Study on the Load Sharing in Piled Raft Foundation

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Research Article

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Abstract

Piled-raft coefficient is becoming popular foundation system among the engineering for heavy structures. For the purpose of economical designing, understanding of the load sharing between piles and raft is very important. This load sharing characteristics depends upon the factors associated with piles, soil and their interaction. In this study series of model test were conducted on the piled-raft foundation to understand the impact of the different factors on the load sharing behavior of pile. The length of the pile, diameter of the pile, number of piles, configuration of the piles and relative density of the soil is considered as variable parameters in this study. The results obtained from the model tests have shown that the pile-raft coefficient increases with increase in the length, diameter and number of piles. While the piled-raft coefficient decrease with increase in the relative density. Also it was found that the piled-raft foundation with the arrangement of the piles nearer to the center of the pile have greater piled raft coefficient. A mathematical model based upon the regression analysis is also developed, which is found satisfactorily in the prediction of the piled-raft coefficient.

Introduction

Day by day rapid growth in infrastructural development is taking place all over the world. The demand for construction even over the poor soil condition is also in practice. The bearing capacity of poor soil is not sufficient to support the shallow foundation with heavy structure. For construction in poor soil either modification in soil property through different ground improvement techniques is adopted or proper foundation is adopted. Soil reinforcement (Yadav et al. 2014, Priyadarshee et al. 2019) utilization of admixtures likes; fly ash, tire chips, grass ash, etc. (Dhane et al 2015, Priyadarhsee et al. 2021) are different options for modification of soil properties. Similarly, it is general practice to adopt a pile or raft foundation in poor soil conditions. But nowadays the construction of high-rise buildings and other heavy structures is becoming popular. For such structures, piles and rafts alone are not feasible options. But the combination of these two foundations is effective for such structures. This new type of foundation system is known as the ‘Piled-Raft’ foundation. Pile, Raft, and soil are three components of the Pile-Raft foundation. A raft foundation can sustain heavy structure load effectively but settlement can exceed the tolerable value. The combined effect of pile and raft, satisfies the foundation’s bearing capacity and settlement aspects effectively (Kumar and Kumar 2018, Singh and Singh 2011). The load-carrying mechanism of the piled-raft foundation depends upon the raft, pile, and the surrounding soil. In piled-raft foundation load from the superstructure is partially carried by the pile and remains by raft (El-Mossallamy and Franke (1997).

The load-carrying capacity of the raft depends upon the resistance provided through the bending action of the raft. While in the case of pile it depends upon pile-soil interaction and interaction between piles. Many researchers like; Abdel-Fattah and Hemada (2016), Saharaejan et al. (2018), Mali and Singh(2018), Kumar and Choudhury (2018), Lee and Chung(2005), Russo G(1998), Horikoshi et al. (2003), Poulos (2001), etc. have done the numerical analysis and experimental studies to understand the mechanism of piled-raft foundation and to understand the factors affecting its load-carrying capacity. Researchers like;

Randolph (1994), Burland (1995), etc. have found that piles act as settlement reducers and raft transfer load to soil and piles. Piled-Raft foundation is also very effective to suppress the differential settlement. Piled-Raft foundation is more economical than pile alone in case of heavy load (Mali and Singh 2018). Nakai et al. (2004) have shown that a piled-raft foundation is also effective to suppress the impact of dynamic response.

Load sharing between the piles and raft is a very important characteristic. It governs the overall load-carrying capacity of the piled-raft foundation. The piled-raft coefficient indicates the part of the load shared by the piles to the total load on the piled-raft foundation. The expression of the Piled-Raft Coefficient ($\boldsymbol{\alpha}_{PR}$) can be written as:

$$\alpha_{PR} = \frac{P_{pile}}{P_{total}}$$

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Where P_{pile} and P_{total} are loads shared by pile and total load respectively. For designing the Piled-Raft foundation, understanding load sharing between the pile and raft is important. It depends upon the properties of the pile and the soil (Dharmrajan et al. 2011). The load shared by the pile in the piled-raft system increases with an increase in the area ratio of piled-raft. The Major portion of the pile load is predominantly transferred through the friction of the piles and very little is transferred through the bearing (Kumar 2020). Settlement influences the load shared by the pile. Also, it depends upon the drainage condition (Tran et al. 2012). The impact of different factors related to pile and soil over the load sharing behavior is not yet properly investigated. In the present study, the impact of soil properties and properties of the foundation on the load-sharing ratio is investigated. The impact of properties of foundations and soil through the model test on the load sharing ratio is investigated. Variables considered for investigations in the study were pile length, pile diameter, number of piles, the pattern of the pile and pile spacing, and relative density of soil. A mathematical model based upon the multivariable regression analysis is developed. Different researchers like; Priyadarshee et al. 2018, Verma et al. 2018, etc. have shown that in the case of complex geotechnical problems multivariable regression analysis can be very effective to develop a mathematical model.

Material Used

Sand

The sand used in this study was river sand obtained from the locally available market. Before utilization for testing purposes, the first sand was properly cleaned to remove the vegetation or organic materials present in the sand. Properties of the sand used are presented in Table 1. Specific gravity obtained was conducted as per ASTM D0854-06 and found 2.65. The particle size distribution curve is depicted in

Fig. 1. As per the USCS classification (ASTM D 2487-06), sand used in this study can be classified as poorly graded sand (SP).

Table 1
Details of the sand used in this study

Properties	**Value**
Specific Gravity	2.65
Coefficient of uniformity (C_u)	2.5
Coefficient of curvature (C_c)	0.22
Maximum Dry Density (kN/m^{33})	16.8
Minimum Dry Density (kN/m^3)	13.5
Angle of friction for D_r = 40%	28.5°
Angle of friction for D_r = 70%	31.6°

Planning of Experiment

In this study, four distinct sets of model tests were carried out on the piled-raft foundation. Length of pile (L), diameter of pile (D), number of piles (N), Pile configuration, and relative density of soil (Dr) are considered as variable parameters in this study. The parameter ‘L’ is varied as 200 mm, 400 mm, and 600 mm. ‘D’ is varied as 10 mm and 20 mm. The number of piles is varied as 1, 5, and 9. Four different patterns of piles below the raft are considered in this study. Two different relative densities, 40% and 70% of sand were considered for testing. The details of the series of the test are presented in Table 2. The model tests on the raft foundation alone are conducted in test series A1. In this series, relative density was only varied. Tests in series A2-A4 were conducted on the piled-raft foundation. In all these series relative densities, length of pile, and diameter of the pile were varied. Tests in Series A2 and A3 were conducted with the number of piles below raft one and five respectively. Tests in series A4 and A5 were conducted on the piled-raft foundation with the number of the pile nine having two different types of configurations of the pile. Figure 2 shows the different patterns used for the arrangement of the piles. Figure 2a shows the patterns P1, P2, P3, and P4 used for the testing in A2, A3, A4, and A5series respectively.

