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Experimental Study of a Square Foundation with Connected and Non-Connected Piled Raft Foundation Under Eccentrically Loaded

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ABSTRACT: In the recent years, non-connected piled raft foundation has been considered as an economical and practical deep foundation in the situation that high shear and concentrated loads may occur at the connection of the raft and pile head. This paper was presented an experimental study of a square foundation on the effects of parameters such as S/D, L/D and etc. in two cases of connected or non-connected piled raft system under the eccentrically loaded raft. The results was showed that square raft in the case of S/D = 3 and L/D = 8, the bearing capacity of the non-connected piles is more than that of the connected piles. The results of the experiments was showed pile length is more effective than the pile spacing in connected pile raft system. However by decreasing pile spacing, bearing capacity is increased in non-connected pile raft and pile spacing is more effective than the pile spacing in non-connected pile raft system. Comparison of bearing capacity and settlement indicated in the non-connected piled raft system, the longer piles not only has not much effect in increasing bearing capacity significantly, but also has lower effect on the reduction of the settlement. Also in non-connected piled raft system by increasing the pile spacing reduced BPI (bearing pile index) wile in connected piled raft system increased.

Keywords: Bearing Capacity, Connected Piled Raft, Eccentrically Loaded, Non-Connected Piled Raft, Settlement.

INTRODUCTION

Piles are usually used in foundations for two major reasons: supplying the required bearing capacity and reducing settlement to an acceptable level. In some cases, the shallow layers of the soil have sufficient bearing capacity, but the foundation can experience very large settlements. In these cases, piles are used with foundations. Using piles for the reduction of the foundation settlements as well as increasing the bearing capacity was proposed by Burland et al. (1977) at first. Prakoso and Kulhawy (2001) reported on the effect of foundation geometry and pile group on the average of various settlements and bending moments. Reul and Randolph (2004) presented a parametric study on the

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effect of the position, number and the length of piles as well as the stiffness of the underlying soil on the behavior of a piled raft. Rabiebi (2009) conducted studies on a piled raft system on the clay soil. Nakanishi and Takewaki. (2013) investigated the optimal arrangement of piles to reduce the different settlements of piled raft foundation systems.

According to these studies, the increasing of the thickness of the foundation besides reducing the number and length of the piles will lead to the increase of the maximum bending moments in the foundation. When the piles are employed for the reduction of the settlement, all of the geotechnical bearing capacity of the piles could be used. This condition would cause very large axial stresses in the pile, therefore, to increase the bearing capacity of the pile and to prevent structural damage, the dimensions of the pile need to be extended. This will lead to the uneconomical design of the foundation system. Therefore, to avoid large stresses between the foundation and the pile, several researchers suggested that the pile should be separated from the foundation so that, instead of a structural element, it functions as a reinforcement element in the soil. In seismic zones, if piles are attached to the rafts, due to the cyclic or dynamic lateral forces, large shear forces as well as overturning moments are created at the connection of the piles to the raft.

To develop an analytical and seismic optimum design method, Nemoto et al. (2006) and Rajib et al. (2015) conducted a series of analytical and laboratory studies on the model behavior of pile groups in the dry sand under both static and cyclic lateral loads. Mahmood et al. (2018) presented the three-dimensional analysis for the dynamic response of a piled raft foundation subjected to vertical vibration. They showed that increasing the distance between the foundation and the boundaries and increasing the relative density of the sand can significantly minimize the dynamic response of the foundation.

Although foundations with non-connected piles function appropriately in dynamic conditions, they should also respond properly in static conditions, as well. Cao et al. (2004) analyzed the behavior of foundations with non-connected piles on sandy soils and observed the foundation response to the change of some parameters such as stiffness, length, arrangement, and the number of piles. The results of the study displayed the important characteristic of the non-connected piles in reducing the settlement and bending moment.

Fioravante and Giretti (2010), using centrifugal modeling, studied the load transfer mechanism in the piled raft system. They also examined the effect of gravel layer on the stiffness of the underlying system in dense, dry sand. They controlled the relative settlement mechanism between the pile and the soil by changing the thickness and stiffness of both middle and bottom layers of the soil.

Saeedi Azizkandi and Fakher (2014) wrote a computer program based on the Finite Element Method (FEM) for analyzing piled raft foundation and comparison of different concepts of pile group design. In this program, a foundation is modeled as a flexible plate, soil and pile are modeled by Winkler springs. Taghavi Ghalesari and Janalizadeh Choobbasti (2016) showed that the bearing capacity of piled raft obviously increased with increasing pile length, pile spacing, and raft thickness, especially in stiff clay by numerical analyses.

Sinha et al. (2016) investigated a numerical study on piled raft system to examine the role of the foundation geometry, including pile spacing in the group, pile length, pile shape, pile diameter, and raft thickness by the software of ABAQUS. They studied the influence of the mechanical properties of the surrounding soils on the load-sharing mechanism.

Jamshidi Chenari et al. (2018) studied the effect of spatial variability of soil parameters on the bearing capacity of piled raft foundation based on the random field theory using the Finite Difference software of FLAC^{3D}. Ruping Luo et al. (2018) performed to investigate the variation of the normalized settlement of the piled raft, including the effects of soil condition, pile dimensions, and soil-pile adhesion. They presented a practical analytical method for a piled raft in clay, Based on the three-dimensional boundary element method. Vikas Kumar and Arvid Kumar (2018) concluded that as the number of settlement-reducing piles increased, the load improvement ratio increased and the differential settlement ratio decreased.

One of the problems that may arise during employing non-connected piled raft foundations is applying eccentric loads to the foundations. In severe wind and seismic prone areas, due to the lateral loads, the foundation is exposed to eccentric loads that may lead to rotating of the foundation, especially in tall buildings. The application of a pile-foundation system in such cases increases the sustainability of the building and reduces the rotation of the foundation.

In order to investigate the performance of the non-connected piled foundation system under eccentrically loaded, El-Sawwaf (2010) conducted a laboratory study on a strip foundation with both connected and non-connected piles on the sand and investigated the effect of the length, number and arrangement of piles. Patil et al. (2016) also studied the bearing capacity as well as the settlement rate for a strip foundation with non-connected piles located on the sandy soil under eccentrically loaded.

Rasouli et al. (2015), using the centrifugal modeling, compared the behaviors of both connected and non-connected foundations for two modes of increasing the bearing capacity and the reduction of settlement. This study aims to examine the response of both connected and non-connected piled foundation systems to the variation of some parameter such as the number of piles, the distance between the piles and the thickness of the gravel layer.

Although most foundations are exposed to lateral and eccentric loads during their lifespan, little studies have compared the behavior of both connected piled raft foundations and non-connected piled raft foundations under eccentric loading. The study carried out by El-Sawwaf (2010) and Patil et al. (2016) on foundations with non-connected piles only covered strip foundations, while other types of foundations were not included. Also, many researchers investigated about non-connected piled raft under dynamic loads (Saeedi azizkandi et al., 2017; Cao et al., 2004).

The main objective of this study was to consider the load-settlement diagrams of a square foundation with both connected and non-connected piles located on the sandy soil under eccentric loading. This was performed through conducting 14 experiments and changing some parameters such as the degree of eccentricity from the axis (e), the length of the pile (L) and the distance between piles (S). The foundation behavior is then evaluated for each case through comparison of the load-settlement curves.

MODELING BOX AND FOUNDATION

In order to model the laboratory conditions, a metal box with dimensions of 0.8 m, 1.2 m and a height of 1 m was used. This box was made of three steel walls with a thickness of 10 mm and a glass wall with a thickness of 20 mm. The walls of the box were supported by 4 columns (IPE14) and 4 beams (IPE12). The loading system was installed horizontally and included an IPE10 beam that was connected to the horizontal beams and supported the beam (Figure 1). In order to apply forces, a hydraulic jack was used. The maximum power of the jack piston was 15 tons (Figure 2).

The load is applied onto a platform by a piston. The platform lets eccentric loading insert onto a base and then onto the foundation. The platform was constructed in a way that lets the eccentric loading be applied in two distances (10 and 20 mm) away from the center of the foundation and also in different directions (Figure 3).

The square foundation model was made of steel. The model dimension was 200 mm and the thickness was 10 mm. The foundation dimensions were also considered 200 × 200 mm to avoid wall effect interference of the box. Two sides of the foundation were slowly smoothed and polished to minimize the effect of friction. The piles used in this study were hollow steel pipes with the external diameter of 25 mm and the internal diameter of 19 mm ($E = 0.2 \times 10^6$ MPa). These piles have a length of 200 and 400 mm, and the ratio of the length to the diameter of the pile is 8 and 16.

