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Centrifuge modeling of non-connected piled raft system

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Abstract

In present research, 17 centrifuge tests have been conducted to study the effect of various parameters such as the number of piles, the distance between piles, gradation and thickness of the granular layer on the load-settlement behavior of a pile raft system. The results showed the importance of granular layer to reduce the settlement of non-connected pile raft system when the roles of piles are to reduce the settlement. In other words when the piles have major contribution on the bearing capacity of pile raft system, presence of a granular layer may increase the settlement.

Keywords: *Piled raft foundation, Non-connected piled raft, Load-settlement behavior and settlement reduction.*

1. Introduction

The pile raft foundation systems have been previously designed assuming the structural loads to be completely carried by the piles even if the piles were added only to reduce settlements. In the recent decades, a new method called pile raft system or pile raft settlement reducer system has been introduced which the bearing capacity mechanism of its system is somehow between shallow and deep foundation systems.

The concept of a pile-raft system was first introduced by Davis and Poulos in 1972 [1]. The application of piles as only settlement reducers was first suggested by Burland et al. [2], Up to now, various studies have been reported on the application of settlement-reducer piles (Hansbo [3], Burland [2], Hirokoshi and Randolph [4], Viggiani [5], Poulos [6], Russo and Viggiani [7], Mandolini [8], Randolph et al. [9]). The basic concept of this approach is to consider the foundation as a number of piles responsible for reducing the settlement to an acceptable level. These piles also carry a portion of the structural loads transferred from the foundation raft to piles. In other words, some portion of the load is taken by the foundation and the rest is tolerated by the piles. When the piles are used as settlement reducer, their entire bearing capacity may be mobilized because, a very little settlement in soil is needed to mobilize the full bearing capacity of shaft pile.

Clency and Randolph [10] suggested that in order to effectively design the foundations with settlement reducer piles, the bearing capacity of piles should be considered equal to 80% of the service load. Generally the low number of piles in a pile raft system can cause very big bending moments as well as cracks and axial stress concentration at the tip of the piles. In the seismically active areas, in the piles sections connected to the raft, very big shear forces as well as failure moments can develop at their tip due to the lateral dynamic load.

Haghbin [11] examines the behavior of soil-reinforced piles and applied loads based on the analytical method and by using the numerical results of FLAC3D software for comparison with the analytical results. The analysis was based on a method called virtual retaining wall, with the following considerations: an imaginary retaining wall that passes the footing edge; the bearing capacity of footing on reinforced soil with piles, which was determined by applying equilibrium between active and passive forces on virtual wall; and a pile row that exists beneath the shallow foundation. To calculate the lateral pile resistance here, an analytical equation was then required. Results showed that the analytical method, while being close to other methods, was more conservative.

In these cases, the possibility of foundation structural failure is greater than the soil failure. Thus, in order to increase the bending moment of piles and prevent the structural damage, the dimensions of piles have to be increased. In most design codes (ASTM 1969, British Standard 1986, Singapore Code 2002) strong limitations have been imposed for the allowable stresses in the piles which may lead to uneconomical design of the foundation system. Therefore, Wang et al. [12] suggested that in order to overcome the large stresses between the foundation and

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piles, piles should be non-connected with the raft and can be considered as the structural reinforcing elements in the soil underneath.

They suggested that in such seismically active area, the pile raft foundation system should be constructed along with a mid-layer under the raft foundation. One example is the Rio–Antirrio bridge in Greece [13] which consists of vertical piles used to improve the soil shear strength and mitigate the danger of asymmetrical settlements as well as a granular layer in order to restrict the transition of shear forces and moments between the structure and foundation. Safeguard system of the Venice lagoon including pipe piles with 0.5m diameter and 19m length emplaced under a 1m coarse dense granular layer is another example. In both projects, the purpose of using piles was to decrease or to eliminate the asymmetrical settlements due to variability of soil characteristics as well as to decrease any defect due to complexities of off-shore construction.

Many researchers in recent years have reported the results of numerical modeling (Wong et al. [12], Liang et al. [14], Oh et al [15], Eslami et al. [16], Sharma et al. [17]), as well as physical modeling on the behavior of non-connected settlement reducer piles (Cao et al. [18], Mostafa El Sawwaf [19], Giretti [13]).

Liang et al. [14] presented a composite pile raft system with cushion. In this approach, short piles made of flexible material were used to increase the strength of the soil near the surface. Also, long piles made of rather rigid material were used to decrease the amount of foundation settlement. The role of mid layer (cushion) was to redistribute the forces to the piles and soil underneath raft.

Cao et al. [18] studied the performance of a foundation constructed on the non-connected piles. These piles were used as the soil reinforcing elements instead of as the structural elements. Varying the parameters such as stiffness of the foundation, length of piles, arrangement and number of piles, it was showed that non-connected piles were effective in the reducing settlement and bending moments at the piles head.

