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RESEARCH ARTICLE

An Investigation of Factors Affecting the Design of Model Piled Raft Foundations in Laboratory

Rahim Kağan AKBULUT[1,*], Özcan TAN[2]

[1] *Ataturk University, Erzurum Vocational College, Erzurum, TURKEY*
[2] *Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Konya, TURKEY*

* *Corresponding author E-mail: rkakbulut@atauni.edu.tr*

HIGHLIGHTS

> A diameter of 600 mm and a height of 1100 mm test tank was used to perform model tests with larger diameter and height than previous studies.
> With the load and deformation reading system developed, the loads coming to the pile and the piled raft can be measured separately.
> In the model piled raft tests, the load was received by the raft at the beginning of the experiment and it was determined that the load was transferred to the piles in very small settlement quantities.
> The test results show that the system in the piles raft foundations can contribute to the total load of the system cannot be neglected.

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ABSTRACT

Piled raft foundation applications are a combined foundation application which is being used frequently today. There are a limited number of studies on the model piled loading tests in the literature. In addition, in the past pile loading experiments, especially in model piled raft experiments; pile tip, skin friction and loads covered by the raft cannot be reliably measured. In the light of the previous studies, large scale model tests were performed in order to minimize boundary effects. In the study, the model piles were manufactured from concrete, like the actual situation, in the soil region where the pile will be formed, thus preventing different environmental conditions from affecting the pile design. Within the scope of this study, the model piled rafts on a sandy soil were axially loaded in the laboratory and the load-settlement curves and the raft load-sharing percentage curves were obtained depending on the settlement ratio. In this experimental study the experiments, the model piles of different lengths (L = 320 mm and 520 mm) and diameters (D = 50 mm and 60 mm) and different raft sections (150x150 and 200x200 mm) were prepared in sand bed. These model piles and rafts are combined with the load cell and model piled rafts are obtained in the middle under the raft and two piles in the corner. Piled rafts were loaded into the model tank by placing two different relative densities such that the test sand was loose (Dr: 27%) and dense (Dr: 65%). The model test results of the study showed that the raft foundation contributes to the total load that the system can carry. In the piled raft foundation system, it was seen that the load was initially carried by the raft and the load was transferred to the piles in very small settlement levels. It has been determined that the raft has a ratio of 25-40% of the total load. The load-sharing ratio corresponding to the 40mm settlement of the raft and the load-sharing ratio corresponding to 1mm settlement increased by 30- 100%.

Contents

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1. Introduction

Piled raft foundation applications are now used as a combined foundation application. This practice has been the subject of many studies in recent years and the behavior of such foundations under vertical, horizontal and dynamic loads has also been investigated with various aspects.

The foundations of the structure should be able to carry the loads coming from the superstructure as well as the required settlement condition. In addition, the type of the selected foundation system within economic limits is another restriction of the foundation engineering requirements. In some foundation conditions, even if the foundation is sufficient in terms of the bearing capacity, a certain number of piles are produced under the raft foundations in order to prevent allowable settlements and to prevent different settlements, and piles play an important role in prevention these settlements.

It is accepted that pile designing (raft) does not bear any load in the classical piled foundation designs. This acceptance is quite conservative, and there are many special situations in which the soil is more settlement than the pile. The pile cap, which is usually in contact with the soil, carries the structure load together with the piles in some way. Load sharing rates between piles and raft and piled-raft behavior have been the subject of various researches in recent years. Because the system has no problems in terms of settlement or, in other words, the fact that the raft carries a certain amount of load with the same settlement value, and using a smaller number of piles, the foundation design of a piled raft is of great economic importance. According to the studies carried out in recent years, the rate of load carried by the raft is gradually decreased by the increase in the number of piles in the system.

