and length of the raft). below is the description of the piled raft scheme and pile groups for the current parametric work, Table 2 gives a summary to that.
7.1. Load transferring on rafts, pile groups and piled with raft

The current part introduces the load-carrying capacity of the raft, piles and piled raft within any group and the loading settlement of piled conduct raft the whole systems of the piled raft (2x1, 2x2 and 3x2) using a circular pile having a diameter of 45 mm. The length of the piles is 40, 50, and 60 cm. for the purpose of simulating the experimentation works along with final loading conditions, the loads continued to fail. Figure (4) shows the characteristic made up of piled raft, unpiled with raft and group of piles, which represents the following:

The piled raft foundation in contact with soil, as shown in Figure (4.a).

The raft foundation without piles, where rafts are tested separately, as shown in Figure (4.b).

The piles' foundation and the raft do not touch the soils where the pile group are tested separately after removing the soil underneath the raft, as shown in Figure (4.c).

![Figure 4. Characteristic configurations of (a) piled with raft; (b) unpiled raft; and (c) group pile.](image)

| Case | Type of soil | Raft specifications | Piles specifications |
|------|-------------|---------------------|---------------------|
|      |             | Width (Br) | Length (Lr) | Dia. | Length | Spacing |
| 1    | 2x1         | Loose sand  | 13.5 cm     | 27 cm | 45 mm  | 40 cm   | 135 mm  |
| 2    | 2x1         | Loose sand  | 13.5 cm     | 27 cm | 45 mm  | 50 cm   | 135 mm  |
| 3    | 2x1         | Loose sand  | 13.5 cm     | 27 cm | 45 mm  | 60 cm   | 135 mm  |
| 4    | 2x2         | Loose sand  | 27 cm       | 27 cm | 45 mm  | 40 cm   | 135 mm  |
| 5    | 2x2         | Loose sand  | 27 cm       | 27 cm | 45 mm  | 50 cm   | 135 mm  |
| 6    | 2x2         | Loose sand  | 27 cm       | 27 cm | 45 mm  | 60 cm   | 135 mm  |
| 7    | 3x2         | Loose sand  | 27 cm       | 40.5 cm | 45 mm | 40 cm   | 135 mm  |
| 8    | 3x2         | Loose sand  | 27 cm       | 40.5 cm | 45 mm | 50 cm   | 135 mm  |
| 9    | 3x2         | Loose sand  | 27 cm       | 40.5 cm | 45 mm | 60 cm   | 135 mm  |

In the following Figures 5 to 13, the settlement is plotted against the vertical applied load. These figures illustrate the load with settlement attitude of piled with rafts, piles, and rafts. regarding the full cases, the load-settling relationship is linear at the start since the piles as well as soils remain within the elastic ranging [5].
Figure 5. Load – displacement curve for (2x1) piled raft, unpiled raft and the total load on piles (L=400 mm and D=45 mm).

Figure 6. Load – displacement curve for (2x1) piled raft, unpiled raft and the total load on piles (L=500 mm and D=45 mm).

Figure 7. Load – displacement curve for (2x1) piled raft, unpiled raft and the total load on piles (L=600 mm and D=45 mm).

Figure 8. Load – displacement curve for (2x2) piled raft, unpiled raft and the total load on piles (L=400 mm and D=45 mm).

Figure 9. Load – displacement curve for (2x2) piled raft, unpiled raft and the total load on piles (L=500 mm and D=45 mm).

Figure 10. Load – displacement curve for (2x2) piled raft, unpiled raft and the total load on piles (L=600 mm and D=45 mm).
There are several standards suggested to define the failure loading of the piled raft. Felleiniius (2006) [6] describes a number of such standards in the following:

1. De Beer (1968) suggestion [7] (as stated according to Winterport and Fang, 1975) [8]. The loading ability can be determined on the breakpoint of the intersection of two straight lines of dissimilar gradients once the loading-settlement relation gets plotted in a log-log plot. Such breakpoint signifies the fail.

2. Terzaghi (1947) suggestion, the fail could be determined as the loading correspondence to the displacing for 10% of the model footing width [9].

3. Butler and Hoy (1977) suggestion, where the fail can be defined depending upon the two tangents intersecting of the loading-settlement curve whereas the another can be tangent to the low flatter ration of the curve. [10].

Figure 11. Load – displacement curve for (2x3) piled raft, unpiled raft and the overall load on piles (L=400 mm and D=45 mm).

Figure 12. Load – movement curve for (2x3) piled with raft, unpiled raft and the total load on piles (L=500 mm and D=45 mm).