Mostafa El Sawwaf [19] studied the connected and non-connected system of pile raft in laboratory under 1g acceleration. He investigated the effect of the short piles, connected or non-connected, in the performance of foundation with asymmetrical loading. Varying the parameters such as the length and number of piles, eccentricity of load and relative density of sand as well as arrangement of piles, he showed that short piles have significant effect on improvement of the performance of pile raft system for eccentric loads. They also showed that the edges of the foundation were the best locations for installing the piles to overcome the eccentricity of loads. In short piles where the mid-layer between the piles and foundation is similar to the tested soil, regarding the compaction and gradation, connected short piles showed a better improvement in the performance of foundation compared to the non-connected case.

Fioravante and Giretti [20] studied the load transition mechanism in pile raft systems, using centrifuge modeling. They studied the effect of the granular mid-layer on the stiffness of the foundation in dense dry sand. The results showed that the load distribution mechanism in the foundation is a function of relative stiffness of pile and soil underneath raft. Also, the initial stiffness of foundation was basically a function of piles stiffness. In the non-connected pile raft systems, presence of a flexible granular layer between head of piles and raft foundation allows the relative settlement between head of piles and soil underneath the raft to occur. Piles carried the loads applied from heads as well as the negative skin friction at the top of the piles caused by relative displacement between granular layer and piles. In other words, if the stiffness of the granular layer is not enough, the bearing capacity of piles will not be completely mobilized and the loading capacity of the non-connected pile raft system can be less than that of a connected one.

Zhang and Ming lei [21] studied the performance of non-connected settlement reducing piles. Based on some simplifications, they suggested a mechanical model of pile penetration into cushion and formulated the pile-soil interaction. With consideration of stress-deformation, coordination of pile-soil-cushion, a calculation method of pile-soil stress ratio is presented. Optimization design of non-connected settlement reducing piles can be performed with their method.

Many researchers in recent years have reported their research about connected and non-connected pile raft. They have been examined the various parameters such as arrangement, length and number of pile, stiffness of the foundation, eccentricity of load and relative density of sand, load transition mechanism. In the present research, connected pile raft system with granular layer, the distance between piles, gradation and thickness of the granular layer as well as non-connected pile raft system with other parameters such as number of piles were investigated.

2. Experimental Methodology

2.1. Acceleration and scaling in the centrifuge tests

The behavior of soil with a pile raft system is nonlinear and stress dependent. If the scaled model is tested under 1g acceleration, the state of stress in the model cannot simulate the real condition of prototype due to extreme decrease in surcharge stress. Thus the results obtained from the model tested under 1g acceleration cannot be a good representative of the real conditions [22]. A practical solution for this case is to test a scaled model and under high accelerations in the centrifuge apparatus. Therefore, the real stress conditions in the field can be easily simulated in the centrifuge with controlling experiment conditions.

A specimen, 1/N scale of the real dimensions, in the centrifuge apparatus under the acceleration N times the gravitational acceleration is able to simulate the stress levels of the real condition for the tested specimen. Therefore the results of such model can be used for interpretation of the pile performance in the prototype condition. The observations made in the model can be correlated to the prototype behavior by the similarity equations noted in Table 1. All the models presented in this study have been tested under 100g acceleration and hence the scaling coefficient was N=100.

Table 1 Similarity relationships

Property	Prototype	Model
Acceleration	1	N
Area	N	1
Length	N^2	1
Volume	N^3	1
Velocity (projectile)	1	1
Velocity (undrained conditions)	1	N
Mass	N^3	1
Force	N^2	1
Energy	N^3	1
Stress	1	1
Strain	1	1
Mass density	1	1
Energy density	1	1
Time (dynamic)	N	1
Time (diffusion)	N^2	1
Time (creep)	1	1
Frequency	1	N

2.2. Model preparation

The broken silicate Firouzkouh sand known, as 161-Firouzkouh sand, with a uniform grading has been used for modeling of soil, and D11-firuzkooh sand has been used for modeling of granular layer (Fig. 1.). The physical properties of the mentioned sands reported In Table 2.

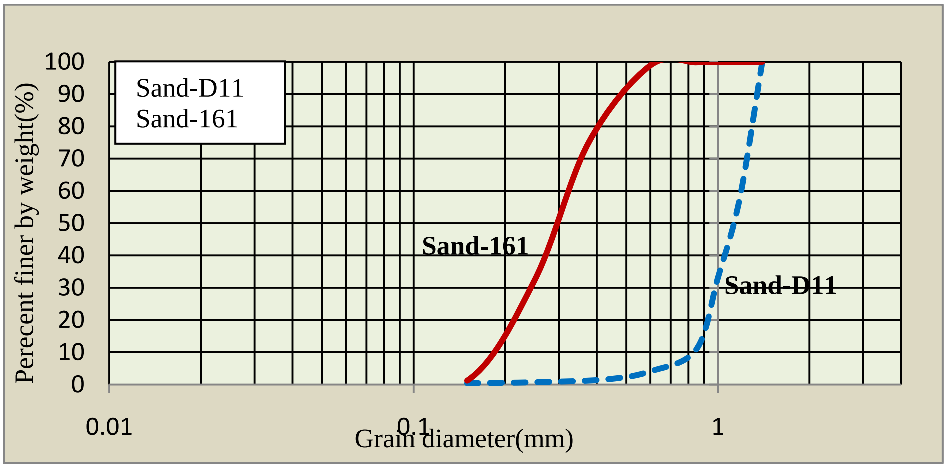

Fig. 1 Gradation curve for sand No 161 and D11 Firouzouh

Table 2 Physical properties of Iran's Firouzkouh sand No 161 compared to Toyora sand