The load provided by the hydraulic jack piston is applied onto a platform through a rectangular plate attached to the piston. The load is then delivered through the platform to the base of the foundation through two holes provided on the foundation. The whole configuration permits the point load to be exerted in different directions and at two eccentricities (10 and 20 mm) (Figure 4).

In order to measure the settlement of the model, a linear variable displacement transducer (LVDT) with a length of 10 cm and a precision of 0.1 cm was used. The transducer was installed on the rectangular plate (rectangular plate attached to the piston) and recorded the foundation settlement under eccentric loading (Figure 2).

MATERIAL

The sand used in the model is Firoozkooh standard sand No. 161. The sand was dry and consisted of uniformly distributed granular and broken particles. The soil mechanic tests were carried out to identify the required characteristics of the sand such as grading, minimum and maximum unit weight and specific gravity of soil solids. The sand relative density was considered as 55% for the tests. Table 1 shows the sand characteristics obtained from the tests. According to the grading test results, the sand is classified as SP (Figure 5). To analyze the gravel grain size, ASTM D422-63 standard test was employed. A large-scale direct shear test was also used to determine the adhesion and internal friction angle. Figure 5 and Table 1 show the results of grain size test as well as the large-scale direct shear test, respectively.

TEST PLAN AND LABORATORY INSTALLATION

14 tests were designed to study the load capacity, the settlement and the rotation of the raft under eccentrically loads. In the first, six tests that aimed to measure the load-settlement curves of the connected piled raft foundation, the box was filled up to 90 cm with sand, and the rest of box (10 cm) was empty due to the platform placement and loading system limitations. In the 6 other tests that performed to measure the load-settlement curves of the non-connected piled raft system, the box was filled up to 80 cm with sand, and the next 10 cm was filled with gravel. Two tests were also carried out for foundations without piles (Table 2).

To determine the positions of the piles more precisely, both in connected and non-connected cases, a template polyethylene frame (30 × 80 cm) was used and all of the pile in connected and non-connected piled raft were driven in the soil (Figure 6).

The parameters that were studied included: the length of the pile (L), the eccentricity (e) and the distance between the piles (S) in both connected and non-connected pile systems.

1. Loading beam
2. Glass wall
3. Supported beam for cylinder
4. Supported beam
5. Cylinder
6. Bearing plate

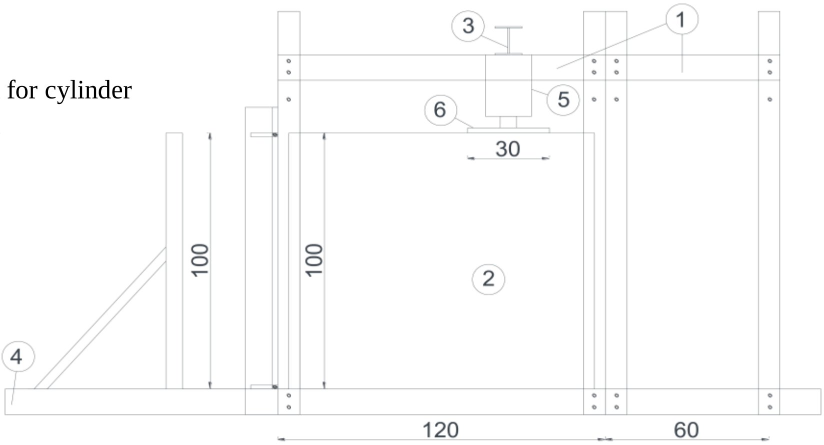


Fig. 1. Schematic view of the experimental apparatus

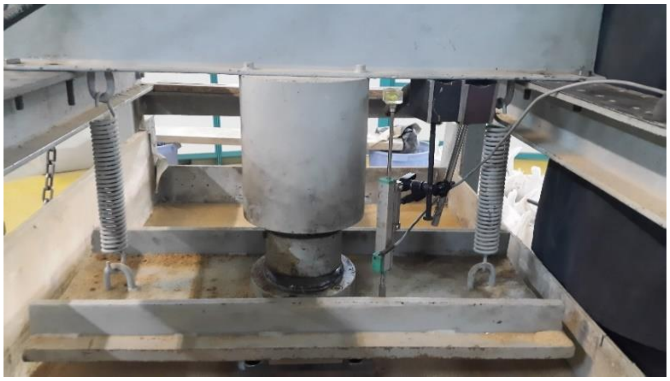


Fig. 2. Loading system (hydraulic jack with bearing plate)

Fig. 3. Pile raft foundation (raft and pile with platform)

Table 1. Physical properties of Iran's Firouzkouh sand No. 161 and gravel

Sand type	C_c	C_u	**F.C (%)**	$C\ (KN/m^2)$	$\varphi°$	$D_{50}\ (mm)$	e_{min}	e_{max}	G_S	**Relative density (%)**
Sand-161	0.97	2.58	0.2	5	32	0.3	0.55	0.97	2.66	55
Gravel	1.07	1.67	0	4.2	40	10	0.3	0.6	2.6	5

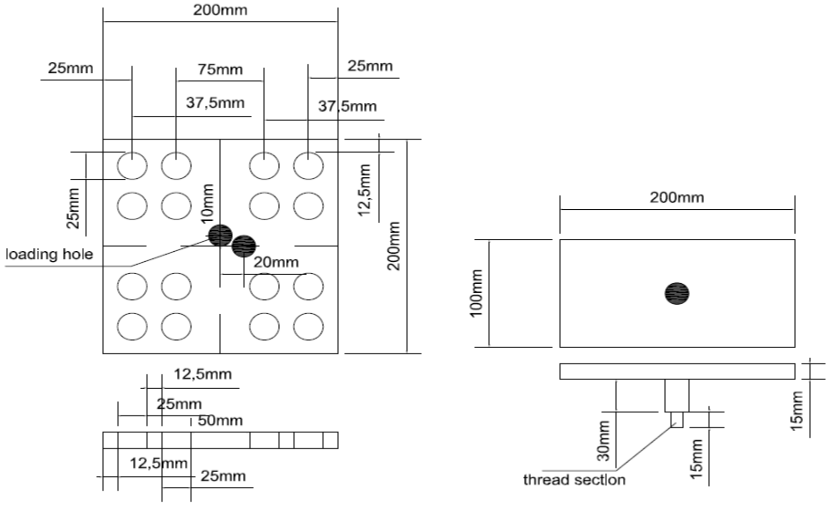


Fig. 4. Platform and raft foundation system

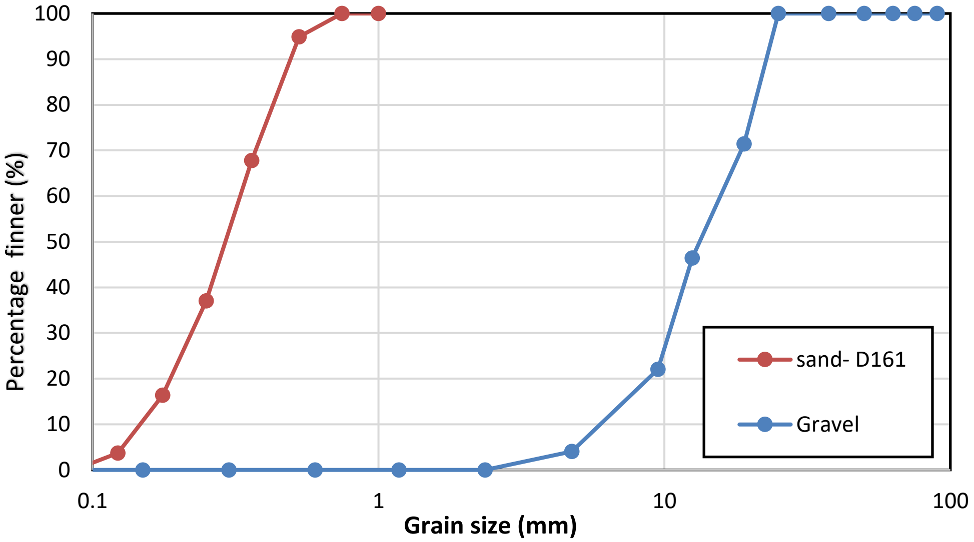
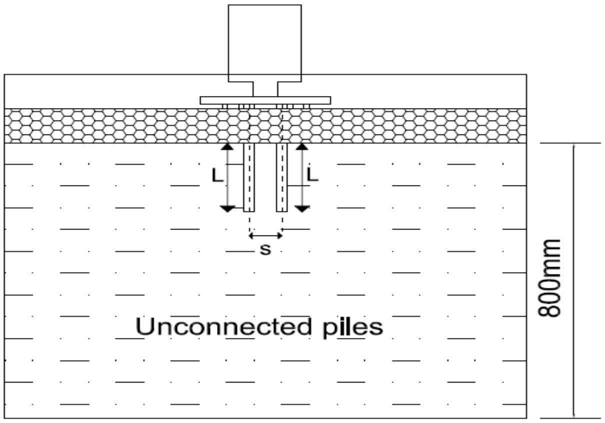


