

Experimental Analysis and Validation Techniques of Piled-Raft Foundation System



R. Vignesh and M. Muttharam

Abstract Due to urbanization, the high-rise building has become a common and growing phenomenon in all over the world. If a raft foundation does not meet the design requirement by itself, then the addition of a pile (piled-raft foundation system) may be possible with the raft. In this paper, the design of piled-raft foundation system has been carried out as the approximate assessment of the required number of piles, asses where piles may be required and refine piling requirements on their locations. The design strategies for the design of piles have been shown, and it has been demonstrated with the effective and efficient foundation can be designed by utilizing the significant capacity of pile. These strategies improve both the ultimate load capacity of the pile and settlement or differential settlement of the raft. In this analysis using of pile as settlement reducer and the condition in which the approach may be successful is derived. The characteristic behavior of the piled-raft foundation system has been considered in the effect of number of piles, nature of loading, raft thickness, and effect of load level on settlement. The behavior of piled raft is determined by complex soil-structure interaction effects, and understanding of these effects is useful for the reliable design of such foundations. The study brings out the effects of number of piles, pile length, raft thickness, and pile configurations; along with the soil-structure interaction by mean of the numerical modeling validation is compared with the measured and computed results.

Keywords Pile-Raft foundation · Pile configuration · Raft thickness · Numerical modeling on pile raft · And Load-settlement curve

R. Vignesh (✉) · M. Muttharam
Department of Civil Engineering, CEG, Guindy-Anna University, Chennai, Tamil Nadu, India
e-mail: vignesh.jec@gmail.com

M. Muttharam
e-mail: muttharam@annauniv.edu; muttharam@gmail.com

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1 Introduction

The performance of any foundation is to transmit the load to the soil so as to provide safety, reliability, and serviceability to the structure. Current practice is to provide a deep foundation, when the shallow foundation isn't sufficient to provide adequate safety and reliability. However, a combination of the shallow and deep foundation can be a price effective design approach. The pile-raft foundation is a grouping of a deep pile group and raft foundation, which has increased in very recent years.

It is evident from the available literature, the piled-raft foundation was constructed about fifty years past and also the attempt to capture its behavior was started within the early eighties, that has intense within the previous few years, however no appropriate design strategy has been formulated. This is often attributable to the complex interactions among the raft, pile, and soil, which is three dimensional in nature and cannot be captured by any analytical technique so far developed. With the advancement of engineering and numerical code, the researchers are currently attempting to model the complicated behavior of pile-raft foundation.

2 Literature

2.1 *Experimental Review*

According to Burland et al. (1977), the standard design methodology for the piled-raft foundation substructure suggests that the pile bears an interconnected load with the raft's input becoming ignored. This method is actually too restrictive as the product of the raft is in direct contact with the surface and therefore bears a significant portion of the load. In the case study of the piled-raft method in clay, Shukla et al. (2013) indicated that the building load, which causes stress within the pre-consolidated clay structure, is borne by piles in creeping loading and therefore the remaining load is held by the raft.

Horikoshi et al. (2003) reported that the settlement-reducing piled strategy is built to mistreat excess piled-raft systems.

Dauids (2008) shown that the various superstructures are distributed among raft and piles, carrying piles around 50–80% of the total load.

To examine the feasibility of the techniques endorsed by the elastic continuum principle for estimation of conformity with piled-foundation subjected to vertical loading.

Wiesner and Brown (1980) worked on raft foundation models in consolidated clay. Measured settlements, strains, and bending moments within the raft have been identified during this research. They suggested that the predictions of the hypothesis based upon the fact that soil can be a linearly elastic continuum would provide suitable predictions of piled-raft foundation behavior.

Cooke (1986) presented model test results on the foundation of piled raft. He contrasted with that of an unpiled raft and free-standing piled group with the behavior of a piled-raft foundation. Cooke (1986) noted that the distribution of loads between piles in a piled raft is reliant on the pile quantity and spacing. He noticed that the middle of the foundation of the raft is greater than that of the raft's sides.