Sand	Gs	e_{max}	e_{min}	$D_{50(mm)}$	F.C %	ϕ	Cu	Cc	K(cm/s)
161-Firouzkouh sand	2.658	0.97	0.55	0.27	0.2	32	2.58	0.97	0.0125
D11-Firouzkouh sand	2.65	0.892	0.626	1.15	0.15	-	1.43	0.96	-

In order to model the piles with the purpose of increasing the bearing capacity or decreasing the amount of settlement, a solid aluminum pipe with 5mm thickness and a hollow aluminum pile with 5.6mm thickness have been used, respectively, as shown in the Table 3. The effect of the soil particles size on the diameter of piles has been studied by Bolton et al. [23]. They concluded that if the ratio of the pile diameter to the average particle size is greater than 20, the scale effect will be negligible.

Table 3 Pile raft model properties

Dimension	Model (mm)	Prototype (m)
Raft(B)	55	5.5
Pile length (L)	84	8.4
Pile diameter (D)	5.6 (Ring)	0.56
Pile diameter (D)	5 (Rod)	0.288

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Gui et al. [24, 25] also suggested the ratio of pile diameter to the average soil particle size should be greater than 20. In the present study, this ratio has been either 20.74 which is near to the recommended values and the purpose of the present research is to compare the behavior of various pile raft systems and the particle size effect existed in all the tests, does not affect the conclusion. Therefore, the particle size effect of the particles has been neglected.

The model raft was a square 55 mm wide (B) and 10 mm thick steel plate characterized by a modulus of elasticity of Er = 2.1×10^5 MPa.

In order to measure the amount of settlement of piles and soil, two Linearly Variable Differential Transformers (LVDT) have been used. Figure 2 shows the boundary conditions, as well as the locations of LDVT sensors and the pile raft system.

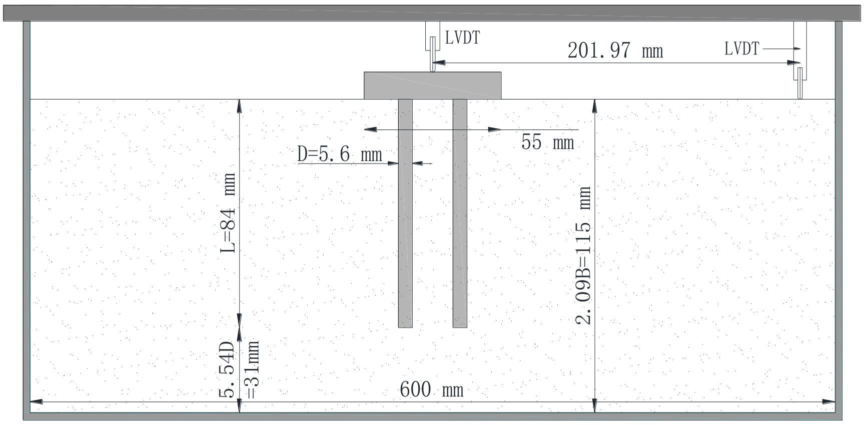

Fig. 2 A schematic illustration of the boundary conditions, location of piles and LDVT sensors in the soil box

3. Test Results and Observations

3.1. Test program

In the present study, all the tests have been performed in 100g acceleration, while the, piles were installed under 1g acceleration. Craig [22] reported that the bearing capacity of the piles installed under 1g acceleration is smaller than the bearing capacity of the piles installed under Ng acceleration. It should be noted that the purpose of this research is to compare the behavior of various pile raft systems and the differences between 1g and Ng pile installation existed in all the tests does not affect the conclusion. The acceleration has been measured at the 1/3 of the specimen depth. All the tests have been performed in sandy soil with 55% relative density. The tests specifications are summarized in Table 4 and Fig. 3.

The presented centrifuge loading tests were performed in the IUST Geotechnical Centrifuge, which has been described by Shahnazari et al. and Azizkandi et al. [26, 27].

Table 4 Test program

No of test	Symbol	No. of Piles	S/d	Depth of Granularly Layer	D_{50} Of Granularly Layer
1	UR	0	--	--	--
2	PG	4	4.9	--	--
3	PR	4	4.9	--	--
4	UR	0	--	1.5	1.15
5	NC-PR	4	4.9	1	1.15
6	NC-PR	4	4.9	1.5	1.15
7	NC-PR	4	4.9	2	1.15
8	NC-PR	4	9	1.5	1.15
9	NC-PR	4	6.57	1.5	1.15
10	NC-PR	4	4.9	1.5	0.3
11	C-PR	4	4.9	1.5	1.15
12	PG	9	3.7	--	--
13	PR	9	3.7	--	--
14	NC-PR	9	3.7	1	1.15
15	NC-PR	9	3.7	0.5	1.15
16	C-PR	9	3.7	1.5	1.15
17	C-PR	9	3.7	0.5	1.15