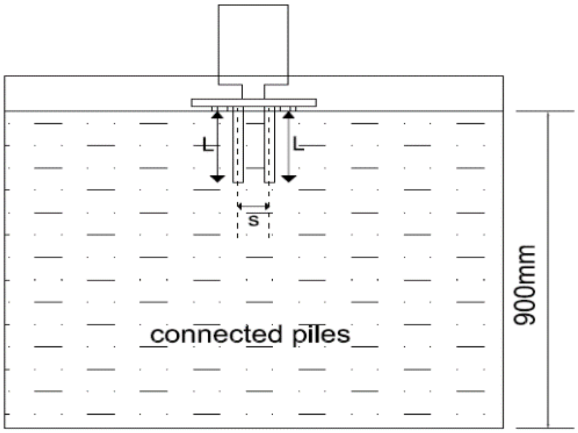
Fig. 5. Gradation curve for sand 161 Firouzkouh and gravel

Table 2. Model tests program

No.	Connection type	Pile length (cm)	Pile distance (cm)	Eccentricities (mm)
1	Connected	20	7.5	10
2	Non-connected	20	7.5	10
3	Connected	20	15	10
4	Non-connected	20	15	10
5	Connected	20	15	20
6	Connected	20	7.5	20
7	Connected	40	15	20
8	connected	40	7.5	20
9	Non-connected	20	7.5	20
10	Non-connected	20	15	20
11	Non-connected	40	7.5	20
12	Non-connected	40	15	20
13	Unpiled raft (without gravel)	-	-	10
14	Unpiled raft (with gravel)	-	-	10



The laboratory model tests for non-connected pile



The laboratory model tests for connected pile

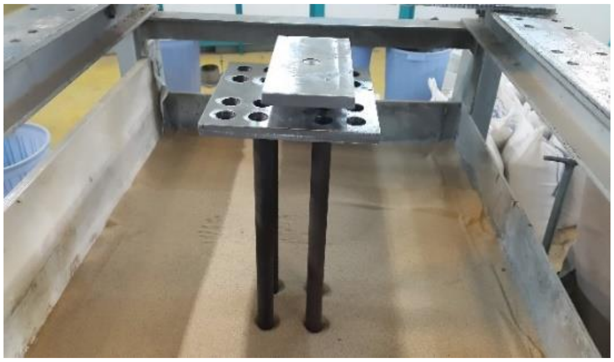
a) Step 1. Filing the box with sand (80 cm)

b) Step 1. Filing the box with sand (90 cm)

c) Step 2. Driving the piles in sandy layer

d) Step 2. Piled raft assembling

e) Step 3. Filling the gravel (10 cm)



f) Step 3. Driving the piles in sandy layer

g) Step 4. Placing the raft on the gravel

h) Step 4. Placing the raft on the sand

Fig. 6. The laboratory model tests for connected and non-connected pile

RESULTS AND DISCUSSION

Based on the modeling conditions, the behavior of the foundation was investigated in both connected and non-connected piles under eccentric loading. In order to evaluate the bearing capacity and settlement, the parameters of soil improvement, the length, and distance of piles, eccentricity and bearing pressure improvement (BPI) were used. The relative improvement of the raft performance is represented using a non-dimensional factor, called the Bearing Pressure Improvement (BPI). This factor is defined as the ratio of the bearing pressure of a piled raft (q_{piled}), to the bearing pressure of an un-piled raft ($q_{un\text{-}piled}$) at the same settlement level. The raft settlement (S) was also analyzed in a non-dimensional form in terms of the raft width (B) as the ratio (S/B, %). In this paper, all percentages of the increase in the bearing capacity of tests are compared to un-piled.

Bearing Capacity and Soil Improvement

Soil Improvement Using Piles

Figure 7 shows the variations of the foundation bearing capacity in both cases of connected and non-connected piles for S/D = 3, L/D = 8, e/B = 0.1, in the state of the piled and un-piled. All tests were performed in both modes of with and without a 10 cm gravel layer. Figure 7 clearly shows that the bearing capacity of both connected and non-connected piles is higher than that of the un-piled foundation. As shown in Figure 7, the bearing capacity of foundation with S/D = 3 and non-connected piles (19.5 kg/cm^2) is higher than that of the connected piles (17.5 kg/cm^2). Therefore, foundations with non-connected piles have greater bearing capacities than the connected piles. This means about 85% increase in bearing capacity for non-connected mode (S/D = 3), and 67% increase for connected mode.

Figure 7 also shows that the bearing capacity is greater when the gravel cushion is used (13.5 kg/cm^2), comparing to the tests in which the cushion layer is not used (10.5 kg/cm^2). This means a 28% improvement in the bearing capacity. Figure 7 generally shows that the use of foundations with non-connected piles improves the bearing capacity of the foundation and in some cases where the pile spacing is 7.5 cm, it can even enhance the bearing capacity, comparing to the connected pile's mode.

The Effect of Pile Length

Figure 8 shows the variations of the bearing capacity for both connected and non-connected piles cases where L/D = 8 and e/B = 0.1. As shown in Figure 8, in the case of the length of pile is 7.5 cm (S/D = 3), the bearing capacity of the foundation with non-connected piles is greater than that of the foundation with connected piles, however, when the length of pile exceeds 15 cm, the bearing capacity of the connected pile foundation is greater than non-connected ones.

This indicates that in the non-connected mode, as the pile span increases, the bearing capacity reduces. This can be explained by the fact that when the pile span decreases in the non-connected piled raft, the improvement zone formed under the raft is more confined and rigid. The rigid elements of the pile along the cushion layer increase the bearing capacity and prevent the formation of a failure ridge. In the non-connected mode, when the pile spacing increases, the rigidity of the improved area under the raft reduces.

Unlike the non-connected mode, in connected mode, the bearing capacity increases when the pile spacing increases. In this mode, by the increase of the pile spacing, the interaction between piles decreases, leading to an increase in the pile group bearing capacity.

This paper suggests that the performance of the long-spanned connected pile foundation is better than the non-connected piles under the eccentric loading, whereas, in non-connected piles, the performance of short-spanned piles is superior.

The results obtained are also consistent with previous researches. Cao et al. (2004) studied a typical loading condition consisting of a uniformly distributed load in the central core area and two symmetrical line loads and reported that concentrating the piles within the central area of the plate reduced the settlement at the center, but marginally increased the settlement at the edge. They also found that for different pile arrangements, the bearing capacity is in reverse relationship with the piles' distance from the center of the foundation. This is in line with the results of El-Sawwaf (2010), as well. The results of their experiments also showed that in a connected piled raft system, the bearing capacity of the pile under the eccentric loading changes inversely with piles' distance from the center. Likewise, Patille et al. (2016) showed that in the connected mode, when a pile is placed in the corners of a foundation, the bending capacity increases under the eccentric loading.

Figure 9 shows BPI variations versus L/D = 8 and L/D = 16. According to Figure 9, the maximum BPI value is equal to 2.18 which results from placing a 40 cm-long pile at a distance of 15 cm from the center. Figure 9 also indicates that BPI is higher for connected piles compared to non-connected piles. Therefore, in order to increase the load bearing capacity, the connected piles have a better performance than the non-connected piles. According to Figure 9, a connected foundation with piles spanned at 7.5 cm possesses the highest growth value for BPI.

The Effect of Pile Spacing

Figure 10 shows the variation of the bearing capacity versus the foundation settlement for the connected pile mode (e/B = 0.1). As one can see, the trends in the diagram show that the bearing capacity for a 40 cm pile length (24.5 kg/cm^2) spanned at the distance of 15 cm from the center of the foundation is more than that of a 20 cm pile (20.5 kg/cm^2) located at the same distance. This means a 20% increase in the bearing capacity. If both 40 cm and 20 cm long piles are spanned at 7.5 cm from the center of the foundation, they will improve the bearing capacity to 22.5 and 18 kg/cm^2, respectively, that means 25% improvement in the bearing capacity.