Figure 13. Load – displacement curve for (2x3) piled raft, unpiled raft and the total load on piles (L=600 mm and D=45 mm).
For all cases, once the preceding suggestions were examined via reviewing a behaviour of the loading-settlement connection for the piles within the present revision, it is concluded that Butler and Hoy (1977) proposal could be accepted to specify the end loading of the piled with raft and piles set. By examining Figures (5) to (13) and Table (3) the following can be noticed:

- There is an increase in the loads conducted via piles to the accumulative load imposed on piled raft when the no. of piles in the group increases, while the group of (3x2) recorded the maximum piles capacity with more than 80% of the total applied load.
- The soils beneath the raft contributed a certain percentage in carrying the applied loads within the piled raft foundation.
- The ratio of the loading taken by slab footing to the overall subjected loading of the piled with slab footing foundation with L= 40 cm and piles number (2x1,2x2 and 3x2) is 28.5, 18 and 12.5%, respectively.
- The ratio of the loading taken by slab footing to the accumulative applied loading of the piled with slab footing with L= 50 cm and piles number (2x1,2x2 and 3x2) is 35.4, 20 and 15.4%, respectively.
- The ratio of the loading executed through slab footing to the total subjected loading of the piled raft foundation with L= 60 cm and piles number (2x1,2x2 and 3x2) is 40, 24.7 and 18.2%, respectively.

**Table 3.** Load sharing between raft foundation and pile groups from static situ tests.

| Case | The ultimate capacity of piled raft (N) | Final capacity (tons) | Load for each pile and raft in piled with raft system (%) |
|------|----------------------------------------|-----------------------|------------------------------------------------------|
|      |                                        | Piles | Raft     | Piles | Raft     |
| 1    | 210                                    | 150   | 60       | 71.5% | 28.5%    |
| 2    | 240                                    | 155   | 85       | 64.6% | 35.4%    |
| 3    | 350                                    | 210   | 140      | 60%   | 40%      |
| 4    | 500                                    | 410   | 90       | 82%   | 18%      |
| 5    | 600                                    | 480   | 120      | 80%   | 20%      |
| 6    | 810                                    | 610   | 200      | 75.3% | 24.7%    |
| 7    | 800                                    | 700   | 100      | 87.5% | 12.5%    |
| 8    | 1300                                   | 1100  | 200      | 84.6% | 15.4%    |
| 9    | 1650                                   | 1350  | 300      | 81.8% | 18.2%    |

7.2. Parametric Study
Several parameters influence the performance of piled with raft footing in the design of piled raft. It is significant to consider such factors to attain the goal of economic constructing with acceptable performing [11].

7.2.1. Effect of piles number
The rest geometric properties of rafts and piles of various configurations are presented in Table 4. The analysis outputs of experimental tests for the number of piles 2, 4 and 6 have been presented in the load settlement behaviour as shown in Figure (14) to (16).
From this figures, it can be noted that:
- for a settlement of 20 mm and L=40, the ultimate loads at the number of piles 2, 4 and 6 are 250, 450 and 675 N, respectively,
- for a settlement of 20 mm and L=50, the ultimate loads at the number of piles 2, 4 and 6 are 315, 490 and 1000 N, respectively
- for a settlement of 20 mm and L=60, the ultimate loads at the number of piles 2, 4 and 6 are 450, 750 and 1350 N, respectively.
This effect is because of increasing within the quantity of piles and the increasing in raft dimensions. The overall trend describes that the increase in the number of piles causes decreasing in the settlements of a piled raft. Yet, the increase of the amount of piles also unfavorably influences the economic design, and it must be cautiously reduced.

While we notice that there is a decrease in the share of the soil beneath the raft for the subjected loads when increasing the no. of piles, which means that the loads are transferred first to the piles because the stiffness of the material of the piles is higher than the stiffness of the soil, so a small part of the loads is transferred to the soil as illustrated within figure 17.

| Pile Spacing& Raft Size (L×B×D) m | No. of Piles |
|-----------------------------------|-------------|
| 3d 27×13.5                         | 2           |
| 3d 27×27                           | 4           |
| 3d 40.5×27                         | 6           |

**Figure 14.** Outcome of the amount of piles on load settlement behavior. (L=400 mm and D=45 mm).

**Figure 15.** Outcome of the amount of piles on load settlement behavior. (L=500 mm and D=45 mm).
7.2.2. Effect of pile length

Pile length plays a major role in transferring the load by shaft friction and toe bearing. The effect of pile length, L, on settlements was investigated by using pile length of 40, 50 and 60 cm. A group of (2×1, 2×2 and 3×2) piles with a space of 3d was utilized for analyzing the piled raft, as illustrated within Table (5).

The experimental model's output for the pile length 40, 50 and 60 cm was introduced in the load settlement behaviour shown in Figures (18 to 20). One can note that there is an important increase in loading capacity of piled-raft foundations when the pile length increases. It also noted that the increase in the piles' lengths reasons an increase in the share of the soil beneath the slab footing, even the area under the raft remains constant for the same group. This is because the increase in the length of the pile in loose soil leads to the occurrence the densification, meaning that the soil turns from loose to medium soil, which leads to increases in the bearing capacity of the soil. Thus, it has an increased of the applied loads and an increase in the rate of the share of the raft, as illustrated within the figure.