The main parameters of the effective design of piled raft foundations are: soil properties, flexible or rigid design of the raft, number of piles, length and diameter of piles, pile layout under the raft and direction of load application. For all the parameters listed here, it is necessary to know the pile-raft-soil interactions, load sharing ratios and settlement behaviors of these foundation systems and with the case analysis, with small scale model experiments in laboratory or with large scale model experiments in the field or expanding the literature is of great importance in terms of foundation engineering. There are many studies on piled raft foundations in the literature. Particularly, the parametric studies conducted with commercial softwares, which use more finite, boundary or discrete element methods and which can carry out advanced numerical analysis in the investigation of the factors affecting the design of piled raft foundations.

Poulos (1993) studied the design of piled rafts on problematic soils (settlement and swelling). Poulos stated that in cases where the raft is sufficient in terms of bearing capacity, several pile reinforcements that are strategically placed on the soil in such soils can be solved by settlement and different settlement problems. In the results of working; if the soil is exposed to the consolidation movement or swelling movement, in both cases, the movement of the piled raft is determined to be greater than the movement of the pile group. The author also stated that avoiding piled raft use would be the best solution in case of external vertical soil motions [1].

Mendonça and Paiva (2000) developed limited element method formulation in piled rafts which take into account the simultaneous interactions between soil, pile and plate. In this approach, the soil is modeled as an elastic linear homogeneous semi-infinite medium, the raft is thin and the piles are modeled as single elements and are expressed by integral equations of both the pile and the raft. In addition, the shear force between each pile was taken as a second order polynomial and the soil-head interface was divided by triangular elements. The load transfer mechanism of rigid and flexible pile groups has been investigated experimentally with limited element method and the results are compared with those of other researchers in the literature [2].

In their study, Prakoso and Kulhawy (2001) simplified linear elastic and nonlinear plane deformation finite element models in the definition of piled rafts. Load capacity and system geometry of the pile group, raft effects, different displacements, raft bending moments and load bearing ratio of piled raft were evaluated fron the averages values [3].

Small and Zhang (2002) examined the behavior of piled rafts under vertical and lateral loads. The raft was modeled as a thin plate and the piles were modeled with elastic beams. Piles and raft are solved by finite element method and soil is solved by finite layer theory. The piled raft has been subjected to both load and moments. 3x3 group 0.564m circular section 10m long piles, raft thickness 0.25 m and s / d = 3 and 5 (range / diameter) was designed and analysis was conducted. As a result of their study, it is possible to produce pile groups in general loading types by the finite layer method, and the availability of this analysis has been proven in case of contact of both the soil surface and the soil contact with the raft [4].

Tan and Chow (2004) studied the design of piled rafts on soft soils. The design of piled raft foundation system design has been investigated with reference to certain structures built on soft soils. Two types of approaches have been developed. The first one is the low-rise buildings (less than 3-storey buildings) and the middle-level buildings (3 to 5-storey buildings) design approaches [5].

Poulos (2005) also made a number of studies on piled raft and equalized piles in soft soil conditions. The author first studied only the conditions where the foundation load was effective, and secondly, the soil conditions that were subjected to both the applied load and the external settlements. In the Poulos study, the soil shows that when the settlements occur, the piled raft reduces the different settlements between the structure and the soil [6].

Liang et al. (2009) studied the integral equation method for the analysis of piled foundations with different piles under vertical loads. As a result of the study, it has been emphasized that the use of pile in different diameters and lengths under certain conditions should be taken into consideration economically in reducing the total and differential settlements in the shearing, moment and piled raft by taking the structural evaluations into consideration [7].

Mu et al. (2012) proposed a simplified analytical method for the analysis of lateral responses of piled rafts used for reducing soil movements in tunnels constructed on layered soils. The proposed method has been verified by comparison with the centrifugal test results. As a result of the study, it was found that additional lateral deformations and bending moments would increase the hardness of the base soil [8].

On the other hand, in the design of piled raft foundations, there are a limited number of studies in which the effect of parameters in terms of settlement and bearing capacity is investigated experimentally in the laboratory.