Table 2
Details of the series of the tests conducted in this study

Test series	Foundation	Variables of the test				
		Configuration of piles	Relative density (D_r) (%)	Length of pile (L) (mm)	Diameter of pile (D) (mm)	Number of Piles (N)
A1	Raft	-	40%, 70%	-	-	-
A2	Piled-Raft	C1	40%, 70%	200, 400, 600	10, 20	1
A3	Piled-Raft	C2	40%, 70%	200, 400, 600	10, 20	5
A4	Piled-Raft	C3, C4	40%, 70%	200, 400, 600	10, 20	9

Details of the Test Setup

All the model tests were conducted in a steel tank of size 1400 mm x 1400 mm x 1000 mm. The wall of the tank was of a 9 mm thick steel sheet supported by steel angles. A model of the raft and pile footing was prepared for testing. Raft footing was prepared by the two square steel plates of size 300 mm x 300 mm x 25 mm. Both plates were bolted together with nine columns of 16 mm diameter. Figure 3 shows the schematic diagram of the foundation used in this study. Threaded holes were provided at the bottom plate to attach the piles with different configurations. Model piles were prepared with mild steel. The lengths of the piles for testing were 200 mm, 400 mm, and 600 mm and diameter 10 mm, 15 mm, and 20 mm. The schematic diagram of the test setup is presented in Fig. 4. A reaction frame was also attached to the steel tank. This reaction frame is used to help the hydraulic jack for applying the load. The load was applied manually through a hydraulic Jack having a capacity of 240 kN. Measurement of settlement of foundation was done through the dial gauge.

Preparation of Test Bed

Before performing the test preparation of the testbed was done. Tests were conducted on the sand with a relative density of 40% and 70%. To prepare the sand bed with these two relative densities specific steps were adopted. The sand was placed in the tank in layers and compacted. First marking in the tank at every 10 cm was done to divide the total height of the tanks into intervals. Through this, the internal volume of the tank was divided into equal parts. After this, weight of sand was taken to achieve the required relative density. Then sand was placed in the tank with uniform density, the sand raining technique was used. In the sand raining technique density of the sand is controlled by the help of the height of the fall of sand particles. The calibration of the sand raining device was done through different trials. The process of filling the tank in layers was done in layers up to the top. The top surface was carefully leveled.

Test Procedure

After preparation of the testbed, the center of the tank was marked. The model foundation was placed in such a way that the center of the foundation should coincide with the center of the tank. Foundation was leveled with the help of the level tube. After the placement of the model foundation, a hydraulic jack was placed over the foundation attached with the reaction frame as shown in Fig. 2. For the test series, A1 only raft foundation was used. So, in case only a model raft was used over the sand bed. But for test series A2 to A4, the raft foundation was first attached with a pile through the threaded hole. After this piled-raft foundation was placed over the soil bed. To measure the settlement of the footing two dial gauges were used. These dial gauges were attached with footing at the diagonally opposite corners. The load was applied on a footing in equal intervals till the clear failure. In absence of a clear failure, the test was continued until the settlement of the foundation reached 40% of footing width.

Results and Discussion

As mentioned above, through model tests the impact of the pile length, pile diameter, the relative density of soil, number of piles, and pile configuration were investigated. The load sharing behavior of piled raft foundation is represented as 'Piled-Raft Coefficient' in this study as discussed earlier. The results obtained from the model tests were presented and discussed in the following sections.

Impact of pile length

The results showing the variation of the Piled-Raft coefficient with settlement for different pile lengths are presented in Fig. 5–7. Figure 5 shows the variation of the piled-raft coefficient for the raft with a single number of piles having a diameter of 10 mm, with varying lengths equal to 200 mm, 400 mm, and 600 mm (For Dr = 40%). It shows that Piled-Raft Coefficient decreases with the settlement of foundation up to the settlement level of about 20–30 mm. After this, no significant change in the coefficient can be observed and an asymptotic minimum value of piled raft coefficient is achieved. This shows that load shared by pile decreases with settlement and load shared by raft increases. In other terms, it can be said that at larger settlements the contribution of rafts increases. In piled-raft foundation, the first load gets transferred to the pile, because of this load sharing of the pile remains greater initially. With settlement contact of the raft with soil increases, this results in an increment of the load sharing by the raft. Cooke 1986, have also reported similar results. It can be further observed that the decrease in the piled-raft coefficient is greater for the smaller pile i.e. for the pile having a length equal to 20 mm. Decrease in the pile-raft coefficient with settlement gets reduced with an increase in the length of the pile. This shows that with the increase in the pile length load sharing by the raft decreases and pile increases. Pile contributes to load sharing by the end bearing resistance and surface friction. Due to an increase in the length of the pile, the magnitude of the surface friction gets increased. Because of this, the load shared by the pile increases with an increase in length.

In Fig. 6, a similar trend of the piled-raft coefficient can be observed for the foundation with the greater number of piles (N = 9) can be observed. For a single piled raft the minimum piled raft coefficient is increased three times from about 0.15 to 0.45 when the length of the pile changes from 200 mm to 600 mm. So, it can be noted that the impact of length of the pile on the load sharing behavior decreased when a greater number of piles were used under rafts. Similarly, in Fig. 7 for piled raft foundation with greater diameter, the minimum piled raft coefficient changes from about 0.35 to 0.45 when length changes from 200 mm to 600 mm. In this case, also the impact of pile length on the load sharing behavior of pile decreases when a pile of greater diameter was used. In both cases due to increment in the number of piles and diameter, surface friction and end bearing get increased. Due to this in both of the conditions (Fig. 6 and Fig. 7), greater load sharing by pile is shown even at lower length.

Impact of pile diameter

The impact of the diameter on the piled-raft coefficient can be understood by analyzing the results presented in Figs. 8 and 9. In Fig. 8 variation of piled-raft coefficient for the single piled-raft foundation with the relative density of soil equal to 40% is presented. It can be observed that the load shared by piles gets increased with increase in the diameter of the pile. Piled-raft coefficient corresponding to 20 mm settlement changes from 0.15 to 0.39 when diameter increases from 10 mm to 20 mm in the case when pile length is 200 mm as the diameter increases, the surface area of the pile increases, resulting in a heightened mobilization of friction on the surface. This, in turn, leads to an increased load borne by the pile. It can be further observed that for piled-raft foundations with pile length 600 mm, the Coefficient changes from 0.5 to 0.65 when diameter increases from 10 mm to 20 mm. This trend shows that the impact of diameter on load shared by piles decreases when the length of piles increases.

In Fig. 9 variation of the piled-raft coefficient is shown with the number of piles below the raft being equal to nine. At 20 mm settlement, the value of the piled-raft coefficient varies from 0.78 to 0.92 when the length of the piles was changed from 200 mm to 600 mm and the diameter of piles was changed from 10 mm to 20 mm. By comparing this result with the result of the pile-raft foundation with a single pile, it can be concluded that with greater numbers of piles the impact of diameter gets decreased. With greater numbers of piles end bearing and surface friction increases even for shorter piles (L = 200 mm). Because of this reason, the difference between the piled-sharing coefficient of piled-raft foundation with shorter and longer single piles is greater than the piled-raft foundation with the greater number of piles.

Impact of relative density of soil

The variation of the piled-raft coefficient of piled-raft foundation with varying lengths supported by sand with the relative density of 40% and 70% are depicted in Fig. 10. The piled-raft coefficient is greater for the soil having a relative density is 40% than the soil with a relative density of 70%. This indicates that the increase in the relative density load shared by the raft increases for shorter (L = 200 mm) and longer piles (L = 600 mm). Similar types of variation were found when piles with larger diameters were used. In the case of dense soil, the significant contact gets mobilized even at the lower settlement level. Lee et al. (2015) have also shown similar behavior. During the test at lower relative density i.e. at Dr = 40%, no heaving was observed. But at higher relative density heaving in the surrounding soil was observed. A similar observation of heaving was reported by Roy and Chattopadhyay (2017).