Figure 10 obviously shows that the effect of the pile length is far greater than the effect of the pile distance. This can be proved by the comparison of 40 cm long piles in S/D = 8 and S/D = 16 modes that have a greater bearing capacity than 20 cm long piles. One can conclude that in a connected piled raft system, to increase the bearing capacity of the foundation, extending the length of the piles is a more effective solution for soil improvement rather than increasing the pile spans.

Another important point is that 20 cm long piles can increase the bearing capacity of the foundation up to 114 percent, compared to the un-piled foundations. However, when the length of the piles is extended to 40 cm, the improvement of the load capacity is only limited to 25%, suggesting that the use of shorter piles is more economical and effective in improving the soil, and can cause fewer tensions to the structure linked to the foundation, leading to an economic design.

Figure 11 shows the variation of the bearing capacity versus the foundation settlements for the non-connected mode. The trends show that in the non-connected pile raft system, the 40 cm long pile with S/D = 3 has the highest bearing capacity (21.5 kg/cm^2), while the 20 cm long piles have 19.5 kg/cm^2. This shows a 10 percent improvement in the bearing capacity. Similarly, the 40 and 20 cm long piles show 17.5 and 16 kg/cm^2 bearing capacity for S/D = 6, which means a 9% improvement. Figure 11 clearly shows that for the same distance, as the length of the pile increases the bearing capacity increases, as well.

Figure 11 shows that in non-connected pile raft system, the effect of the pile spacing is greater than the length of the pile. Also as one can see in Figure 11, when the piles are spanned at a distance of 7.5 cm, both in L/D = 8 and L/D = 16, they possess a higher bearing capacity compared to the time when they are at a distance of 15 cm. This again shows that in a non-connected pile raft system, by the increase of the rigidity of the soil located under the foundation and affected by loading, the bearing capacity approaches its maximum value.

The comparison of Figures 10 and 11 show that the bearing capacity of the connected pile raft system with 40 cm long piles in S/D = 6 is greater than the non-connected pile mode in S/D = 3. Taking into account the two factors of "length" and "distance from the foundation center", one can conclude that the bearing capacity for connected pile mode is better than the non-connected mode.

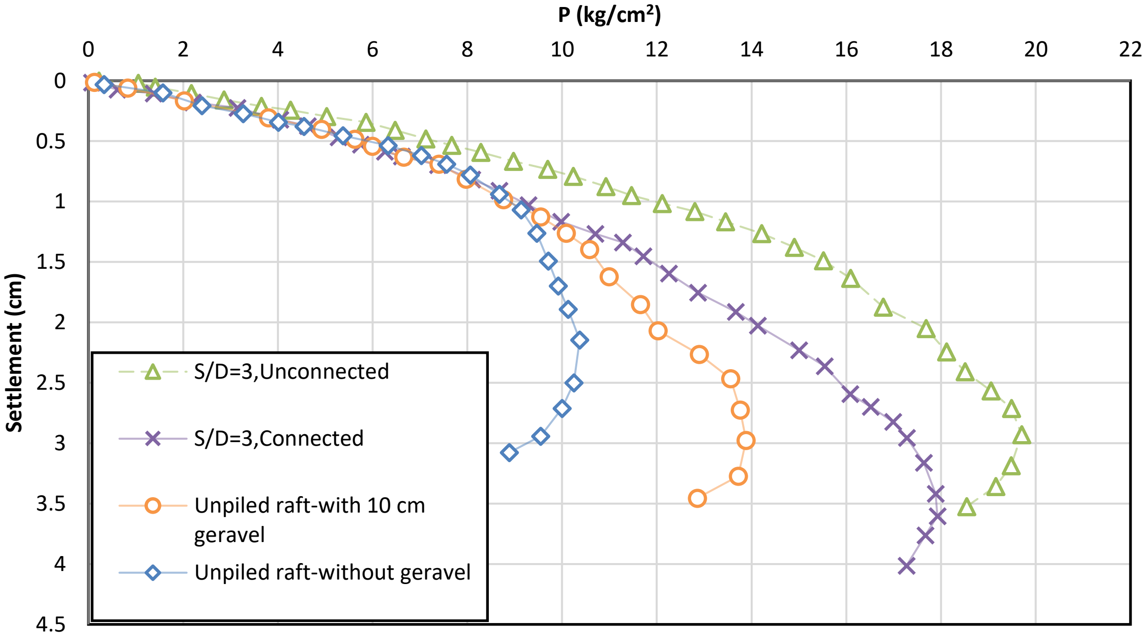


Fig. 7. The variation of the bearing capacity of the foundation with a connected and non-connected piles in S/D = 3, L/D = 8 and e/B = 0.05

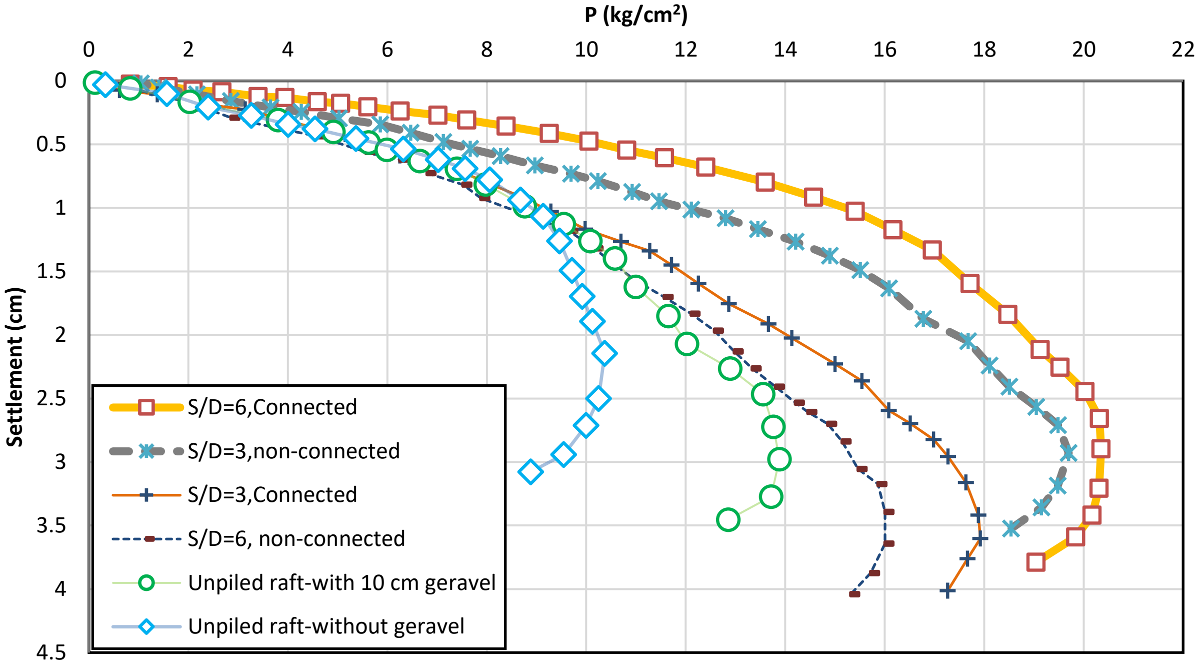


Fig. 8. The variation of the bearing capacity of connected and non-connected piles in L/D = 8 and e/B = 0.05