Horikoshi and Randolph (1996) carried out centrifugal experiments on piled-raft foundations models to research the settling of piled-raft foundations on clay soil. They noticed that sometimes a small group of piles might significantly reduce the proportional raft settlement. This study suggested that the bearing efficiency of the system could be significantly increased by a small cap on a single pile.

Horikoshi et al. (2003) carried out centrifugal testing of piled-raft foundation models on sandy soil subject to vertically and horizontally loading. They evaluated the impact on the actions of piled-raft foundations of the rigidity of the pile head relation. These results showed that whenever the cap is in contact with soil the pile's strength increases due to the improvement in the confining stress around the pile. Horikoshi et al. (2003) reported that the piled-raft ultimate horizontal ability is greater than the unpiled-raft foundation.

Lee and Chung (2005) conducted tests on piled-raft foundations models to analyze the effect of pile installation and interaction between the raft and also the piles on the behavior of piled-raft system. They found that cap-soil-pile interaction impact is influenced by pile location and spacing. They determined that pile installation may compensate the decrease in cap capacity due to cap-soil-pile interaction effect.

Fioravante et al. (2008) conferred results of extensive centrifuge tests modeling of a rigid circular piled-raft on sand soil to assist in finding out the role of piles as settlement reducers and to quantify the load sharing between the raft and piles. They determined that raft settlement decreases as the number of piles will increase. The results showed that displacement piles are more effective in reducing the settlement of the raft than the non-displacement piles. Fioravante et al. (2008) found that the contribution of the raft starts when the piles approach the ultimate capability. They also determined that piled-raft stiffness increased with the increase within the number of piles supporting the raft.

2.2 Finite Element Method Review

One of the effective tools to evaluate piled rafts is the finite element method. The dissertation is required for both the structure and the soil foundations. The Hooper (1973), which used an axis symmetrical model of eight noded isoperimetric components, provided an early example of the study of a piled raft (The Hyde Park Barracks). In comparison, the relative rigidity of the pile group was approximated to the degree that the condensed rows of piles were based on a continuous annulus with a total rigidity equal to the overall rigidity of the piles.

Chow and Teh (1991) had presented a numerical method for examining the behavior, in a non-homogeneous soil of the static piled raft.

Liu and Novak (1991) used the approach for finite elements to analyze the output of a single-center pile raft.

The study of a circular piled raft made in Cairns was given by Wiesner (1980). The raft was viewed as a thin elastic plate and based on plate bending finite elements.

Clancy and Randolph (1993) stated a piled-raft foundation strategy for tall buildings.

Smith and Wang (1998) suggested the use of iterative methods using a finite element approach to analyze the behavior of a non-uniformly loaded piled raft.

Prakoso and Kulhawy (2001) studied the foundation of the piled raft through the use of finite element model linear elastic and non-linear strain planes, which included the evaluation of a piled three-dimensional raft in the form of a two-dimensional raft.

In the case of a rigid circular piled-raft models in over-consolidated clay Fioravante (2011) have conducted centrifugal experiments, which have shown that the load allocation under a rigid piled raft is not compatible within the working load range which is consistent with a linear/elastic analysis.

2.3 Theoretical Studies

Ta and Small (1996) developed a method of analysis for piled-raft foundations on layered soil which takes into account the interaction among the raft, piles, and soil by using the finite layer method for the analysis of the soil and the finite element method for the analysis of the raft to avoid the cost of a rigorous three-dimensional analysis. They claimed that their method can be used for the analysis of a raft with any geometry or stiffness because the raft is considered as a thin elastic plate and can be used for rafts on isotropic or cross-anisotropic horizontally layered soil with piles randomly distributed beneath the raft. They also found that the relative thickness and stiffness of soil layers can also influence the load distribution along the shafts of piles in piled-raft foundations. Some simplifications are needed to avoid the excessive computing time and other limitations when developing analysis methods of large piled-raft foundations.

Ta and Small (1997) proposed an approximate numerical method of analysis to estimate the influence factors for piled-raft foundations that can reduce computer run time. According to a numerical analysis, Ta and Small (1997) observed that the portion of the load carried by the piles increases and that by the raft decreases as the bearing stratum becomes stiffer.