Impact of number of piles and configuration of piles

In Fig. 11 the variation of piled-raft coefficient for different numbers of piles is presented. It shows that piled-raft foundations with a single pile have a piled-raft coefficient of around 0.35 at a settlement level of 20 mm. The case, when the number of piles increased to five and nine shows the piled raft coefficient around 0.7 and 0.8 at 20 mm settlement level. This indicates that the load shared by piles increases with an increase in the number of piles supporting the raft. Due to an increase in the number of piles surface friction increases, because of this load shared by pile increases.

Two types of configurations were used in this study for experimentation to understand the impact of configuration on the load sharing behavior of pile and raft. The details of the configuration are discussed earlier (Fig. 2 and Table 2). The impact of configuration on the piled-raft coefficient is presented in Fig. 12. It can be observed that the piled-raft coefficient in the case of configuration C3 is greater than configuration C4. It means load sharing by pile in the case of C3 is greater than C4. Load sharing by pile increases when piles are arranged nearer to the center of the piled-raft foundation. In configuration C3 the arrangement of piles is nearer to the center, while in configuration C4 the piles are distributed over the raft area. Because of this C3 performs better than C4. Similar behavior was reported by Cao et al. 2004.

Mathematical model

A mathematical model to predict the piled-raft coefficient is developed through multivariable linear regression analysis (MLRA) in this study. The equation was developed by the help of Microsoft excel. In MLRA set of independent and dependent variable were selected. Piled-raft coefficient was taken as dependent variable. Settlement of piled-raft foundation, number of piles, relative density, and diameter of pile, length of the pile and area distribution of pile under raft are considered as independent variable in analysis. A general expression for the developed model can be written as follows.

$$Y = A_o + A_1 X_1 + \ldots\ldots\ldots\ldots\ldots\cdots + A_n X_n + \epsilon$$

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Where, Y is dependent variable; A_i is Coefficient need to be find out and X_i is independent variable. ϵ indicates error. Different forms of models were considered during the analysis. Finalization of the model was done by trial and error method. The form of model with best prediction capability was finally selected. Data analysis tool of excel was used for trial and error process of MLRA. The prediction model of piled-raft coefficient obtained from the analysis can be presented as:

$$\alpha_{PR} = S^{0.25} * Log\left(N_p\right) * \frac{1}{D_r} * D * Log\left(L\right) * A_r$$

3

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Here, α_{PR} is piled-raft coefficient, S is settlement of foundation, N_p is number of piles, D_r is relative density, D is diameter of piles, L is length of piles and Ar is area ratio of piles. From the analysis coefficient of determination, R2 came out to be 0.82. Figure 13 shows the comparison of observed and predicted value of piled-raft coefficient with settlement. It can be observed that the model can predict well. Figure 14 shows the scattered plot of the predicted and measured value of the piled-raft coefficient. It shows that the scattering is not much. It also shows that model is predicting the piled-raft coefficient in good manner.

Conclusions

In this study laboratory model test were conducted to understand the pile load sharing behavior of piled-raft foundation. The results of the model tests were presented in terms of piled-raft coefficient. Based on the analysis of the results, several key conclusions have been drawn.

- Load sharing by the pile increases with increase in the pile length due to increment in the surface friction. The increment in the piled-raft coefficient taken place up to three times. The rate of increase shows a decreasing tendency with the rise in both the number and diameter of the piles.
- The piled-raft coefficient rises as the pile diameter increases, attributed to the increase in surface friction and end bearing. This behavior was found more dominant in case of shorter pile and smaller number of piles.
- The piled-raft coefficient declines with an increase in the relative density of the soil, signifying that the load distributed by the raft intensifies as the soil's relative density increases
- The number of piles significantly affects the pile load carrying capacity. It increases with an increase in the number of piles, as the resistance in terms of surface friction and end resistance intensifies. As a result, the piled-raft coefficient increases more than twice.
- Piled-raft coefficient increases when the arrangement of pile is near to the center of the pile i.e. configuration C3 in this study.
- The mathematical model developed through the MLRA can predict the piled-raft coefficient in satisfactory manner. The R^2 vale of the equation was found around 0.82.

Declarations

Declaration of Competing Interest

We know of no conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome. As Corresponding Author, I confirm that the manuscript has been read and approved for submission by all the named authors.

CRediT authorship contribution statement

Akash Priyadarshee: Writing original draft, Methodology, Conceptualization, and supervision Vikas Kumar: Methodology, Software, and Formal analysis

Kuldeep Sharma: Manuscript presentation, analysis, writing, review and editing

Ashish Kumar: Validation of results and Investigation

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Figures

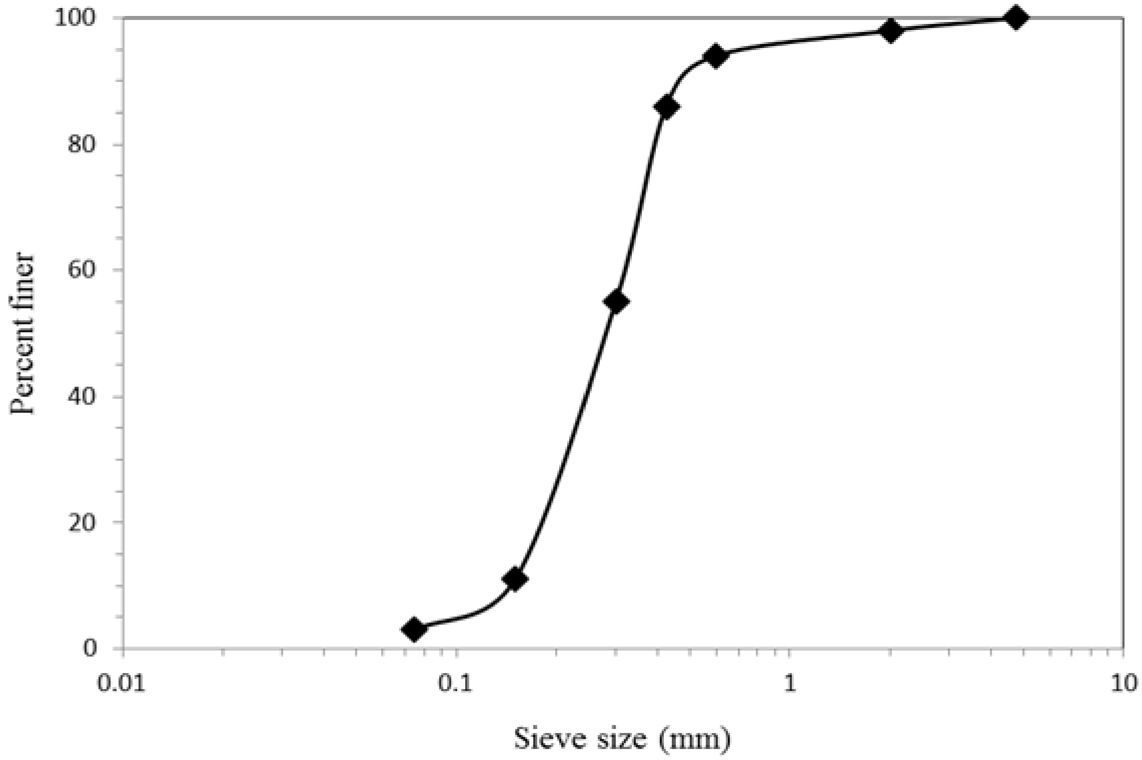
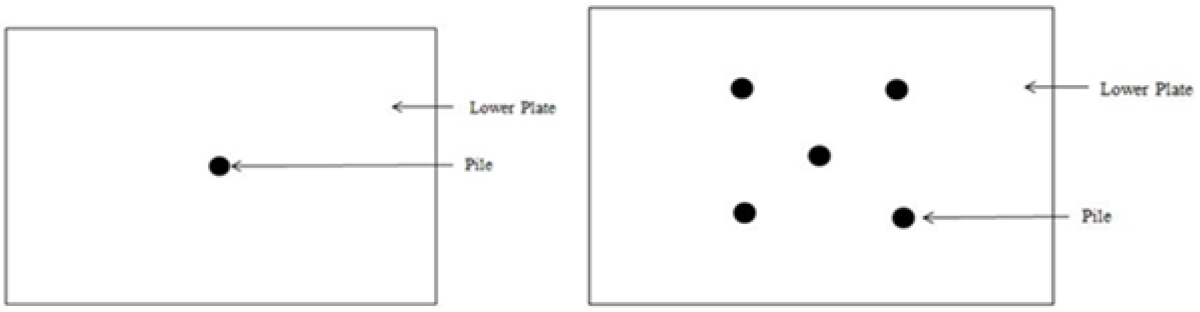