Cao et al. (2004), on the sandy soil supported by piles. Model rafts are modeled in laboratory situation for various parameters such as raft stiffness, pile length, pile distribution and number of piles. In this study, a model tank with a depth of 170x24 cm and a depth of 80 cm was used. The sand was placed in a funnel by sprinkling in layers of 15 cm with a relative density of 50%. Then each layer was compressed by manual compactor until the density of the sand was 70%. In the model, the raft is chosen between thickness of 5-10-25 mm and in dimensions of 44x22 cm. The piles are 9,5x9,5 mm square cross section and 1 mm thick. The pile lengths are 35 cm and 55 cm. Loads were transferred to the raft plate with steel blocks at the Q (a load value) at the two edges and the 2Q into the middle. It was mentioned that piles in piled rafts were used as settlement reducers for load bearing and it was stated that the design of these foundations was often tried to minimize the number of piles [9].

Khoury et al. (2011), the longest building in Newyork Brooklyne (155 m) (the first building constructed with piled raft in the USA) was analyzed with a 3D finite element program (Plaxis 3D Foundation). In the study, it was determined that the initial analyzes were not able to reduce the different settlements of the continuous raft foundation only with their own structure, and they were found to have settled the historical buildings that damaged the surrounding buildings. For this reason, high capacity mini piles are modeled in order to reduce settlement levels at the corners to acceptable levels. Raft thickness was selected 1.8 meter thin elastic plate in the program. Mohr-Coulomb was selected as the base model. The result of the analysis of the raft was 4-5 cm, exceeding the acceptable limits. In the Plaxis 3D with 7.5 m long mini-piles, 72 pile of strategically placed mid-point and 11 piles in north and south sides were placed under the weighted areas of the typical sample building. Thus, in terms of settlements in the middle 2-3 cm in the margins are smaller than 2 cm. In addition, the results were compared with the Plaxis 3D Foundation finite element program [10].

In this study; large-scale model experiments were carried out in the laboratory to clarify the load-settlement behaviors of the piled raft foundations under vertical static loads and the pile-raft load sharing mechanisms. The effect of the parameters affecting the pile length, pile layout, soil density and the effect of the piled raft design on the bearing capacity and settlement behavior of this foundation system were investigated.

2. Material and Method

Piled raft foundation design is a design method which is taken into consideration together with pile and raft which has become widespread in recent years. Within the scope of the design of piled raft foundations, as can be seen in the literature research, important steps have been taken in analytical and numerical methods using softwares which can do theoretical and advanced numerical calculations. However, the number of experimental studies to examine the factors affecting the behavior and design of piled raft foundations is quite limited. As the number of experimental studies and data increase, the reliability of the numerical methods and the developed software and their applicability under different conditions will also increase. Modeling pile foundation or pile foundation behavior with field tests is very difficult in terms of cost and feasibility. For this reason, the behavior of piles, raft and piled rafts or parametric studies on this subject can only be done by using model laboratory experiments.

2.1. Soil properties used in model experiments

In the model experiments, washed natural sand obtained from a special aggregate quarry in the Selçuklu district of Konya province was used. The soil class of the sand used in the experiments was determined as SW according to the Unified Soil Classification System (USCS). The test results and some index properties of sand are given in Table 1.

Table 1 Index properties of sand used in experiments [11]

Gravel ratio		%0
Sand ratio		%98
Clay+Silty ratio		%2
Coefficient of uniformity,	C_u	6.1
Coefficient of gradation,	C_c	1.16
Soil class,	(USCS)	SW
Specific gravity		26.3
Max. void ratio,	e_{max}	0.82
Min. Void ratio,	e_{min}	0.32
Water content,	w	%0.15

The degree of relative density is the most important factor affecting the design of piled raft foundations constructed on sandy soils. In order to examine this factor effect on the piled raft foundation design, the experiments were carried out in two different relative densities, corresponding to the loose and dense state. The sand was placed in layers of 300 mm thickness into the tank and a 5 kg-weight rammer with a square cross section was dropped from a height of 200 mm and 12 times for each layer. In this way, the relative density of the sand was achieved to dense condition (Dr= %65). On the other hand, the sand was placed into the tank by means of a funnel through its own weight to obtain a loose state condition. In this way, the relative density of Dr= %27 was observed.