Russo (1998) proposed an approximate numerical method (hybrid model) for the analysis of piled rafts which accounts for the non-linearity of the unilateral contact at the raft-soil interface and the non-linear load-settlement relationship. Russo (1998) stated that because piles are used as settlement reducers and their ultimate load capacity may be reached, non-linear analysis should be considered for piled-rafts analysis. Russo (1998) reported that most of the numerical analysis efforts have considered solving either simple axial-symmetric or plane strain problems to reduce the huge computational efforts of analyzing large piled foundations. He claimed that

introducing some approximations to the numerical methods can assist in solving such a problem.

Mendonca and de Paiva (2000) introduced a boundary element method for analyzing piled-raft foundations which accounts for the interaction among the raft, the piles, and the soil. The method developed by Mendonca and de Paiva (2000) can be used for analyzing piled-raft foundations with rigid or flexible caps. In the analysis method proposed by Mendonca and de Paiva (2000) each pile in the group, the soil, and the raft were modeled as a single element, an elastic linear homogeneous half space, and a thin plate, respectively.

Prakoso and Kulhawy (2001) used simplified linear elastic and non-linear (elastic-plastic) 2-D plane strain finite element models to predict the performance of piled-raft foundations and proposed a displacement-based design procedure for piled rafts based on this analysis. They used PLAXIS (software based on finite element method) in their study and they claimed that a 2-D plane strain analysis could yield satisfactory results for analyzing the piled-raft system without excessive time for modeling and computing.

Poulos (2001) introduced a simplified analysis method for piled-raft foundations as a tool for preliminary design of such foundations. Other solutions for the limitations of numerical modeling techniques were suggested by using hybrid models. Small and Zhang (2002) presented a method of analysis for piled-raft foundations on layered soil subjected to vertical loads, lateral loads, and moments by using the finite layer theory to model the layered soil and the finite element theory to model the piles and raft. El-Mossallamy (2002) employed a mixed technique of the finite element and boundary element methods to develop a numerical model which accounts for the raft stiffness, the non-linear behavior of the piles, and the slip along the pile shafts for analyzing piled-raft foundations.

Mendonca and de Paiva (2003) presented a static analysis of piled-raft foundations using a combination of finite element and boundary element methods in which interaction between soil, flexible raft, and piles was considered. Kitiyodom and Matsumoto (2003) developed a simple analytical method by using a hybrid model for piled-raft foundations embedded in non-homogenous soil considering the effect of vertical and lateral loads.

Reul (2004) conducted a rigorous numerical study using the three-dimensional finite element analysis to study the behavior of piled-raft foundations in over-consolidated clay. He used the finite element method to model the soil and foundation to obtain detailed information about soil-structure interaction. Reul (2004) stated that it is important to understand the interaction among the piles, the raft, and the soil which controls the behavior of piled-raft foundations. Reul (2004) observed that pile-raft interaction leads to an increase in the skin friction with an increase of the load or increase of the settlement.

Wong and Poulos (2005) presented a simplified method to estimate the pile-to-pile interaction factor between two dissimilar piles based on a parametric study which was conducted using the computer program GEPAN developed by Xu and Poulos (2000). The computer program GEPAN is based on the boundary element analysis. They claimed that this method can be beneficial for predicting the settlement

behavior of pile groups or piled-raft foundations with dissimilar piles. Garcia et al. (2005) studied piled-raft foundations supported by clay soil using a visco-hypoplastic constitutive law in a three-dimensional finite element analysis. Vasquez et al. (2006) used three-dimensional non-linear finite element analysis to predict the response of piled-raft foundations taking into account the non-linear behavior of the soil while linear elastic behavior was assumed for the raft and piles.

3 Methods of Analysis

Several methods for deciding the relationship of the piled-raft combination were available. It includes simplified methods of estimation, computer-based approaches, and more rigorous computer-based processes. The simplified methods of estimation are analytical methods with various simplifications, particularly with regard to the soil profile and the load. The raft is designed like a strip and the soil and piles are based on springs of varying stiffness in approximate computer methods. Computer-based, more rigorous approaches comprise different model methods such as boundary element approach, boundary elements combined with finite element analysis, a single strain problem finite element analysis, or an axisymmetrical issue. The main focus of this work is computational modeling of PLAXIS 3D applications relative to studies.