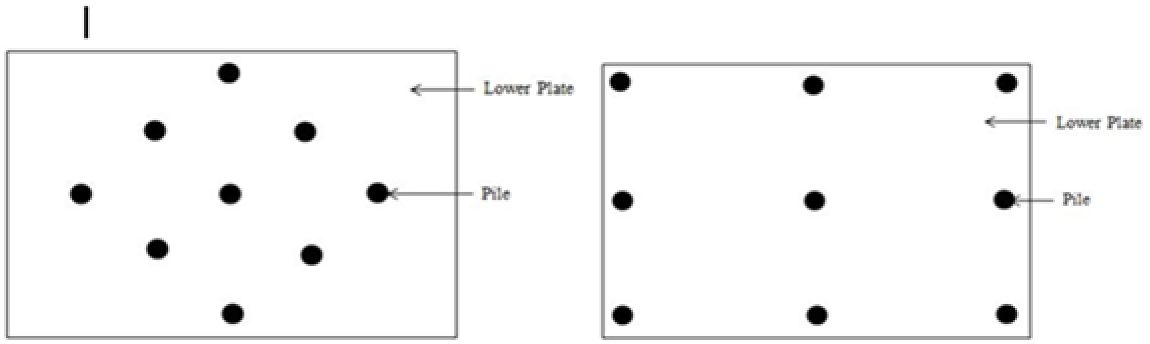
Figure 1

Grain size distribution of soil



a. Single piled-Raft (C1)

b. Piled-Raft with five piles (C2)



c. Piled-Raft with nine piles (C3)

d. Piled-Raft with nine piles (C4)

Figure 2

Patterns of pile considered in the study

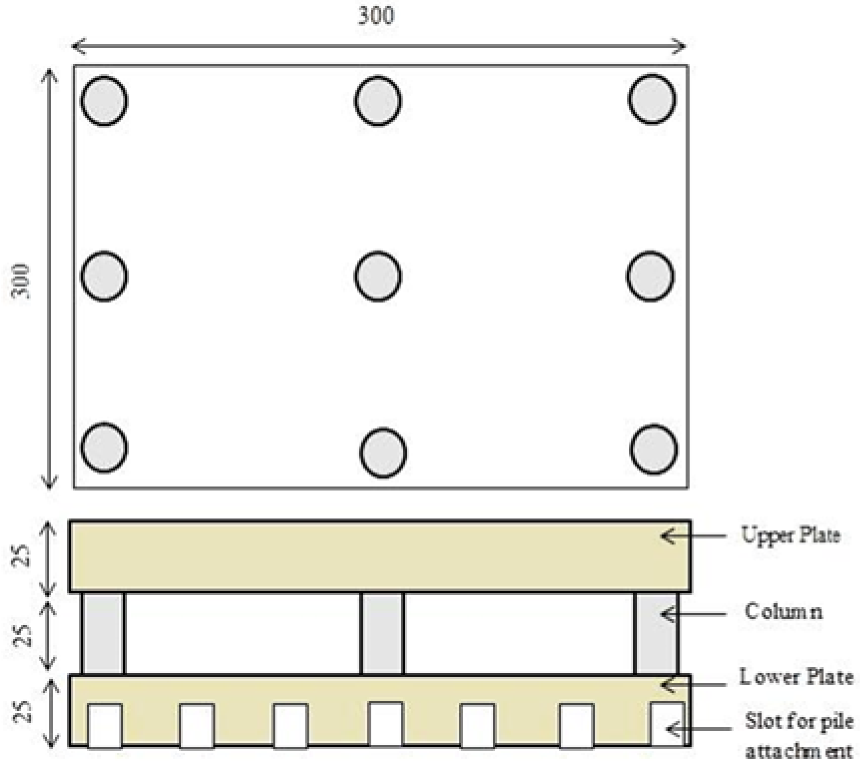


Figure 3

Schematic diagram of raft foundation (all dimensions are in mm)