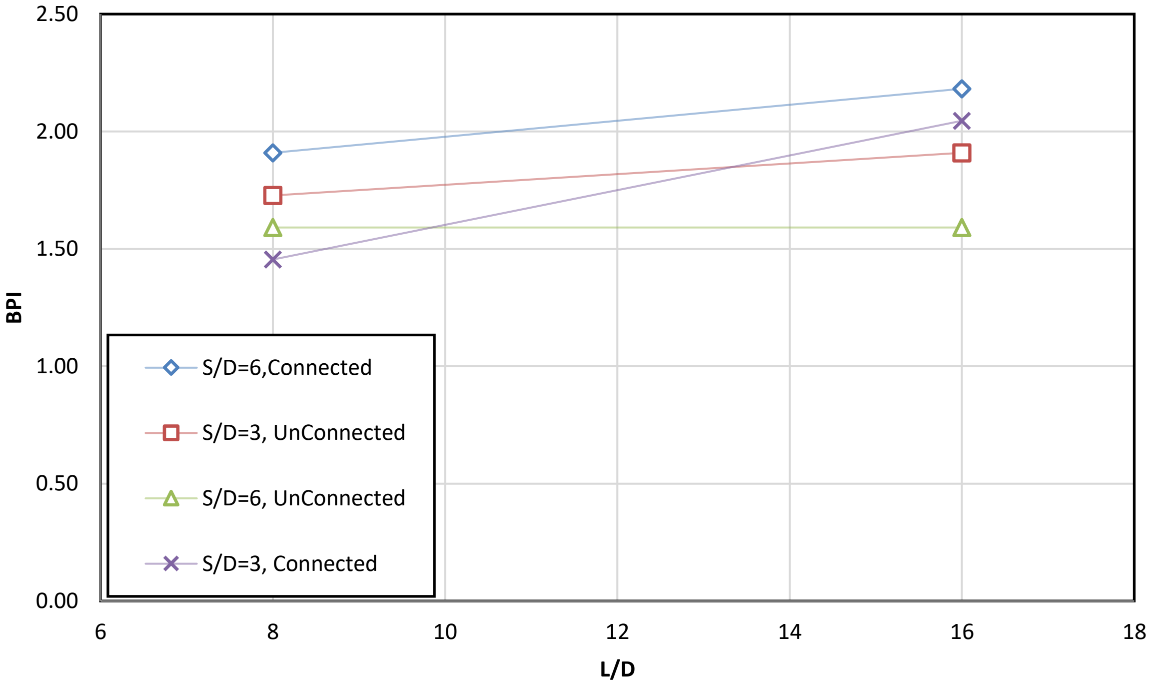


Fig. 9. The BPI variations versus L/D = 8 and L/D = 16

Figure 12 shows BPI variation for both connected and non-connected pile raft system in S/D = 3 and S/D = 6. As the results show, the highest values (2.33 kg/cm^2) occur for connected 40 cm long pile in S/D = 3 and S/D = 6. Figure 12 also shows that the 40 cm long piles have a greater BPI than 20 cm long piles when placed at a distance of 7.5 cm from the foundation center. However, when the distance exceeds 15 cm, the BPI value of the connected piles is greater than that of the non-connected, indicating that when the distance exceeds 15 cm, the connectivity or non-connectivity parameter is more effective than the pile span. Figure 12 also shows that in non-connected mode, as the pile span increases, the BPI value decreases, unlike the connected mode in which the BPI increases with the increase of pile span.

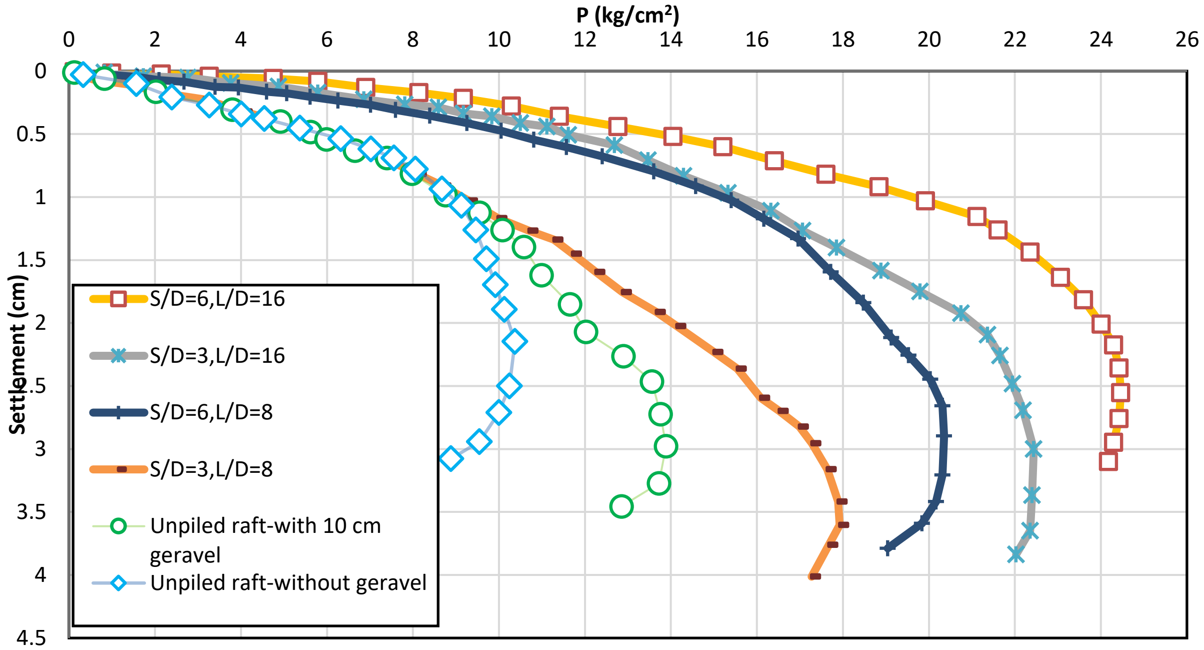


Fig. 10. The variation in bearing capacity versus settlement for foundations with connected piles (e/B = 0.1)

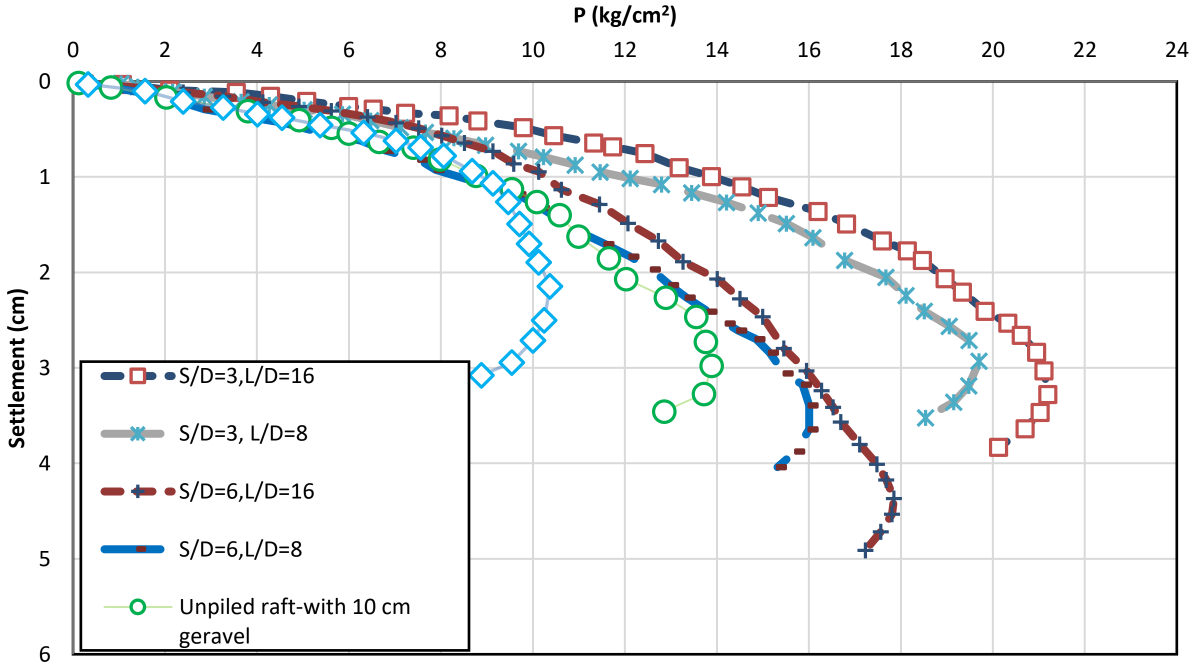


Fig. 11. The variation in bearing capacity versus settlement for foundations with non-connected pile (e/B = 0.1)