In addition, in order to determine the internal friction angle of the sand used in the model experiments, direct shear test was performed both on Dr= %65 and Dr= %27 sand samples. The direct shear tests were done in accordance with ASTM D 3080-98 [12]. From these tests, the friction angle of prepared sand samples were obtained as 49° and 37° for dense and loose condition, respectively.

2.2. Model experimental setup, method and test program

In order to manufacture model piled raft elements (piles and raft) and to carry out the loading tests, a cylindrical tank was constructed with a length of 1100 mm and a diameter of 600 mm. During the experiments, the wall thickness of the tank was selected as 5 mm to prevent deformations in the tank side wall. In order to ensure that the surface roughness of the model piles was compatible with the production in the field, the piles were manufactured in the sandy soil. For this purpose, the model piles were made by filling the inside of the cylindrical molds, which serve as covering pipes. The concrete mixture prepared in the hollow cylindrical molds placed in the tank was poured, and the model piles were formed by drawing the molds simultaneously (different pile diameters: D = 60-50 mm) on the soil inside the test tank. In the concrete pouring stage, a diameter of 100 mm length of bolts is placed axially on top of the molds (Figure 1-a). With this application, it was aimed to provide the connections between pile-load cell-raft during the experimental phase. In this study, the model piles were produced directly in the sandy soil and the pile roughness was close to the field situation.

For the model raft foundations, wooden molds with six openings of 100x100 mm, 150x150 mm and 200x200 mm square dimensions and d = 25 mm height were prepared. The molds were placed on the sand surface to be used in the experiment. The prepared concrete mixture was poured into molds and model rafts were obtained. In the preparation of the model raft on the sand, the bottom surface of the raft was contacted with the sand and the soil roughness was suitable for the real situation (rough surface) (Figure 1-b).

In order to increase the flexural rigidity of the raft, random reinforcements (ϕ6 and construction nails) were used.

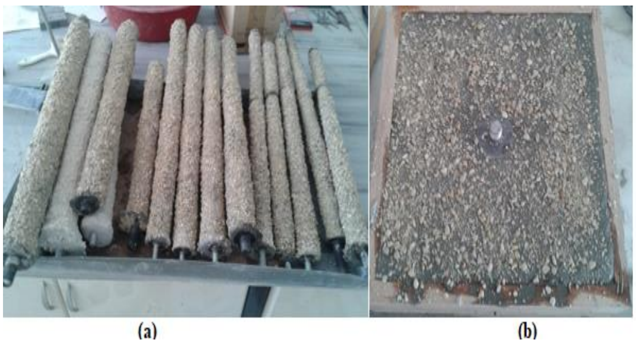

Figure 1 Screws at the beginning of model piles (a) pile (b) raft (for the detection of load cells) [11]

The steel plates with dimensions of 1150x600 mm and wall thickness of 55 mm for the loading frame were fixed to each other by four corners with cylindrical steel bars of about 1750 mm in length and 40 mm in diameter. In the middle of the upper steel plate used as reaction beam, the load of 50 tons and the hydraulic press trying to pull were fixed. A cylindrical tank with a height of 1100 mm and a diameter of 600 mm was placed inside the loading frame (Figure 2-a). In order to minimize deformations during loading, the tank was surrounded by a single level steel belt. In the model experiments, digital deformation watches with a maximum deformation amount of 0.01 mm (2 mm) were used to measure deformations that may occur in piles and raft. In order to measure the loads applied by hydraulic press, one and three-ton capacity, "s" type load cells were used. In order to collect the data to be obtained from the dial gauge and the load meters, a special software called, "TDG" was used to transfer this data to the computer with the reading unit (8 channels) (Figure 2-b).