4 Soil Properties

An experimental testing program was conducted to determine the behavior of piled-raft foundation installed in sand. Sieve analysis for the sand soil was carried out. Physical properties, shear strength, and compressibility parameters are shown in Table 1.

5 Tank Description

In this analysis, on a plain raft and piled raft in identical homogeneous loose sand conditions, a small laboratory experiment was carried out. The sand characteristics used on the foundation medium were studied and recorded.

A square tank scale of 1000 mm \times 1000 mm \times 1000 mm was carried out for the laboratory prototype modeling as shown in the arrangement of the tank in Fig. 1. The piles used for this analysis were 1 \times 1, 2 \times 2, and 3 \times 3 pile setups. Studies have shown that settlement is substantially reduced relative to that of the plain raft foundation by the piled-raft foundation in sand.

Table 1 Soil properties

Sl. no.	Example description	Values
1.	Specific gravity	2.63
2.	Coarse sand	4.3
3.	Medium sand	60.7
4.	Fine sand	21.7
5.	Uniformity co-efficient	2.53
6.	Co-efficient of curvature	0.73
7.	Classification of sand	Poorly graded sand
8.	Maximum dry unit weight	17.59 kN/m ³
9.	Minimum dry unit weight	15.40 kN/m ³
10.	Maximum void ratio	0.71
11.	Minimum void ratio	0.46
12.	Unit weight	15.71 kN/m ³
13.	Relative density	26.63%
14.	Angle of internal friction	30°
15.	Module of elasticity	10.22 MN/m ²

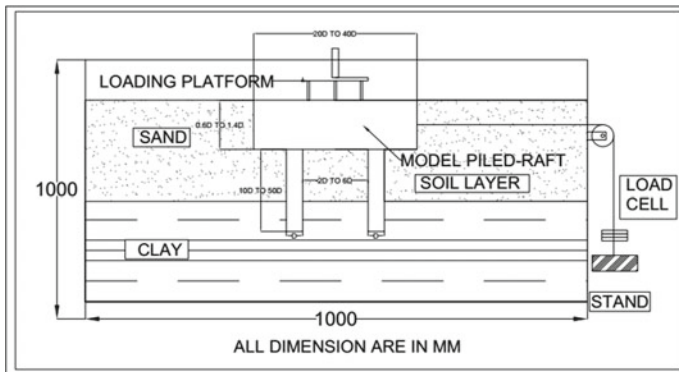


Fig. 1 Schematic diagram of the tank

6 Parametric Study

Parametric study is depending on the load sharing and the load-settlement relationships are the most important aspects in designing piled-raft foundations. El-Mossallamy et al. (2009) stated that the main criterion, which governs the design of piled-raft foundations, concerns the load sharing between the raft and piles and the effect of additional pile support on the foundation settlement. In this study, the effect of some parameters on the load-settlement relationship and the load sharing

between the raft and the piles was investigated. The aim of this study is to identify the very important parameters which affect the performance of piled-raft foundations and then to develop a model to predict the settlement and the load sharing between the raft and the soil.

Identifying the important parameters which significantly affect the performance of piled-raft foundations can assist in optimizing the design of such foundations. Therefore, studying the effect of different design parameters on the behavior of piled-raft foundations was carried out. This study focused on the effect of some parameters on the load-settlement relationship and the load sharing between the raft and piles of piled-raft foundations. The effect of the selected parameters on the load-settlement relationship will be investigated at small and large settlements. The tests in this study were carried out using the developed PLAXIS 3D model. Three-pile arrangements were considered in this study. Square piled rafts supported by 1, 4, and 9 piles, as shown in Fig. 2, were studied. The parameters considered in this study can be summarized in Table 2 as follows.