Table 5. Geometric properties of pile raft models for effects of the no. of piles.

| Pile Spacing & Raft Size (L×B×D) m | Piles length |
|-----------------------------------|--------------|
| 3d 27× 13.5                      | 40 cm        |
| 3d 27× 27                        | 50 cm        |
| 3d 40.5× 27                      | 60 cm        |

Figure 16. Outcome of the amount of piles on load settlement behavior. (L=600 mm and D=45 mm).

Figure 17. Outcome of pile amount on the load contribution among the slab footing and piles for different pile length.
7.2.3. Effect of Raft Dimension Ratio

The effect of raft length to raft width ((Lr/Br)) with the percentage of a load carried by raft only is shown in Figure 22. The (Lr/Br) ratio was varied from 1 to 2, while the number of piles varied from 2x1 to 3x2 and the length of piles is kept constant for each case. From results, it be noted that the slab width does not influence on the attitude of curve at few settlements of the system. The influence of the slab width happens at more than settlements only. At great settlements and the similar load state, the slab footing width increase causes the piled with slab foundations' stiffness to rise. However, with an increase in the amount of piles encouraging the slab footing, the increase in the stiffness with the increase in the slab width develops fewer significant.
Table No. 6 compares between the maxi settlement that the raft foundation can reach when a failure load with the expected settlement of the piles’ group and piled raft foundation at the same failure load. Note that the maximum settlement of the piled raft system does not exceed 5% of the raft width in all cases.

Table 6. The maximum settlement of raft, piles and piled raft at failure load of Raft

| Case          | Br cm | Lr cm | Br/Lr | Failure Load For Raft N | Max. Sett. at Failure Load of Raft mm | Raft | Piles | Piled Raft | Max.Sett./Br |
|---------------|-------|-------|-------|-------------------------|--------------------------------------|------|-------|------------|--------------|
| 2x1 (L=40; D= 45 mm) | 13.5  | 27    | 2     | 150                     | 50                                   | 12.2 | 6.3   | 5%         |
| 2x1 (L=50; D= 45 mm) | 13.5  | 27    | 2     | 150                     | 50                                   | 8.8  | 5.6   | 4.1%       |
| 2x1 (L=60; D= 45 mm) | 13.5  | 27    | 2     | 150                     | 50                                   | 5.8  | 3.2   | 2.3%       |
| 2x2 (L=40; D= 45 mm) | 27    | 27    | 1     | 200                     | 50                                   | 7.3  | 5.1   | 1.9%       |
| 2x2 (L=50; D= 45 mm) | 27    | 27    | 1     | 200                     | 50                                   | 7.0  | 4.9   | 1.8%       |
| 2x2 (L=60; D= 45 mm) | 27    | 27    | 1     | 200                     | 50                                   | 4.5  | 3.2   | 1.2%       |
| 3x2 (L=40; D= 45 mm) | 27    | 40.5  | 1.5   | 270                     | 50                                   | 7.1  | 4.8   | 1.8%       |
| 3x2 (L=50; D= 45 mm) | 27    | 40.5  | 1.5   | 270                     | 50                                   | 4.2  | 3.2   | 1.2%       |
| 3x2 (L=60; D= 45 mm) | 27    | 40.5  | 1.5   | 270                     | 50                                   | 3.9  | 2.4   | 0.9%       |

8. Conclusions
In the light of experimental models tests, the coming findings are concluded:
1. The soil under the raft contributed a certain percentage in carrying the applied loads in the piled raft foundation for all cases.
1.1 The ratio of the loading conducted via slab footing to the accumulative subjected loading of the piled raft foundation with $L=40$ cm and piles number $(2 \times 1, 2 \times 2$ and $3 \times 2)$ is $28.5, 18$ and 12.5%, respectively.
1.2 The ratio of this load taken by raft footing to the overall loading of the piled with slab footing with $L=50$ cm and piles number $(2 \times 1, 2 \times 2$ and $3 \times 2)$ is $35.4, 20$ and 15.4%, respectively.
1.3 The ratio of the loading on slab footing to the accumulative implemented by load of the piled with slab footing with $L=60$ cm and piles number $(2 \times 1, 2 \times 2$ and $3 \times 2)$ is $40, 24.7$ and 18.2%, respectively.
2. There is also an increase in loading taken by piles to the accumulative loading compulsory on piled with salb when the no. of piles in the group increases. In contrast, the group of $(3 \times 2)$ recorded the maximum piles capacity with more than 80% of the overall applied load and the share of the soil underneath the raft for the applied loads decreases with increasing the number of piles because of the stiffness of the material of the piles is higher than the stiffness of the soil, so a small portion of the loads is redeployed to the soil.
3. The increasing in the pile length causes a considerable decreasing in total settlement of the piled slab footing system. The increasing in the piles' lengths caus an increasing in the soil's share below the raft due to densification because of turns the soil from loose to medium.
4. The $(Lr/Br)$ ratio has a significant influence upon the piled with raft group, and the maximum settlement of the piled with slab footing group does not exceed 5% of the raft width in all cases.

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