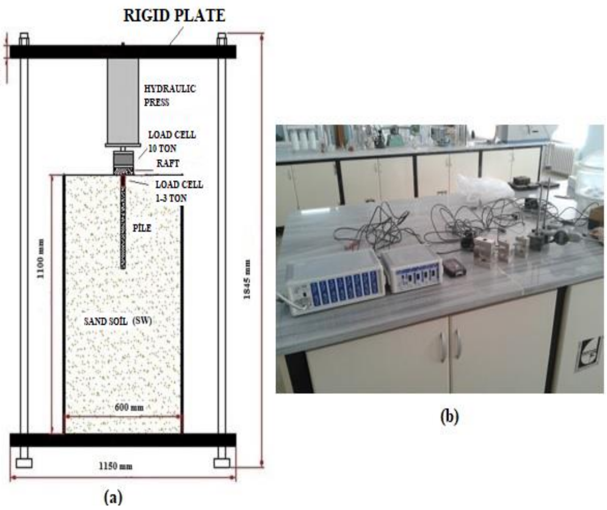

Figure 2 (a) Schematic representation of model test tank (b) Instrumentation devices

2.3. Model piled raft foundation experiments

"s" type 1-ton and/or 3-ton capacity load cells were produced when piles were constructed and bolts were placed inside them (Figure 3-a). Then the load cells were fixed on them, the rafts were installed by combining the raft. In this system, to ensure the connection between the load cells and the raft, the model rafts were produced with bolt fastening as required in the same pile production. Then, the related pile, raft and soil densities were determined and the model piled rafts were placed in the tank (Figure 3-b). In these experiments, the total load taken by the piled raft was measured with a load cell of 10 tons. The load received by the pile was measured with a 1-ton load cell connected to the pile. The load taken by the pile and the raft was determined by the load of the pile. In this scope, the experimental program prepared for the model experiments, which are made by combining the pile and raft together with the load cell, is given in Table 2.

Figure 3 (a) D = 60 mm, L = 520 mm load cell placement on the pile and bolted pile production in different diameter, (b) D=50 mm, L=520 mm 150x150 mm installation of the piled raft (2 piled in the corner) into the tank [11]

Table 2 Model piled raft foundation test series

Test No	Test Name	
1	D=50 mm L=320 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%27)	The model foundation created with the load cell
2	D=50 mm L=320 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%65)	
3	D=50 mm L=520 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%27)	
4	D=50 mm L=520 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%65)	
5	D=60 mm L=320 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%27)	
6	D=60 mm L=320 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%65)	
7	D=60 mm L=520 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%27)	
8	D=60 mm L=520 mm 150x150 mm Single Pile of Raft in the Middle (Dr=%65)	
9	D=50 mm L=520 mm 200x200 mm Single Pile of Raft in the Middle (Dr=%27)	
10	D=60 mm L=520 mm 200x200 mm Single Pile of Raft in the Middle (Dr=%27)	
11	D=50 mm L=520 mm 150x150 mm Two Pile of Raft in the Corner (Dr=%27)	
12	D=50 mm L=520 mm 200x200 mm Two Pile of Raft in the Corner (Dr=%27)	

3. Results and Discussion

Load tests were performed by combining the load cell with the pile and raft. In these experiments, load deformation curves were obtained with the help of the data obtained from the load cells on the piles with two deformation gauges on the raft to measure the settlements. In the curves, the loads carried by the raft in the model were calculated by subtracting the load carried from the piles from the total load applied to the model [11]. A total number of 12 experiments were carried out on piled raft formed by combining with load cell (Table 2).

3.1. Single pile loading test results under a raft

Four different loading tests were carried out for single piled model. For this model test, a diameter of 50 mm pile was placed in the center of the raft and this pile was equipped with the load cells. The single pile model tests were performed both on dense and loose soil conditions. The graphs of the load-settlement relationships obtained from these experiments are given in Figure 4, respectively.