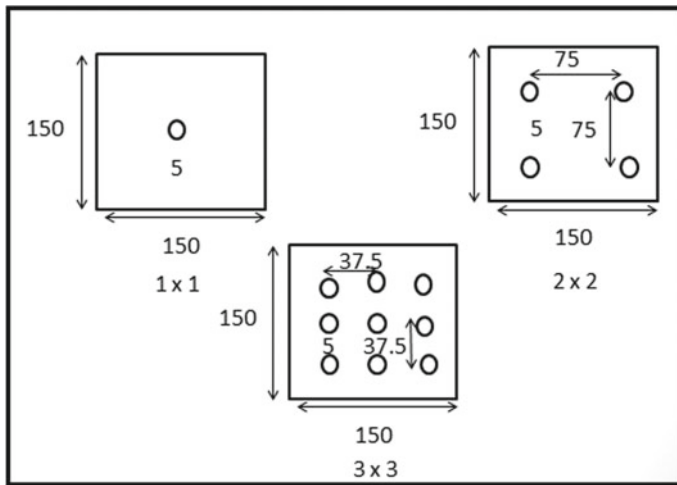


Fig. 2 Piled-raft model* 1 × 1, 2 × 2, and 3 × 3 pile

Table 2 Parameter validation study

Parameter name	Range of parameter				
Pile diameter D (mm)	3	4	5*	6	7
Pile spacing (mm)	10D	20D	30D*	40D	50D
Raft width (mm)	20D	25D	30D*	35D	40D
Raft thickness (mm)	0.6D	0.8D	D*	1.2D	1.4D

* indicates experimental model dimension is taken and analysed as shown in Fig. 2

7 Experimental Program and Numerical Validation

In this experimental setup, model pile is based on the mild steel rod having diameter 5 mm and length 150 mm, forming configurations 1×1 , 2×2 , 3×3 , and the piled-raft model used in the study. The piles are rigidly fixed to the raft by welding. The property of mild steel is shown in Table 3.

7.1 Loading Setup

The load frame consists of proving ring of 2kN capacity with 0.0025kN accuracy for load determination and two numbers of 25 mm dial gauge with 0.01 mm sensitivity for settlement prediction. The entire loading setup is shown in Fig. 3.

Table 3 Properties of mild steel rod

SI. no.	Properties	Values
1	Yield stress (N/mm ²)	411.21
2	Ultimate stress (N/mm ²)	432.61
3	Modulus of elasticity (N/mm ²)	2.34×10^5



Fig. 3 Loading frame setup

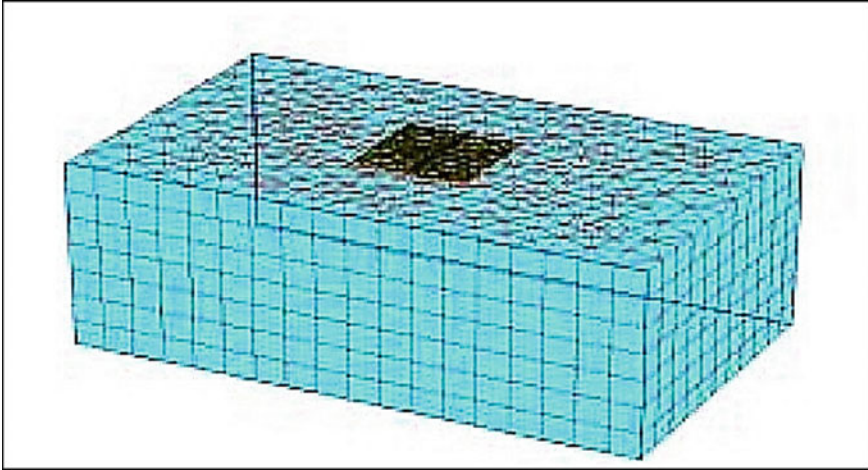


Fig. 4 Meshing

8 Numerical Validation Using Plaxis 3D

During the complete research process, vertical load was introduced at a constant loading pace of 1 mm/min. The remedy for each rise in load was calculated by means of dial gauges until the settlement is smaller than 0.02 mm/min. For each design of the piled-raft foundation, the load vs. settlement graph was compiled.

The values obtained are measured and calibrated using the Plaxis 3D tools and each configuration is shown in a cross section under Figs. 4, 5, 6, 7, and 8.