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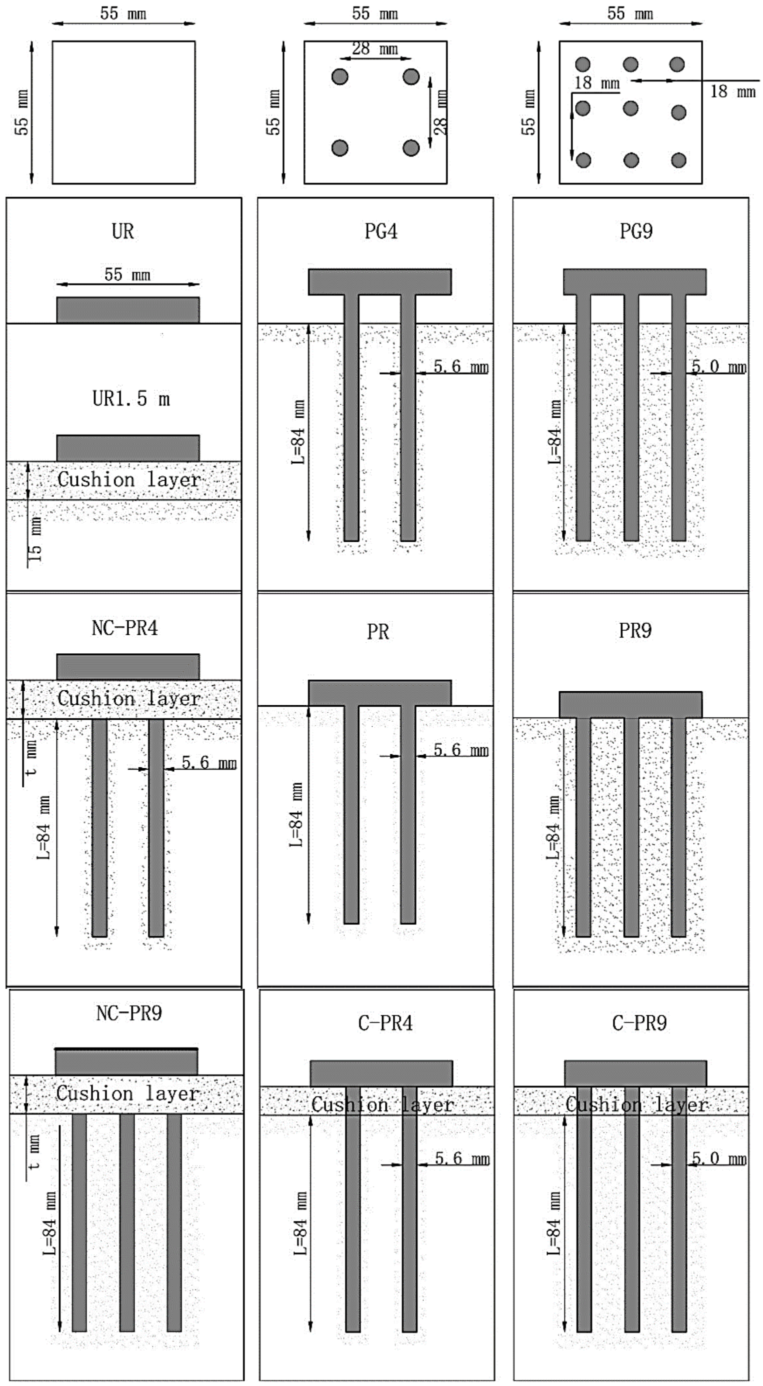

Fig. 3 A schematic illustrations of the tested models. UR (foundation without piles), PG4 (group of 4 piles), PR4 (pile raft system with 4 piles), NC-PR4 (disconnected pile raft system with 4 piles), CPR4 (connected pile raft with 4 piles and granular layer), UR1.5m (foundation without any piles with 1.5m thickness granular layer), PG9 (group of 9 piles), PR9 (pile raft with 9 piles), NC-PR9 (disconnected pile raft system with 9 piles), CPR9 (connected pile raft system with 9 piles and granular layer)

3.2. Test procedure

In order to construct the soil profile, pluvial deposition method has been used and in order to get a uniform compaction throughout the soil, the profile has been constructed as 6 layers and then, using templates to vertical aluminum tubes up to 84 mm in length were placed in the soil. However, in non-connected model after pile installation by temple, granular layer with 90% relative density were placed on the sandy soil.

In order to prevent the errors in measuring displacements and to get a better involvement between the skin of piles with the soil, the specimens of soil with penetrated piles and granular layer, have been given 100g acceleration before the test and then the acceleration has been decreased to 1g. Finally, the raft model in non-connected condition has been placed on the granular layer by chaplains and two LDVT sensors have been installed, one on the soil surface and the other one on the loaded raft model. (Fig. 2).