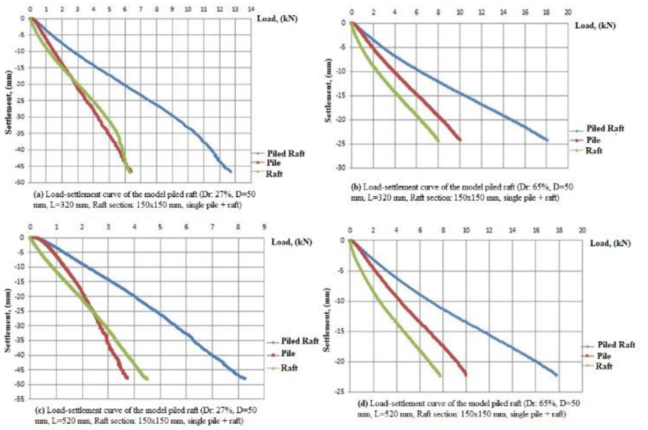

Figure 4 Load-settlement curves for model piled rafts (D=50mm)

Four different models (Dr=0.27 ve Dr=0.65) and two different pile lengths (L = 320mm and L = 520mm) with a single pile and raft system in the center of the pile diameter fixed (D = 60mm) piled raft loading tests were performed. The load- settlement relationships drawn as a result of these experiments are given in Figure 5.

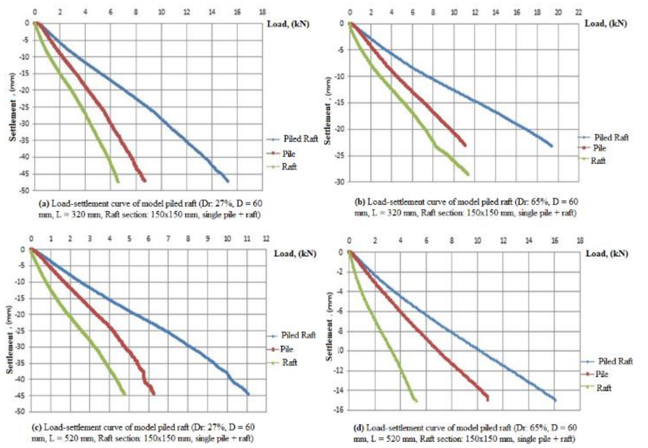

Figure 5 Load-settlement curves for model piled rafts (D=60mm)

In order to investigate the effect of raft width and pile diameter on piled raft foundation systems, two loading tests were performed on single pile model test. At this model test, the dimension of raft foundation (200x200mm) and the length of pile (L=520 mm) was kept constant. However, the diameter of piles was chosen as 50mm and 60mm and these piles were placed at the center of the raft foundation (Table 2). The experiments were carried out in the case that the load cell capacity was exceeded due to the increase of the load to be carried by the raft, and it could not be carried out in the dense sands and the soil was placed in a loose condition (Dr=%27). The load- settlement relationships obtained as a result of the model experiments are given in Figure 6, respectively.

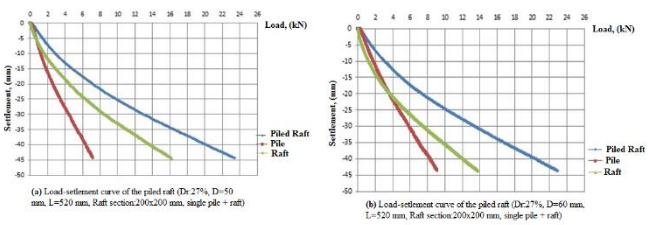

Figure 6 Load-settlement curves for model piled rafts (Raft section:200x200mm)

In the case of piled raft experiments, the raft load takes the full load before the system starts to load at very small levels. Afterwards, the piles are mobilized as a result of the small amount of raft settlement and the load acting on the system is shared between piles and raft.

The raft load sharing percentages and the settlement ratio curves obtained from single-pile model tests are given in Figure 7. As can be seen from the figures, when the settlement ratio approaches 20 mm, the raft load sharing rates generally reach 40% and remain constant. The fact that this ratio is not negligible in terms of design engineers can allow for more economical dimensioning by adopting the assumption that the raft load is in contact with the soil in the piled raft design [11].