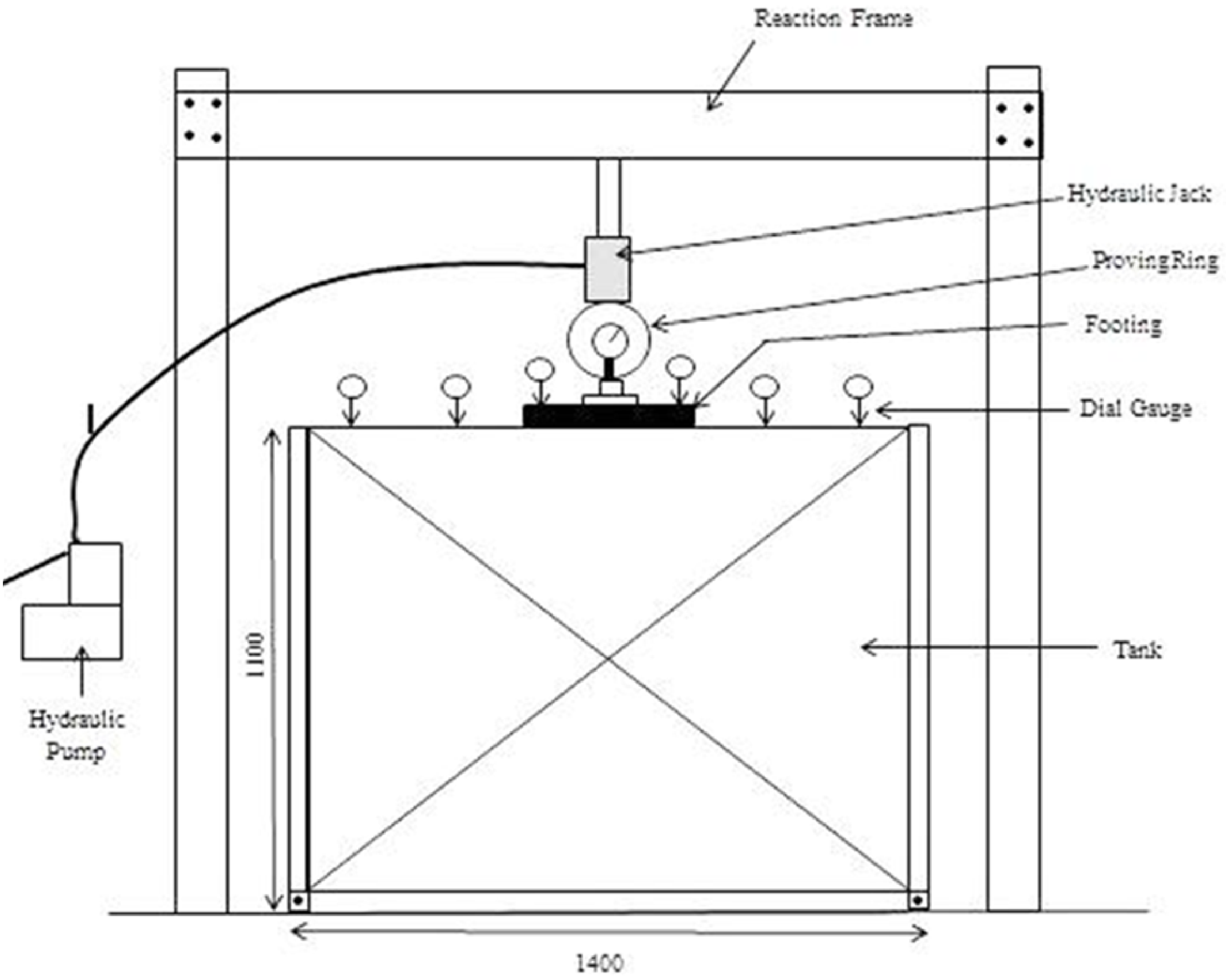


Figure 4

Schematic Diagram of test setup (all dimensions are in mm)

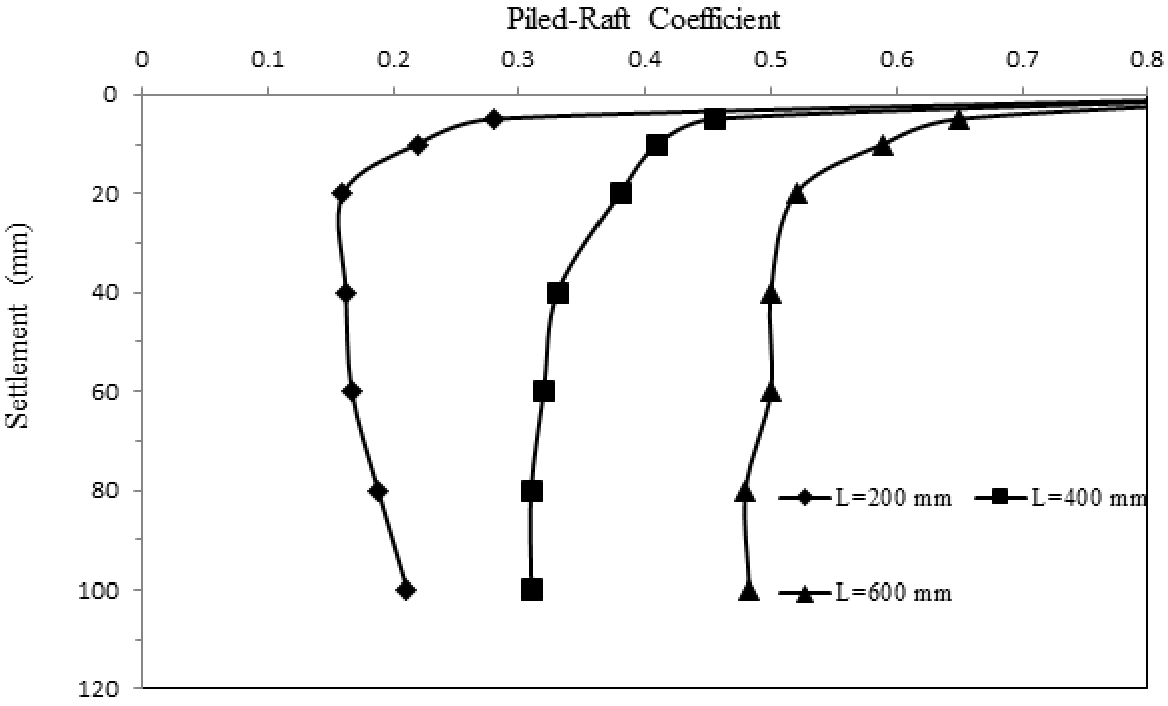


Figure 5

Variation of Piled-Raft Coefficient with settlement for different pile length (D = 10 mm, N= 1, D_r = 40%)

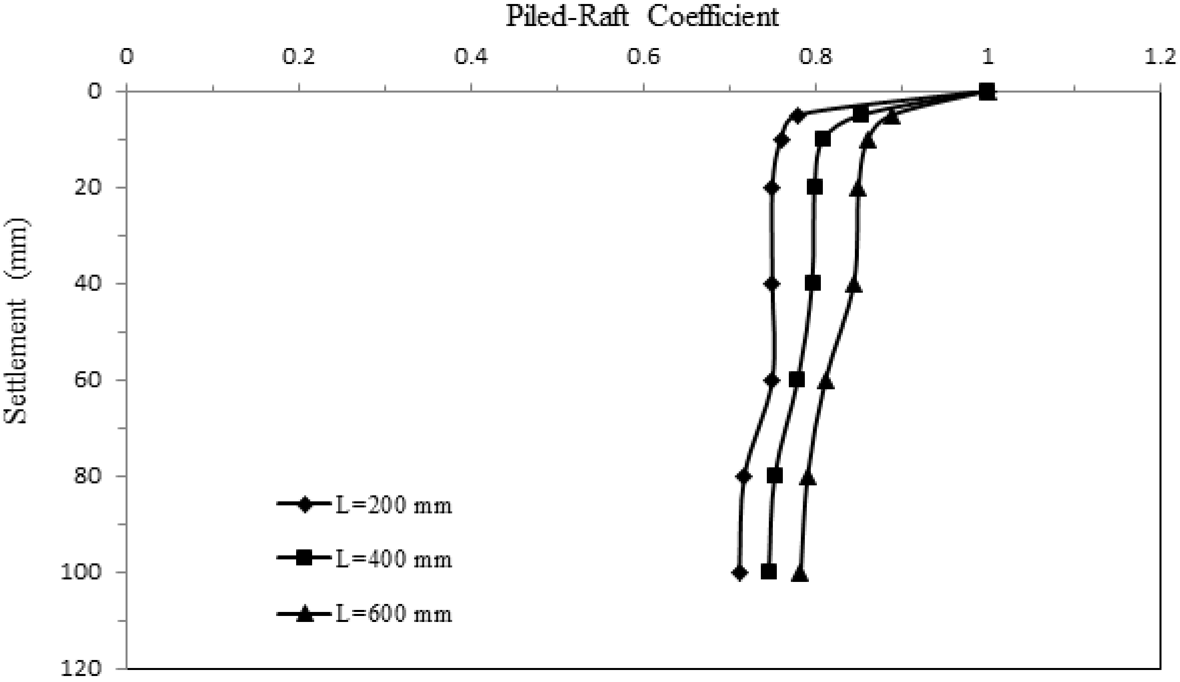


Figure 6

Variation of Piled-Raft Coefficient with settlement for different pile length (D = 10 mm, N= 9, D_r = 40%)