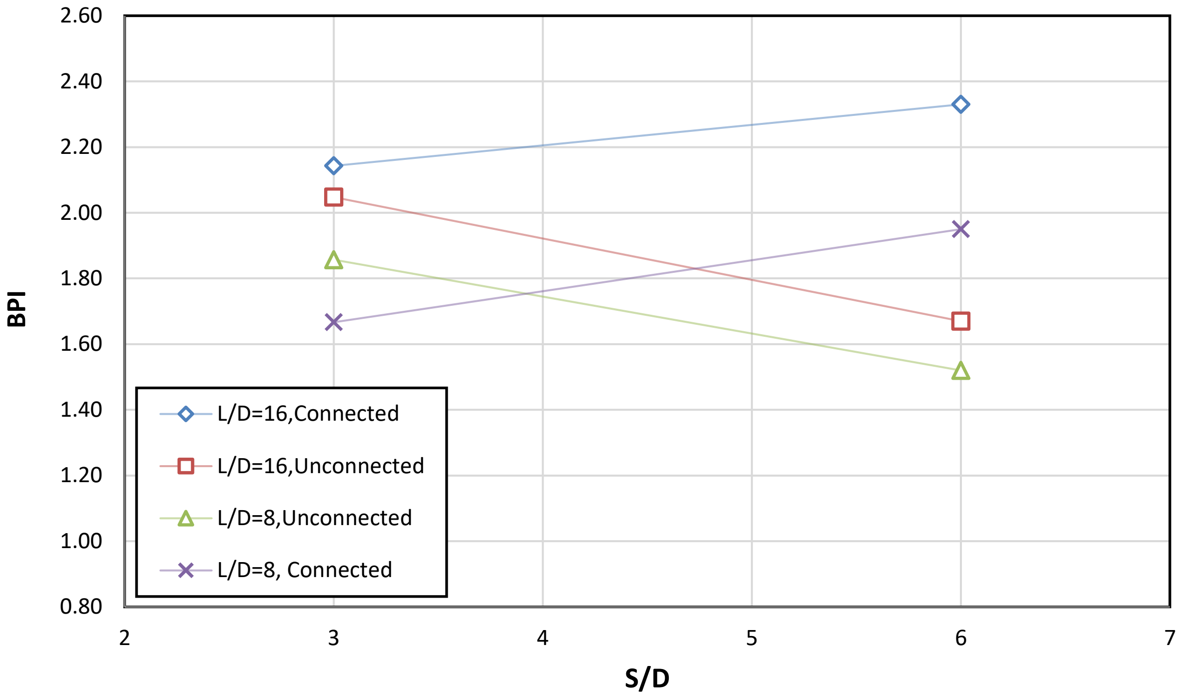


Fig. 12. The BPI variations for S/D = 3 and S/D = 6 for connected and non-connected piles (e/B = 0.1)

The Effect of Eccentricity

In order to compare the effect of the eccentricity on the load-settlement curve, two eccentric loads were imposed at 10 mm (e/B = 0.05) and 20 mm (e/B = 0.1) from the foundation center connected to 20 cm long piles. Figure 13 shows the variation of the bearing capacity-settlement for e/B = 0.05 and e/B = 0.1 for connected pile mode. As one can see, among the different pile arrangements, the foundations with connected piles in S/D = 6 and e/B = 0.05, possess the highest bearing capacity. Likewise, the bearing capacity of the connected piled raft with the eccentricity of e/B = 0.05 (22.5 kg/cm^2) is greater than e/B = 0.1 (17.5 kg/cm^2) in S/D = 6. This means 29% improvement in the bearing capacity. These values are 21.5 and 17.5 kg/cm^2 in S/D = 3, respectively, causing 23% improvement in the bearing capacity.

Based on the results, both in S/D = 3 and S/D = 6, as the eccentricity decreases, the load-bearing capacity increases. The increase of eccentricity from the center of the foundation will have an adverse effect on the performance of the foundation-pile system. As Figure 13 represents, in both e/B = 0.05 and e/B = 0.1, the bearing capacity increases when the piles are located at far corners from the center of the applied load. This also shows that when the eccentricity increases, the performance of the corner piles located far from the applied load center reduces. This is due to the fact that the eccentric load from the center of the foundation causes an uplift on the one side of the foundation, which also leads to the creation of tensile force in the piles on the same side of the foundation (the one far from the loading center) that finally reduces the bearing capacity and all the load-bearing capacity of the pile-raft system is not employed.

Figure 14 shows the variation of the bearing capacity versus the foundation settlement for the non-connected mode in e/B = 0.05 and e/B = 0.1. As shown in Figure 14, among the different arrangements for the foundation with non-connected piles, the highest bearing capacity is for S/D = 3 and e/B

= 0.1 case. The trend of changes shown in Figure 14 also confirms that the bearing capacity of the foundation for piles spanned at 7.5 cm is greater than that of the piles spanned at 15 cm. For example in S/D = 3, for e/B = 0.1 and e/B = 0.05, the bearing capacity is 22.5 and 21 kg/cm^2, respectively. This shows a 5% increase in the bearing capacity. Similarly, in S/D = 6, these values are 17 and 15.2 kg/cm^2 which represents a 12% improvement in the bearing capacity.

The results obtained show that, in the non-connected pile raft system, when the eccentricity increases, the bearing capacity increases. This is due to the presence of a gravel sub-layer which distributes the load across the foundation surface and transfers it to the piles. This reduces the lifting amount of the far side of the foundation (the one far from the loading center) and, provided that the piles be close enough to the loading center, allows the use of bearing capacity of the piles.

Comparison of Figures 13 and 14 shows that in general, when the eccentricity increases, the behavior of the non-connected pile raft system is better than connected one. The results also show that in the non-connected pile raft system, the performance of shorter spanned piles is more effective than longer ones.

Settlement Assessment

Soil Improvement Using Piles

As shown in Figure 7, the settlement of the un-piled foundations for two cases of "with" and "without" the gravel cushion is 3 and 2.5 cm, respectively. As shown in Figure 7, the settlement in the non-connected pile raft system (3 cm) is less than that of connected one (3.5 cm). The results also suggest that not only the bearing capacity increases in the non-connected pile raft foundations but also the settlement is less, compare to connected ones. Referring to the optimal values obtained during the assessment of the bearing capacity for non-connected mode, one can find that likewise, the optimal settlement performance is in S/D = 3 and L/D = 8. This is due to the presence of a gravel cushion which creates a hard substrate under the foundation, resulting in the settlement reduction.

The Effect of Pile Spacing

As shown in Figure 8, the settlement for 7.5 and 15 cm pile spacing is 3.5 and 3 cm, respectively in the connected piled raft foundation. As one can see, in the connected mode, the settlement decrease with the increase of the pile spacing for greater bearing capacities. This is vice versa in the non-connected mode. The settlements for 7.5 and 15 cm pile spacing are 3 and 3.5 cm, respectively. This suggests that, in the non-connected piled raft system, with the decrease of the pile spacing, the settlement reduces, while the bearing capacity increases. Cao et al. (2004) showed that in a flexible foundation, the settlement increases when the pile spacing is short and they concentrate at the center of the foundation. Their results also confirmed that the settlement reduces in the connected pile raft system when the piles are at a farther distance from the foundation.

The Effect of Pile Length

As Figure 10 shows, in connected pile mode, in S/D = 6, the settlements are 3 and 2.5 cm for L/D = 8 and L/D = 16, respectively. As the results show, for a closer spacing, the foundation with 20 cm long piles has a bigger settlement, compared to a foundation with 40 cm long piles. This is because of the fact that when piles are close, the rigid elements transfer the load to the soil through a smaller surface. This causes high settlements compared to the state in which the load is distributed to the soil through a bigger surface.

Figure 11 shows that in the non-connected mode, in S/D = 3, for L/D = 16 and L/D = 8, the settlements are 3.5 and 3 cm, respectively. Unlike, in the non-connected mode, with the increase of the pile length, the settlement increases. Figure 10 also reveals the fact that "pile spacing" has a greater role in settlement reduction than the "pile length". The fact also applies to the bearing capacity. In the non-connected mode, the settlement is smaller, when the underlying surface of the foundation is more rigid at the imposed load area. The results are also consistent with the results obtained by El-Sawwaf (2010) and Patil et al. (2016).

The Effect of Eccentricity

Figure 13 shows that the amount of foundation settlement in the connected piled raft system increases with the increase of eccentricity from the loading center. Based on Figure 13, in S/D = 3, the amount of settlement of a connected piled raft with 20 cm pile length at the eccentricity of 10 and 20 mm are 28 and 55 mm, respectively. The settlement has been nearly doubled. The above example clearly shows the significance of "eccentricity" as an important factor influencing the foundation settlement. Figure 13 also shows that in S/D = 6, the total settlement at the eccentricities of 10 and 20 mm is smaller than that of S/D = 3. This indicates that the performance of the piles is better when the pile spacing is greater and also at different eccentricities.