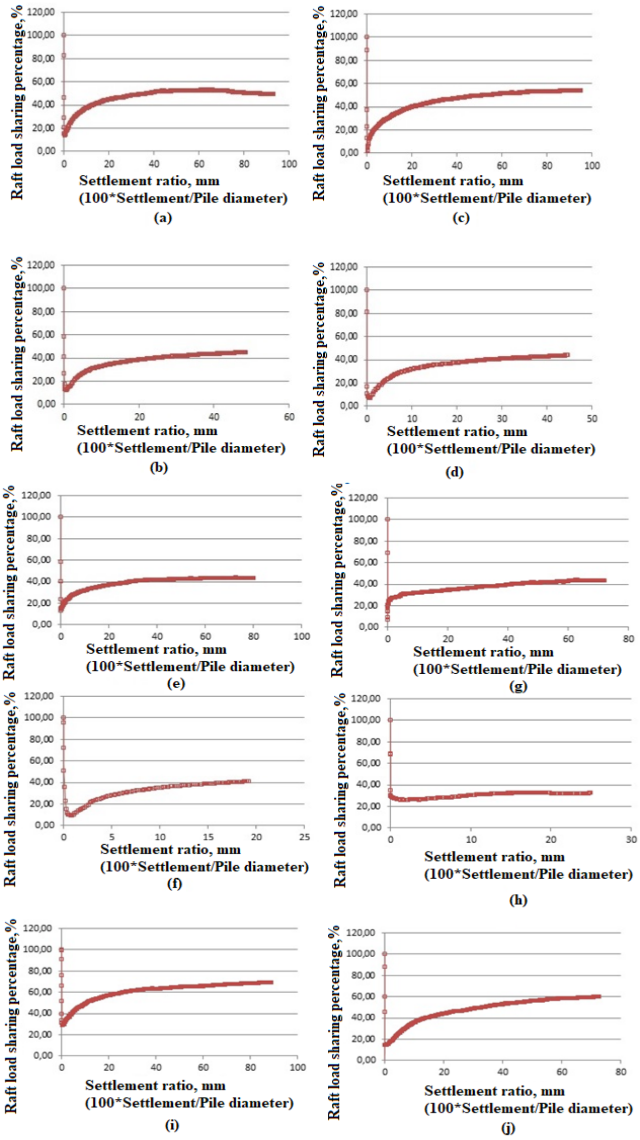

Figure 7 Raft load sharing percentage - settlement ratio curves for model's single piled rafts at the center
(a:Dr: %27, D=50 mm, L=320 mm, Raft size:150x150 mm)
(b:Dr: %65, D=50 mm, L=320 mm, Raft size:150x150 mm)
(c:Dr: %27, D=50 mm, L=520 mm, Raft size:150x150 mm)
(d:Dr: %65, D=50 mm, L=520 mm, Raft size:150x150 mm)
(e:Dr: %27, D=60 mm, L=320 mm, Raft size:150x150 mm)
(f:Dr: %65, D=60 mm, L=320 mm, Raft size:150x150 mm)
(g:Dr: %27, D=60 mm, L=520 mm, Raft size:150x150 mm)
(h:Dr: %65, D=60 mm, L=520 mm, Raft size:150x150 mm)
(i:Dr: %27, D=50 mm, L=520 mm, Raft size:200x200 mm)
(j:Dr: %27, D=60 mm, L=520 mm, Raft size:200x200 mm)

3.2. Two pile loading test results under a raft

In this study, 2 loading tests were performed for 150x150 mm and 200x200 mm dimensioned raft formed by combining with the load cell at two corners under the piled raft (Table 2). In this model, two different values were chosen for the raft width by keeping constant of the pile diameter, length, number (2) and soil density. In the experiment, 1 ton of "s" type load cells were formed on both piles. In the foundation system of the piled raft model, the load to the raft was calculated by substracting the two piles load from the whole system. As a result of the model experiments, the load- settlement relationships and the load-sharing percentage and the settlement ratio curves obtained for the piled rafts are given in Figure 8. As seen in Figure 8c and d, when the settlement ratio is close to 20 mm, the raft load sharing ratio in the soil area small raft is approximately 20%, while the soil area in the large raft is about 40% as obtained in the model of single-piled rafts.