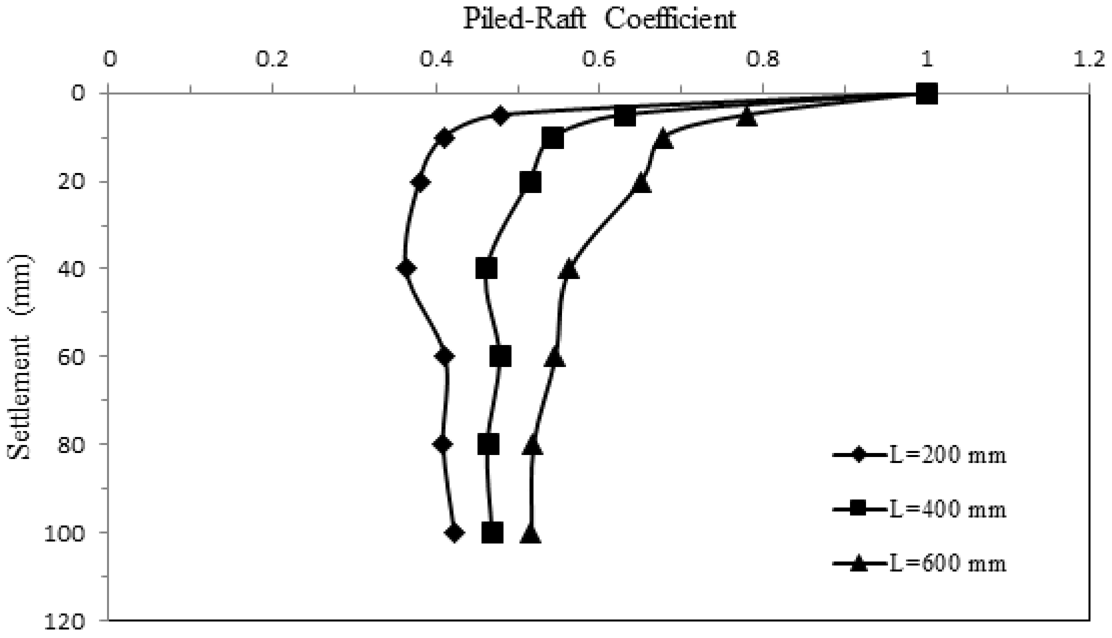


Figure 7

Variation of Piled-Raft Coefficient with settlement for different pile length (D = 20 mm, N= 1, D_r = 40%)

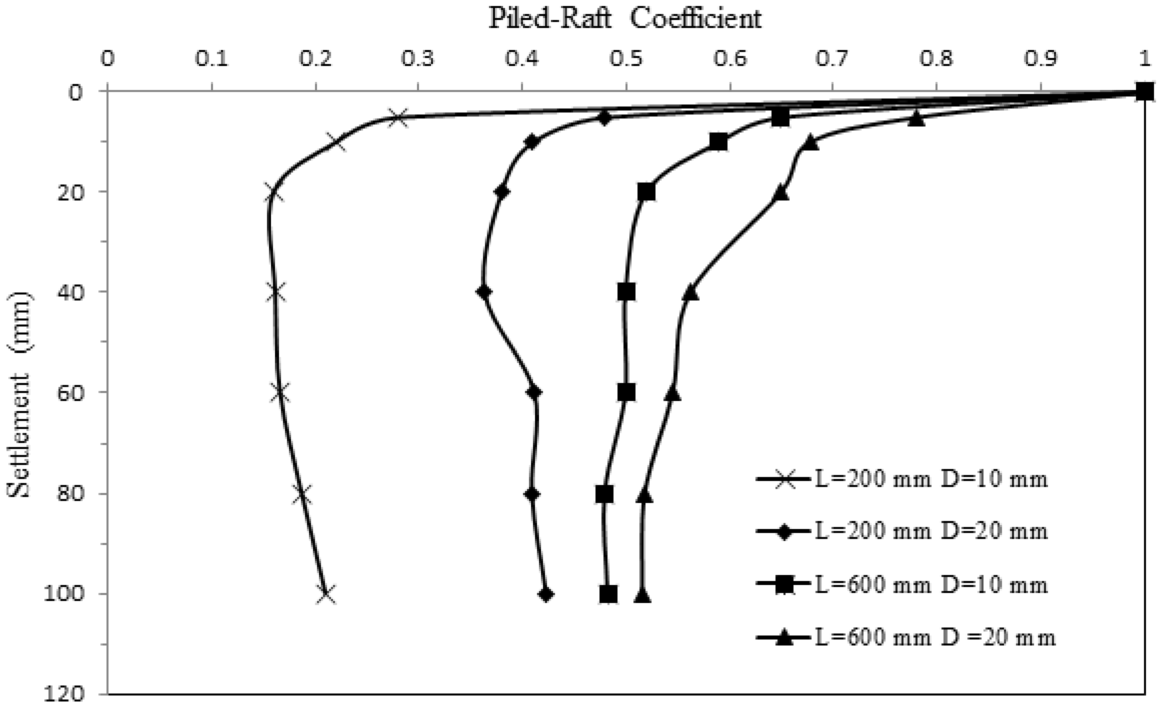


Figure 8

Variation of Piled-Raft Coefficient with settlement for different pile length and diameter (N= 1, D_r = 40%)

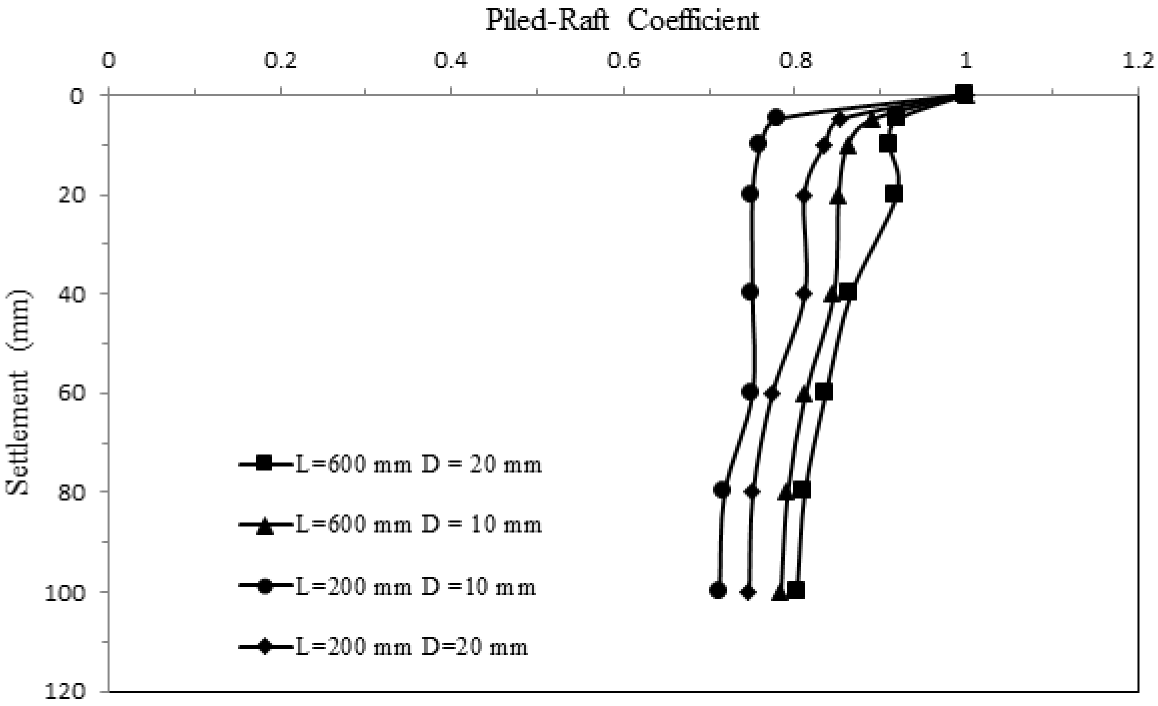


Figure 9

Variation of Piled-Raft Coefficient with settlement for different pile length and diameter (N= 9, D_r = 40%)