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4. Test Results

4.1. Pile raft system with 4 piles under the cap

In this part, 11 tests have been performed on piled raft foundation with 4 piles under cap and this tests focus on following topic:

- Normalized settlement-load curve
- Optimum thickness of the granular layer
- Effect of the distance of piles on the load-settlement
- Particle size effect of the granular layer on the performance of non-connected pile raft system
- Load-settlement behavior of a connected pile raft system by a granular layer

For studying the load-settlement curve in various conditions, three tests of a single foundation, a pile group (PG4) and pile raft (PR4) system have been performed in sandy soils with average compaction (D_r=55%). Figure 4 shows the normalized load-settlement curves in these three tests. As can be observed, loading capacity of the piles group is small compared to the raft. Therefore, it can be assumed that the main role of using piles was to reduce the settlements as well as increasing load capacity.

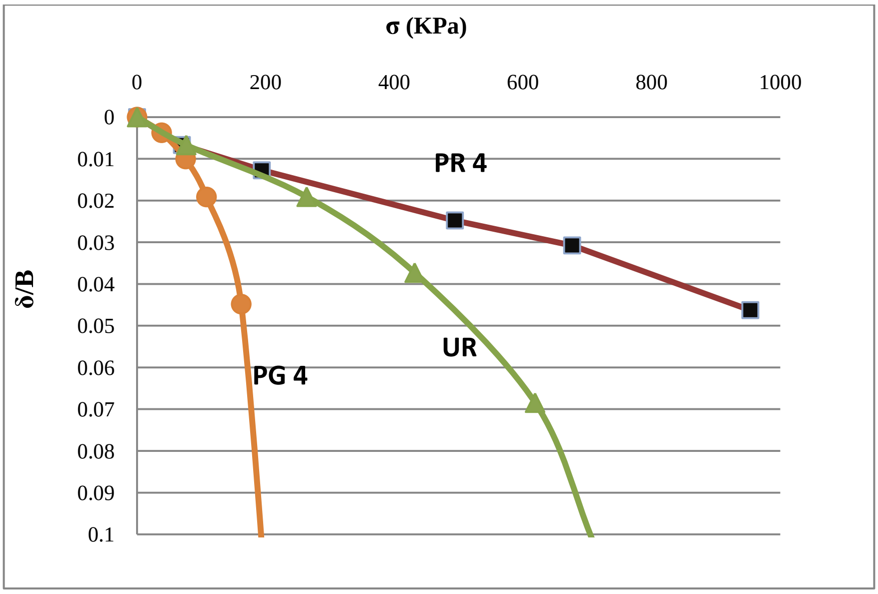

Fig. 4 Normalized load settlement curve

To study the optimum thickness of the granular layer, three tests with granular layer thicknesses of 1, 1.5 and 2m on a pile raft system composed of non-connected piles have been tested. The purpose of these tests was to investigate the effect of the granular layer thickness on the amount of settlement. The granular layer has been constructed between the piles and cap with 90% relative density. Considering the high compaction and stress distribution in coarse grain material, as shown in Figure 5, the stress applied on the surface of sandy soil is considerably decreased for the non-connected pile-raft system with 1m granular layer. As the thickness of granular layer is increased to 1.5m, the settlement is even more decreased. In another test, the thickness of the granular layer was increased to 2m and as can be observed in Figure 5, the settlement of the system with 2m cushion thickness is increased compared to the case with 1.5m thickness.

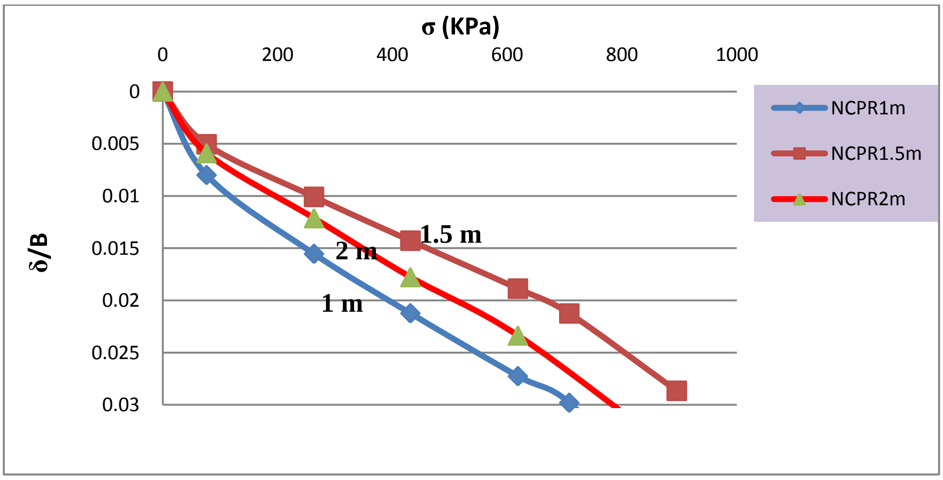

Fig. 5 The load settlement curve for non-connected pile raft system using layers with 1, 1.5 and 2cm thickness

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As a result, based on the experiments mentioned above, the optimum thickness of the granular layer in the pile raft systems in sandy soil is suggested as 1.5m and therefore, in the following experiments the thickness of the granular layer is considered as 1.5m.