As shown in Figure 14 in S/D = 3 and S/D = 6, for the non-connected piled raft system with 20 cm pile length, similarly to the connected piled raft, the settlement increases with the increase of the amount of eccentricity from the foundation center. As shown in Figure 14, in S/D = 3, the settlement of foundations for the eccentricity of 10 and 20 mm is equal to 22 and 28 mm, respectively. These values for the same eccentricities, in S/D = 6 is equal to 30 and 35 mm. Therefore, in foundations with non-connected piles, no matter how far the piles are placed from the foundation center, the settlement of foundation increases with the increase of eccentricity.

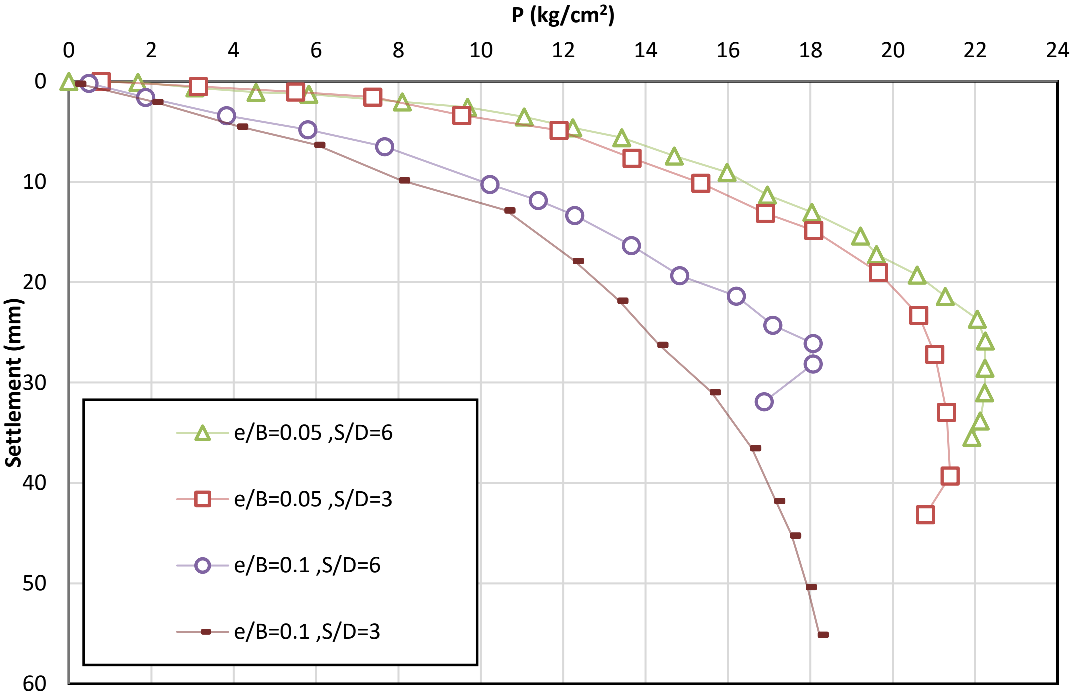


Fig. 13. The variations of bearing capacity-settlement for e/B = 0.05 and e/B = 0.1 foundations with the connected piles

Table 3. Tilt of model raft

No.	Connection type	Pile length (cm)	Pile distance (cm)	Eccentricities (mm)	Tilt of model raft
1	Connected	20	7.5	10	1.53
2	Non-connected	20	7.5	10	2.29
3	Connected	20	15	10	2.41
4	Non-connected	20	15	10	2.78
5	Connected	20	15	20	2.86
6	Connected	20	7.5	20	2.92
7	Connected	40	15	20	3.43
8	Connected	40	7.5	20	3.46
9	Non-connected	20	7.5	20	3.81
10	Non-connected	20	15	20	3.81
11	Non-connected	40	7.5	20	4.11
12	Non-connected	40	15	20	5.33
13	Unpiled raft (without gravel)	-	-	10	5.39
14	Unpiled raft (with gravel)	-	-	10	6.09

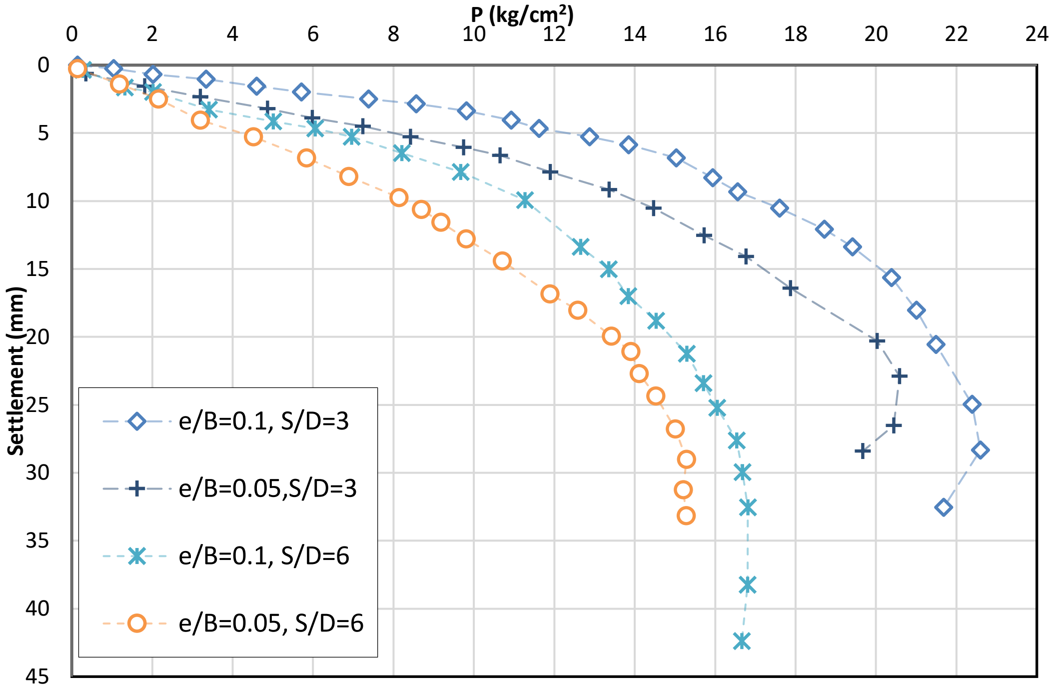


Fig. 14. The variations of bearing capacity-settlement for e/B = 0.05 and e/B = 0.1 foundations with the non-connected piles

The Assessment of Raft Rotation

Table 3 and Figure 15 show the amount of raft rotation in different test conditions. Figure 15 clearly shows that the rotation of foundation in e/B = 0.05 is less than e/B = 0.1. For example, the amount of rotation for the foundation with four 20 cm piles length at the distance of 7.5 cm with e/B = 0.05 in connected mode is equal to 1.53 degrees, while for the same model with e/B = 0.1 it is 2.92 degrees.

One of the other general results obtained from Figure 15 is that the rotation for a foundation with connected piles is less than non-connected one. The results are shown in Table 3 obviously shows that the rotation of a foundation connected each time with various piles length and spanned at different distances is generally less than a foundation with non-connected piles in similar conditions.