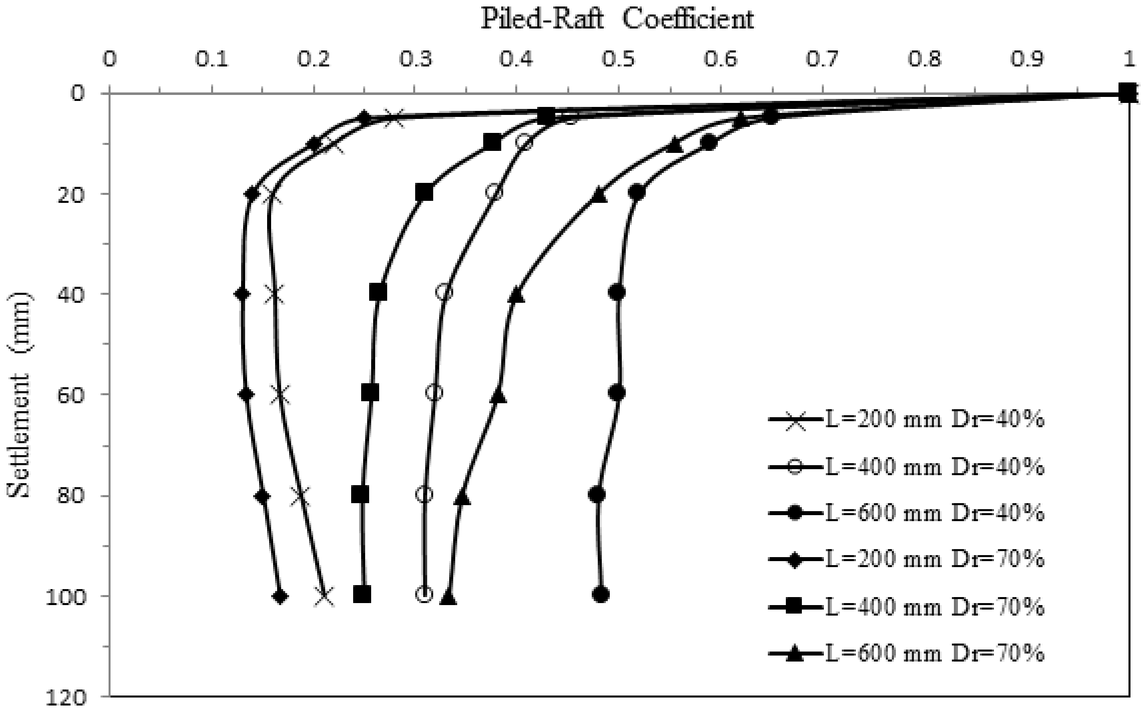


Figure 10

Variation of Piled-Raft Coefficient with settlement for different pile length and relative density of soil (N= 9)

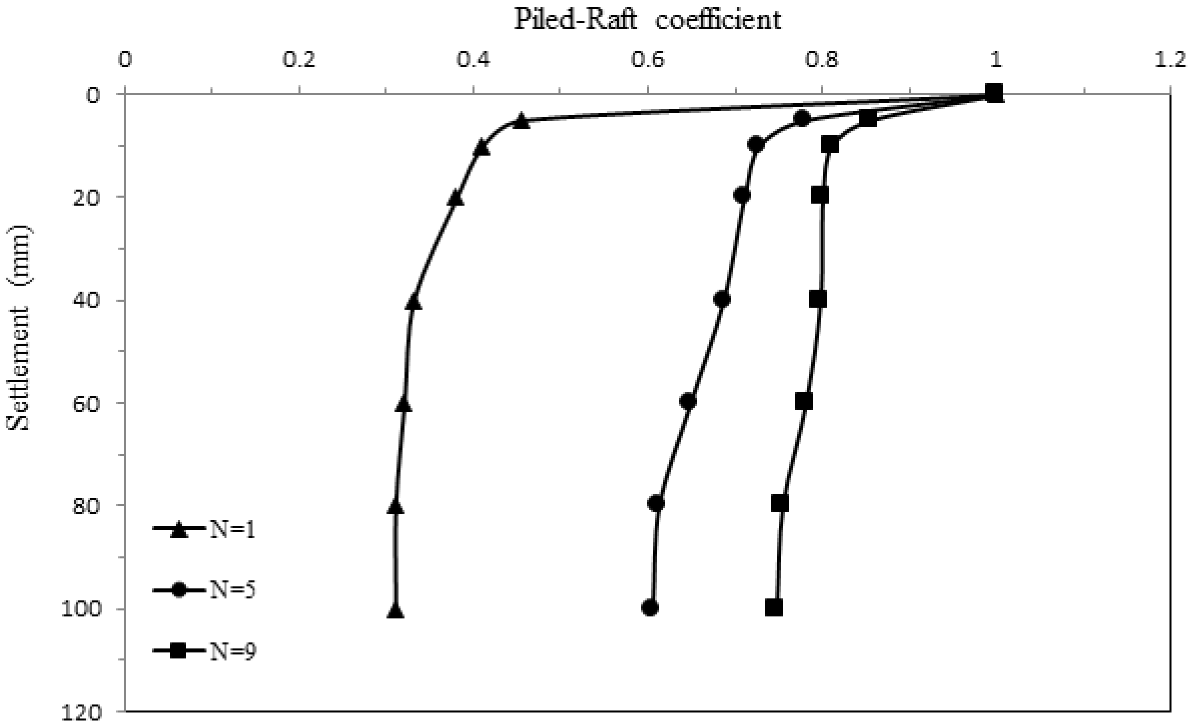


Figure 11

Variation of Piled-Raft Coefficient with settlement for different numbers of pile (L = 400 mm, D =10 mm, Dr = 40%)