In the pile raft system with piles connected to the cap (with a relatively rigid cap) as the distance of piles from each other is increased, the settlements are decreased due to a decrease in the interaction between piles. As can be observed in Figure 6, by increase in s/d ratio from 4.9 to 6.57 the amount of settlement is considerably decreased due to a decrease in the interaction between the piles. However, by increasing the s/d ratio to 9, the settlement increases because the stiffness of reinforced soil model is decreased which leads to greater settlements compared to S/d=6.57. In another experiment, a shallow foundation has been placed on the granular layer with 1.5m thickness. It was observed that in low stresses, the amount of settlement does not differ much in a non-connected pile-raft system but as the stresses are increased, the amount of settlement in two cases is considerably different (Figure 6).

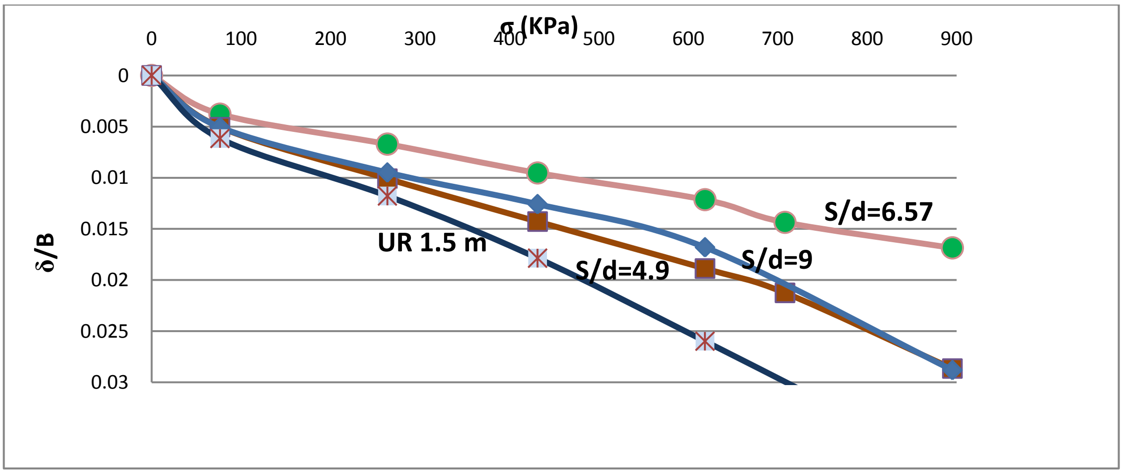

Fig. 6 The effect of s/d ratio on the load settlement curve for non-connected pile raft system, using a granular layer with an optimum thickness of 1.5m

In this part, one non-connected pile raft system with a different granular layer (D_{50}=0.27mm) is tested to see the size effect of the granular particles on the performance of non-connected pile raft system. With regard to Figure 7, under low stresses the size of granular particles is not that much effective on the load- settlement curve. However as the stresses are increased, the non-connected pile raft system with D_{50}=1.15mm shows a better performance and smaller settlements due to settlement occurred in the granular layer. Theses because the maximum friction angle of sand increasing when the size of particles increases and higher friction angle is more effective in reducing settlement at higher stresses [28].

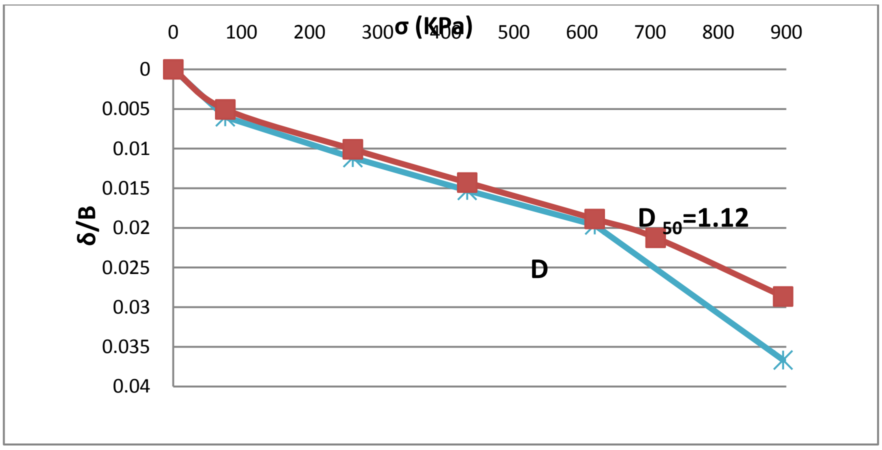

Fig. 7 The size effect of granular particles on the amount of settlement (1.5m thickness)

In this part, one experiment has been conducted on a connected pile raft system with 1.5m thickness granular layer. The purpose of conducting this experiment is to study the load-settlement behavior of this system and compare it with settlement in this piled raft system by four piles. As can be observed in Figure 8, the connected pile raft system with granular layer has shown a better performance compared to non-connected pile raft systems both with granular layer.