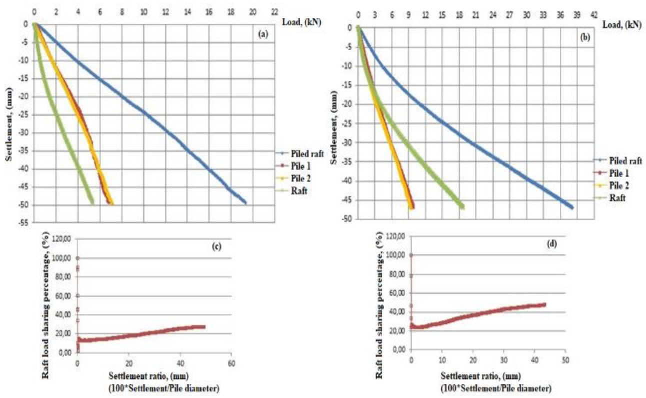

Figure 8 Laod- settlement and raft load sharing percentage - settlement ratio curves for model's two piled rafts in the corner
(a:Dr: %27, D=50 mm, L=520 mm, Raft size:150x150 mm)
(b:Dr: %27, D=50 mm, L=320 mm, Raft size:200x200 mm)
(c:Dr: %27, D=50 mm, L=520 mm, Raft size:150x150 mm)
(d:Dr: %27, D=50 mm, L=320 mm, Raft size:200x200 mm)

4. Conclusion

Factors affecting the design of piled raft foundations were investigated experimentally. There are a limited number of studies on piled raft loading tests in the literature. In these studies, generally model profile (steel) piles were used instead of concrete piles, and a number of operations (sanding paper bonding, embossing on the profile etc.) were applied to bring the pile roughness close to the roughness of the concrete. The degree to which such work represents the real situation has always been the subject of debate. In the past, especially in model piled raft experiments; pile tip, skin friction and loads covered by the raft cannot be reliably measured. In such studies, a part of these loads (eg total load) is generally measured by non-sensitive methods and others are estimated by static pile formulas, numerical methods or optimization techniques. Again, according to previous studies, the experiments in larger (long, long and deep) test tanks were selected and the boundary effects were minimized and thus large scale model experiments could be performed. In this study, the model piled raft foundations were constructed from concrete, like the actual situation, in the soil where the pile will be formed, thus trying to prevent different environmental conditions from affecting the pile formation. The main conclusions and assessments obtained from the study are given below:

• With a test tank of 1100 mm in diameter with a diameter of 600 mm, model experiments with larger diameter and height have been performed.

• With the developed load and deformation reading system, the loads on the pile and the piled rafts could be measured separately.

• In the case of model piled raft tests, the whole load is carried by the raft at the beginning of the experiment. Starting from the very small order of the raft settlement (0.3-0.6% of the pile diameter), the piles also start to load. When the piles are mobilized, the axial load is shared between the piles and the rafts.

• The model tests show that the raft foundations generally carry the total load at the amount of 20%-50% where the settlement is close to 20mm. As the amount of settlement increases, the load sharing rate of the raft increases. Considering a certain ratio (10%) of the foundation width (diameter), it will be appropriate to take the load sharing ratio of the raft between 20-40% in piled raft designs in the sandy soils.

• In cases where the pile foundation system can be applied (situations where the soil will not sit more than the pile, etc.), the foundation design of the piled raft will provide a significant economy rather than the classical bored pile foundation design.

The authors believe that researches can be made in different soil types, soil conditions and pile design parameters and may contribute to the development of piled raft design and manufacturing criteria and the system used in the study was developed and proposed for future studies on cohesionless soils of different dense and cohesive soils with different consistency, in layered soils.

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