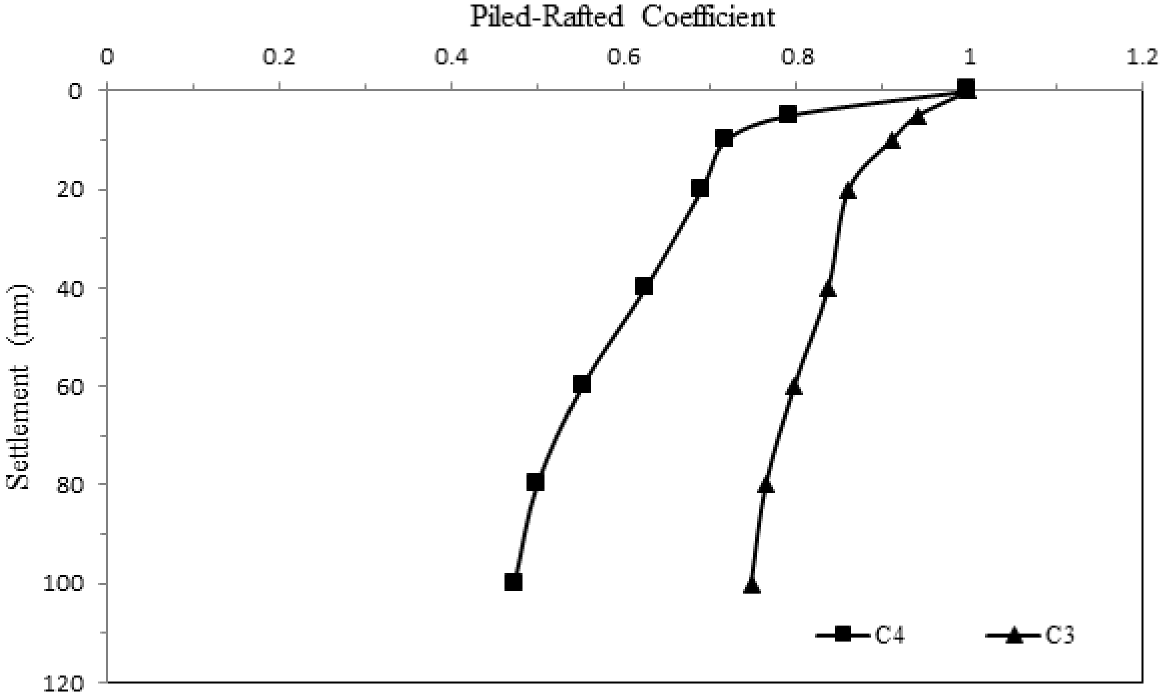


Figure 12

Variation of Piled-Raft Coefficient with settlement for different numbers of pile (L = 600 mm, D =20 mm, N = 9, Dr = 40%)

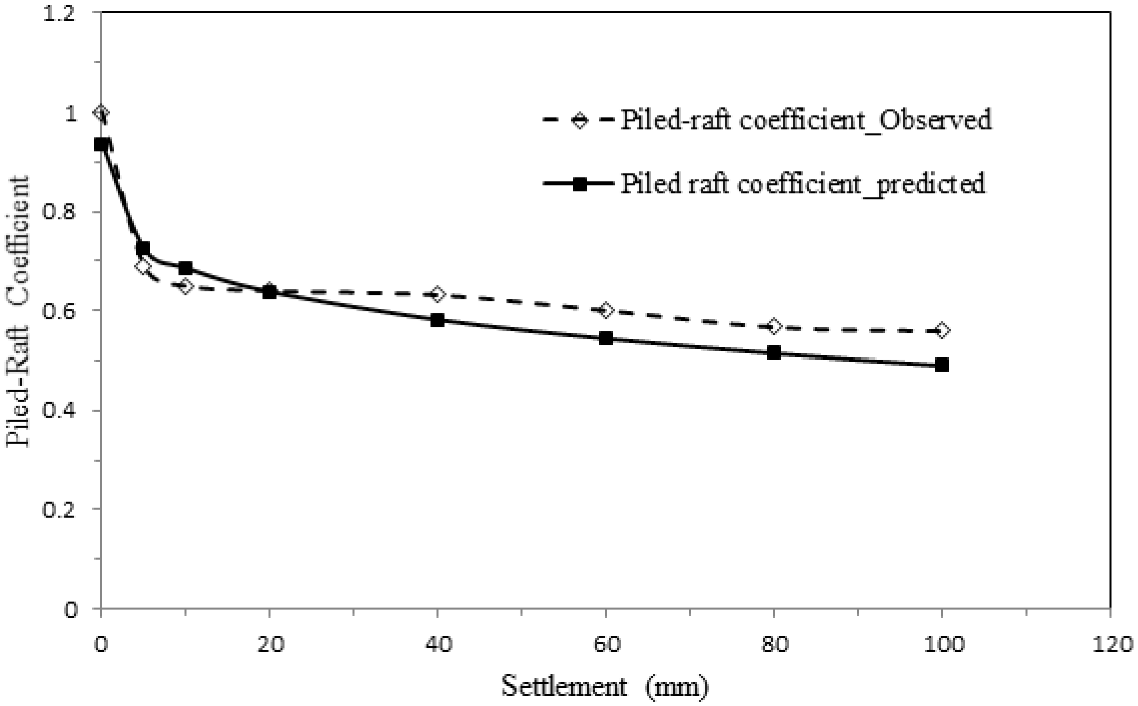


Figure 13

Comparison of observed and predicted value of piled-raft coefficient with settlement

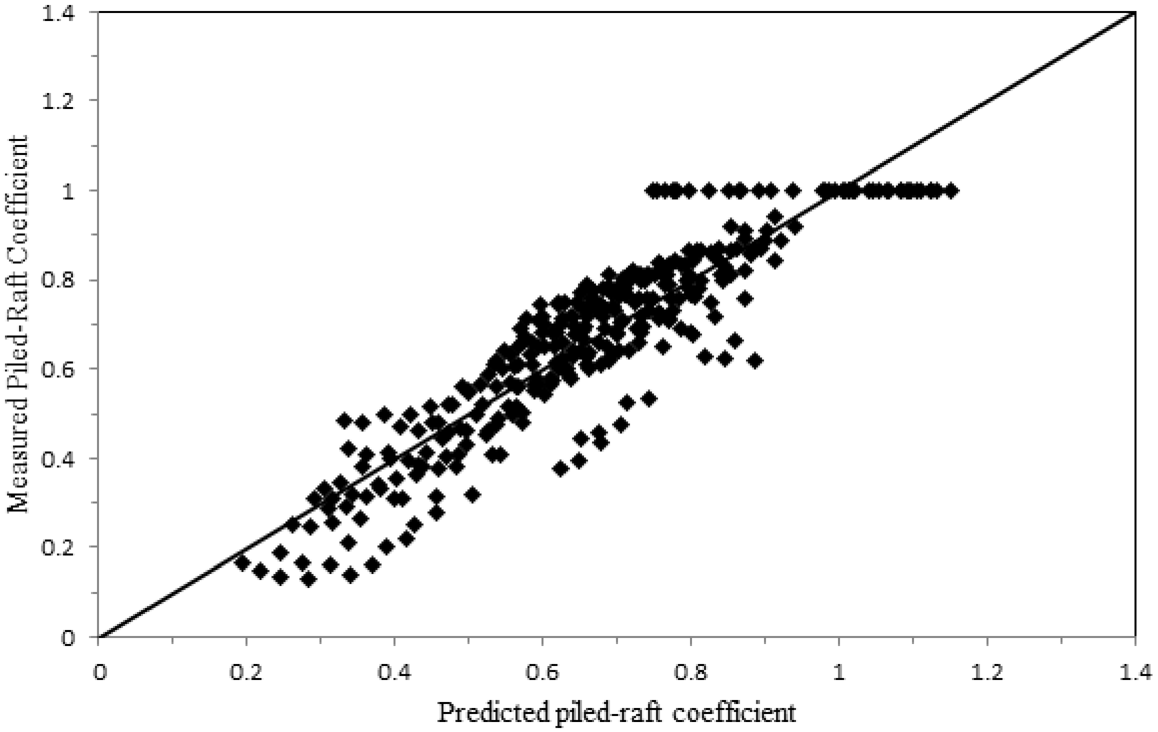


Figure 14

Scatter plot of measured and predicted piled-raft coefficient