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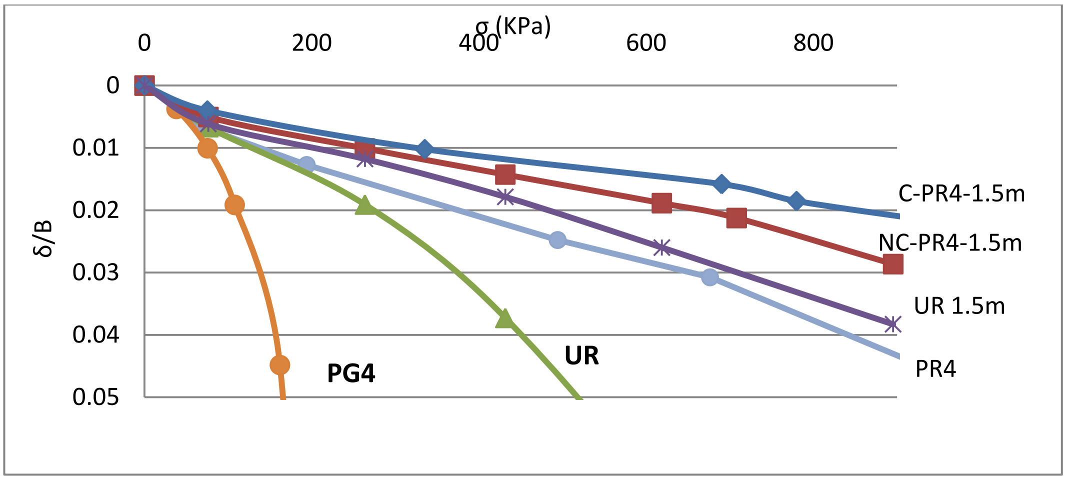

Fig. 8 Normalized load settlement curve

4.2. Pile raft system with 9 piles

In this part, the results of 6 tests on piled raft foundation with raft and 9 piles have been reported to focus on following topics:

- Normalized settlement-load curve
- Optimum thickness of the granular layer
- Load-settlement behavior of a pile raft system by a granular layer

To investigate the settlement-load behavior, two experiments on a piles group and a pile raft system with 9 solid piles are tested. The purposes of doing these experiments were to investigate the performance of soil-structure load transition mechanism in sandy soil with 55% relative density and also, to study the bearing capacity as well as load settlement performance of a piles group. As can be observed in Figure 9, the bearing capacity of a piles group is almost equal to the raft system without any piles. Therefore the bearing capacity of piles is considerable. As can be observed, the amount of settlement in the connected pile raft system with 9 piles is much lower than the case with 4 piles.

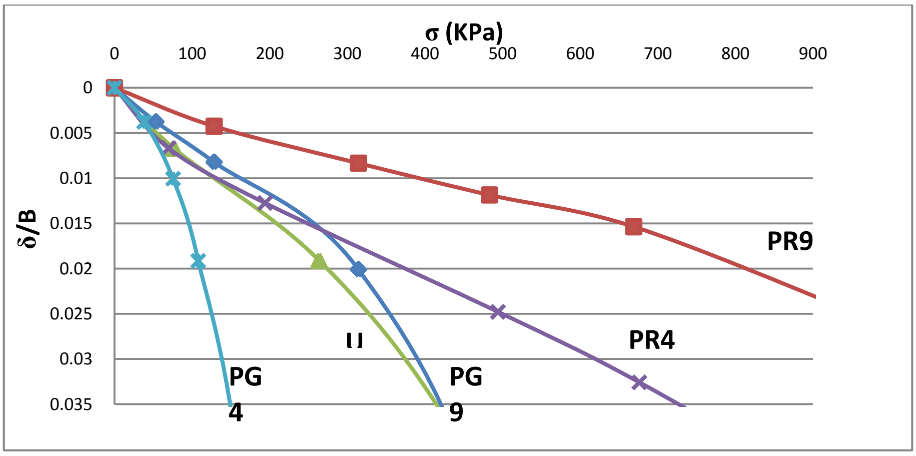

Fig. 9 Normalized load settlement curve

To investigate performance of connected and non-connected system tests is done. Two non-connected pile raft systems with a granular layer of 0.5 and 1m thickness have been modeled. The granular layer was constructed below the cap with 90% relative density. With regard to the Figure 10, the non-connected pile raft system with 0.5m thickness of granular layer has shown a close performance compared to the case of non-connected without any granular layer. As the thickness of the granular layer is increased to 1m, the amount of settlement is increased. Therefore it seems that the pile raft system with 9 piles performs better than the non-connected system with granular layer.

In this series of experiments, two connected pile raft systems with two granular layers with thicknesses of 0.5 and 1.5m have been modeled and tested.

As can be observed in Figure 11, the amount of settlement for the connected pile raft system with a 0.5m thickness of granular layer is increased compared to the case without any granular layer. Then by increasing the thickness of the granular layer to 1.5m, the settlement is more increased due to the coarser gradation of the granular layer. Therefore, the contact area between the particles of the granular layer and shaft piles is decreased and consequently the friction between the piles is more decreased by increase in the thickness of the layer which,

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in turn, causes a reduction in the shaft resistance and an increase in the settlement.