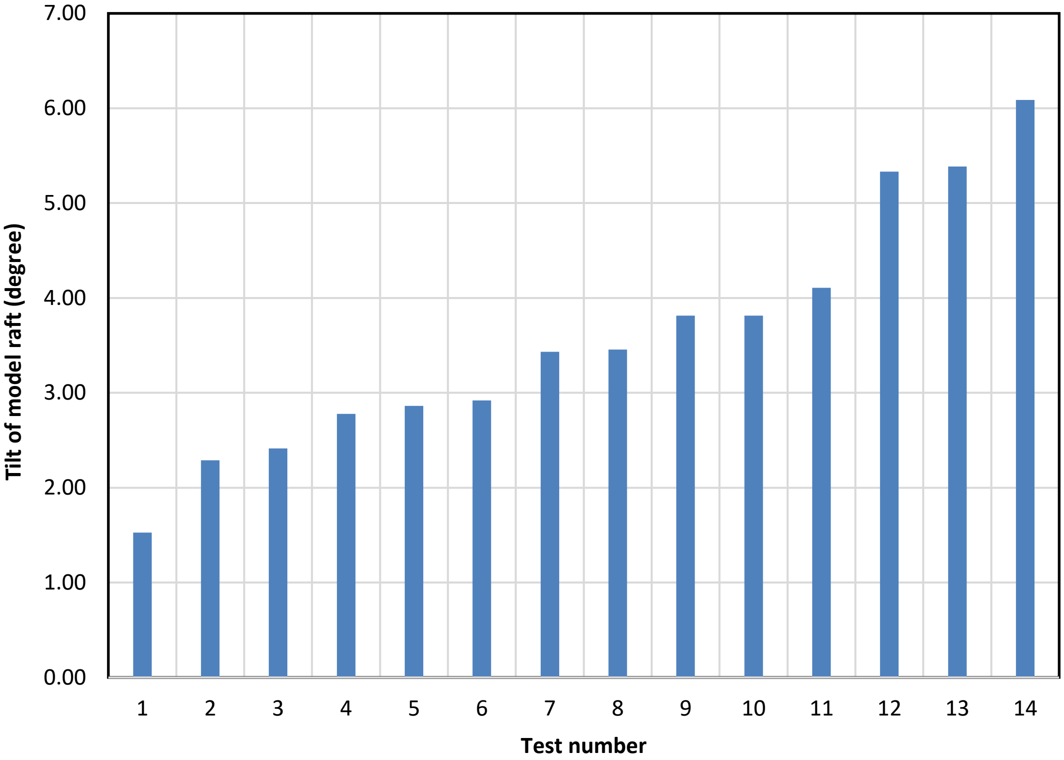


Fig. 15. The amount of the rotation of foundation with different modeling conditions

The results also show that when the eccentricity decreases, both in connected and non-connected modes, a foundation with close spanned piles have a smaller rotation than the one with far spanned piles. For example, in e/B = 0.05, the rotation of a foundation with four 20 cm long piles spanned at 7.5 cm in connected and non-connected modes are 1.53 and 2.29 degrees, respectively. In the similar conditions, when the pile span is 15 cm, the rotation is equal to 2.41 and 2.78 degrees.

CONCLUSIONS

The present study examined the effect of pile length, spacing and eccentricity on the load-settlement curves of square foundations in both connected and non-connected pile modes. According to the results, the bearing capacity of a piled foundation for a definite settlement is more than that of an un-piled one.

Although it is obvious that using longer piles causes more rigidity in the foundation of a piled raft system, using shorter piles is more effective in improving the settlement of the foundations exposed to eccentric loads. This can lead to the development of an economic design and facing fewer problems during using piled foundations. The findings also show that the increase of the pile length has a greater effect in the connected mode, while in the non-connected mode, the pile spacing has a greater effect. This can also help in designing more economic piled raft foundations as well as reducing of the stresses between foundation and piles. In this study, bearing capacity and settlement for non-connected piled raft system under the eccentrically loaded was obtained. Hence, the results will be different for the same system under the lateral load according to references. Based on the experiments conducted, the main results are as follows:

- The performance of foundations with connected piles spaced at far distances is better than non-connected piles under eccentric loading as El-Sawwaf (2010) and Patille et al. (2016) were said in their research on a strip foundation. While in foundations with non-connected piles, the performance of the foundation is better when the piles are close, compared to connected mode.
- Among the different parameters investigated, increasing the "pile length" is more effective in increasing the bearing capacity of the connected piled raft. In the non-connected piled raft, the effect of “pile spacing” is greater than the pile length. The amount of BPI in the connected mode increases when the pile length or spacing increases. In the non-connected mode, it is vice versa, meaning that the amount of BPI decreases in similar conditions.
- The performance of foundations with connected piles at different eccentricity enhances when the piles are far apart. In the non-connected mode, independently of pile spacing, the amount of settlement increases with the increase of eccentricity. Moreover, in both connected and non-connected pile modes, when the eccentricity is little, the plies with closer spacing rotate less than far spanned piles.

REFERENCES

Burland, J.B., Broms, B.B. and De Mello, V. F. (1977). “The behavior of foundations and structures”, *Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Vol. II, 495-546.

Cao, X.D., Wong, I.H. and Chang, M.F. (2004). “Behavior of model rafts resting on pile-reinforced sand”, *Journal of Geotechnical and Geoenvironmental Engineering*, 130(2), 129-138.

El-Sawwaf, M. (2010). “Experimental study of eccentrically loaded raft with connected and unconnected short piles”, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 136(10), 1394-1402.

Fioravante, V., Giretti, D., (2010). “Contact versus noncontact piled raft foundations", *Canadian Geotechnical Journal*, 47(11), 1271-1287.

Jamshidi Chenari, R., Ghorbani, A., Eslami, A. and Mirabbasi, F. (2018). "Behavior of piled raft foundation on heterogeneous clay deposits using random field theory", *Civil Engineering Infrastructures Journal*, 51(1), 35-54.

Kim, K.N., Lee, S.H., Kim, K.S., Chung, C.K., Kim, M.M. and Lee, H.S. (2001). “Optimal pile arrangement for minimizing differential settlements in piled raft foundations”, *Computers and Geotechnics*, 28, (4), 235-253.

Kumar, V. and Kumar, A. (2018). “An experimental study to analyse the behaviour of piled-raft foundation model under the application of vertical load”, *Innovative Infrastructure Solutions*, 3, 1-17.

Liang, F.Y., Chen, L.Z. and Shi, X.G. (2003). "Numerical analysis of composite piled raft with cushion subjected to vertical load", *Computers and Geotechnics*, 30, 443-453.

Luo, R., Yang, M. and Li, W. (2018). “Normalized settlement of piled raft in homogeneous clay”, *Computers and Geotechnics*, 103, 165-178.

Mahmood, M., Al-Wakel, S. and Abdulwahhab, I. (2018). “Three-dimensional analysis for piled raft machine foundation embedded in sand”, *In: MATEC Web of Conferences*, Vol. 162, pp. 01023, EDP Sciences.

Nakanishi, K. and Takewaki, I. (2013). "Optimum pile arrangement in piled raft foundation by using simplified settlement analysis and adaptive step-length algorithm", *Geomechanics and Engineering*, 5(6), 519.

Nemoto, H., Yaegashi, K., Takeuchi, Y., Nishimura, N., Matsmoto, T. and Kitiyodom, P. (2006). "Vertical load tests of model piled rafts with different pile head connection conditions", *Proceedings of the Sixth International Conference on Physical Modelling in Geotechnics*, Hong Kong, pp. 853-859.

Patil, S.A. Vasanwala and C.H. Solanki. (2016).”An experimental study of the eccentrically loaded piled raft”, *International Journal of Geotechnical Engineering*, 10(1), 40-45.

Prakoso, W.A. and Kulhawy, F.H. (2001). “Contribution to piled raft foundation design”, *Journal of Geotechnical and Geoenvironmental Engineering*, 127(1), 17-24.

Rabiebi, M. (2009). "Parametric study for piled raft foundations", *Electronic Journal of Geotechnical Engineering*, 14, 1-11.

Rajib, S., Dutta, S.C. and Haldar, S. (2015) "Effect of the raft and pile stiffness on seismic response of soil-piled raft- structure system", *Structural Engineering and Mechanics*, 55(1), 161-189.

Rasouli, H., Saeedi Azizkandi, A., Baziar, M., Modarresi, M. and Shahnazari, H. (2015). “Centrifuge modeling of non-connected piled raft system.” *International Journal of Civil Engineering*, 13 (2), 114-123.

Reul, O. and Randolph, M.F. (2004). “Design strategies for piled rafts subjected to non-uniform vertical loading”, *Journal of Geotechnical and Geoenvironmental Engineering*, 130(1), 1-13.

Saeedi Azizkandi, A., Baziar, M.H. and Fallah, A. (2017). “3D dynamic Finite Element analyses and 1 g shaking table tests on seismic performance of connected and no-connected piled raft foundations”, *KSCE Journal of Civil Engineering*, 22(5), 1750-1762.

Saeedi Azizkandi, A. and Fakher, A. (2014). "A simple algorithm for analyzing a piled raft by considering stress distribution", *Civil Engineering Infrastructures Journal*, 47(2), 215-227.

Sharma, V.J., Vasanvala, S.A. and Solanki, C.H. (2011). "Effect of cushion on composite piled-raft foundation", *Journal of Engineering Research and Studies*, 2(4), 132-135.

Sinha, A. and Hanna, A.M. (2016). “3D numerical model for piled raft foundation”, *International Journal of Geomechanics*, 17(2), 04016055.

Taghavi Ghalesari, A. and Janalizadeh Choobbasti, A. (2018). “Numerical analysis of settlement and bearing behaviour of piled raft in Babol clay”, *European Journal of Environmental and Civil Engineering*, 22(8), 978-1003.