Therefore, it can be concluded that the connected pile raft system with 9 piles performance better compared to non-connected system with a granular layer.

Some studies have been devoted to study the effect of sand or gravel cushion on the non-connected piled raft performance, while no studies were aimed to connected piled raft with cushion and the gradation of cushion. The load-settlement behavior of non-connected pile-raft systems with 4 and 9 piles and raft foundation alone are very close to the result reported by Fioravante and Giretti [20] and Cao et al. [18].

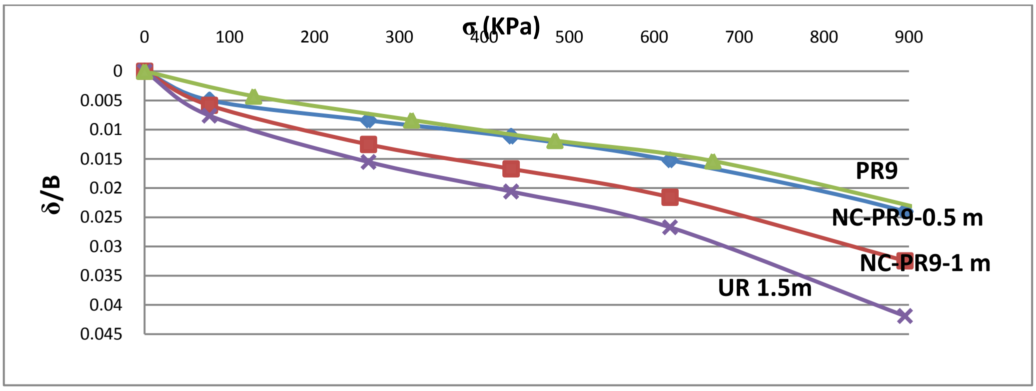

Fig. 10 Load settlement curve for non-connected pile raft system using a granular layer with two thicknesses of 0.5 and 1 m

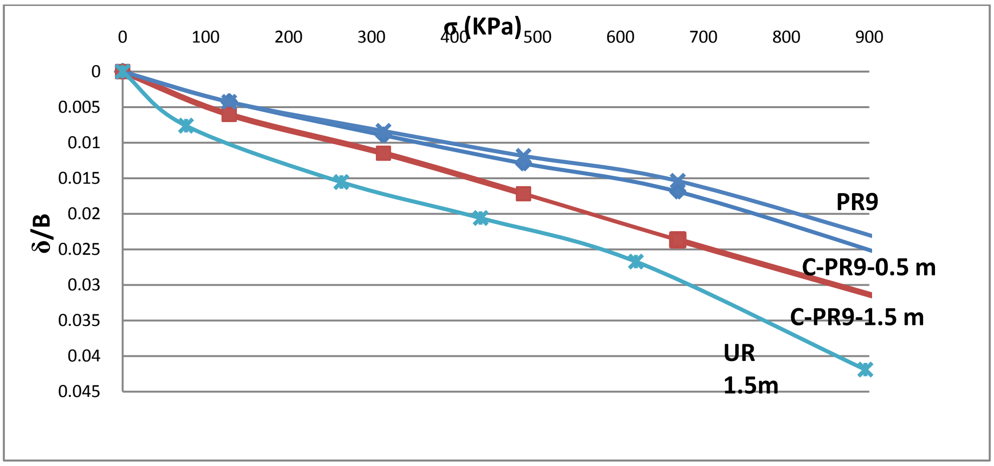

Fig. 11 Normalized load-settlement curve for connected pile raft system along with a granular layer

5. Summary and Conclusion

In this experimental centrifuge modeling, performance of connected and non-connected pile raft systems on the load settlement behavior have been investigated. The results showed that where the purpose of using piles is to decrease the settlements, the non-connected pile raft system performs better than the connected system. Based on the experiments conducted in this study, the following conclusions can be drawn:

1- In the non-connected pile raft system with a granular layer compared to the connected system without granular layer, the amount of settlement is considerably decreased.
2- The amount of settlement for an optimum thickness of the granular layer is minimum. However further increase in the thickness causes an increase in the settlement. Based on the results of this study, the optimum thickness of the granular layer is 1.5m.
3- The amount of settlement in the connected pile raft system with a granular layer is smaller compared to the same case without granular layer. However the settlement observed in a connected pile raft system with a granular layer compared to the non-connected pile raft model did not show significant differences and they showed almost similar behavior.
4- In the non-connected pile raft foundation, with 1.5m thickness granular layer, an increase in the s/d ratio causes the settlement at first to considerably decrease. However, further increase in the s/d ratio after certain value, the settlement begins to increase.
5- It was shown that under small stresses, the size of the granular particles is not very effective on the load settlement behavior of non-connected pile raft system. However as the stresses are increased the non-connected pile raft system with a coarse grains granular layer shows better performance.
6- When number of piles under the raft increases in the amount of settlement for the non-connected system with granular layer is considerably increased compared to the same system with connected piles and without

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any granular layer. Therefore, using the cushion and non-connected system must be selected based on the number of pile under the cap.

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