9 Comparison of Experiment and Plaxis 3D Result

The experimental study and FEM analyses reveal that the load-settlement difference across experiments and PLAXIS 3D is less than 15% up to the ultimate load, with FEM analytical review underestimating settlement and overestimating the ultimate load in contrast with experimental study. The load-settlement heterogeneity between experimental studies is 15% up to the final load, as well. The relation between the research sample and PLAXIS 3D is demonstrated in Figs. 8, 9, 10, and 11. In all these examples, it has been observed that the computational analysis has shown somewhat more load than the experimental work.

A contrast of raft load versus piled-raft load and raft with various configurations such as PR 1 × 1, PR 2 × 2, and PR 3 × 3 is shown in Fig. 12. The work-load capacity of the piled-raft system is significantly increased as the quantities of piles are increased.

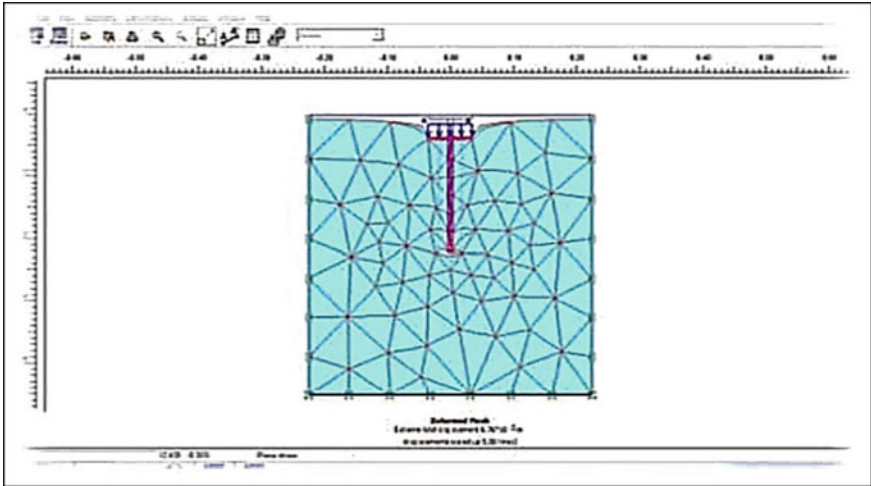


Fig. 5 Model piled raft 1 × 1

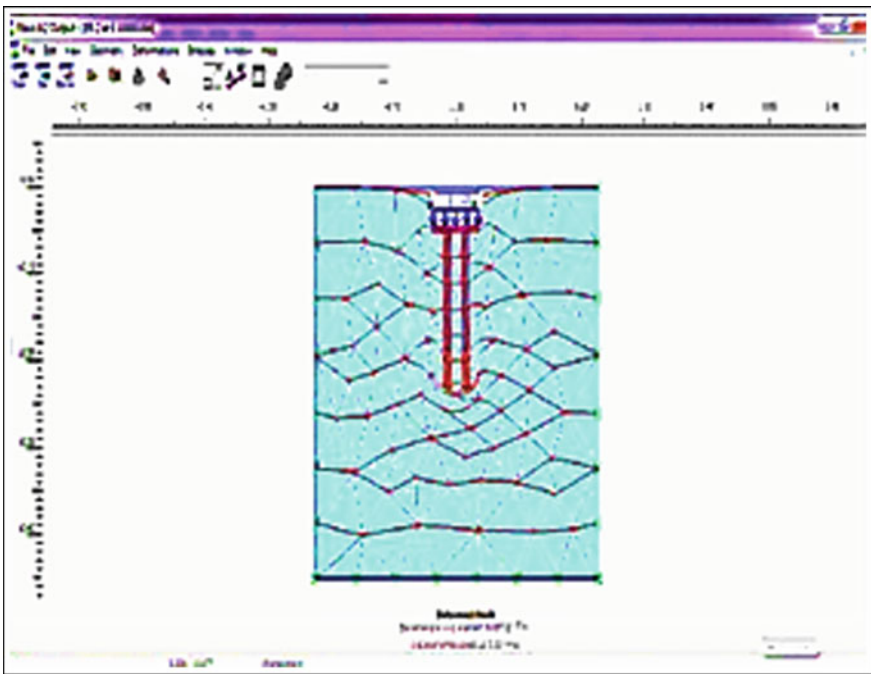


Fig. 6 Model piled raft 2 × 2

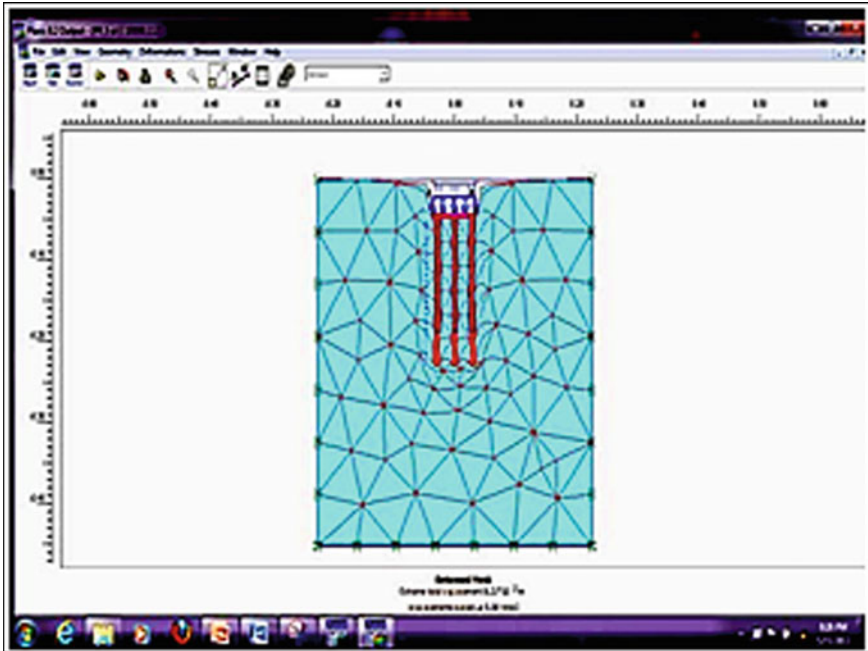
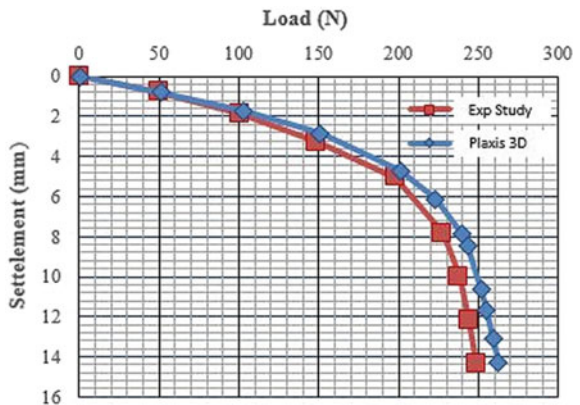


Fig. 7 Model piled raft 3 × 3

Fig. 8 Plain raft load versus settlement curve



10 Conclusion

It could be inferred on the basis of the current studies that the raft load rate in the piled-raft configuration is around 38% in sand. With the pile length and quantity decrease, the proportion of load borne by the raft increases. The raft load increases by up to 37% as the length of the piles reduces. The number of piles borne by the

Fig. 9 PRF 1×1 load versus settlement curve

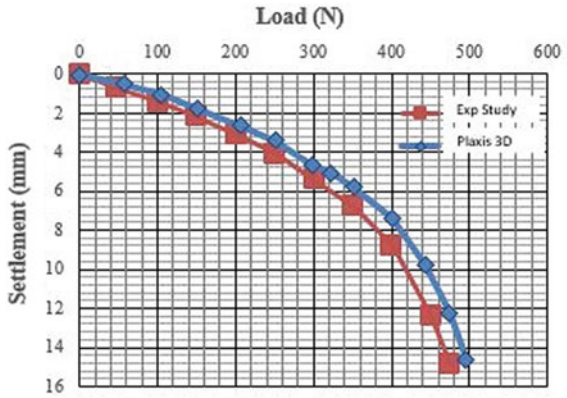


Fig. 10 PRF 2×2 load versus settlement curve

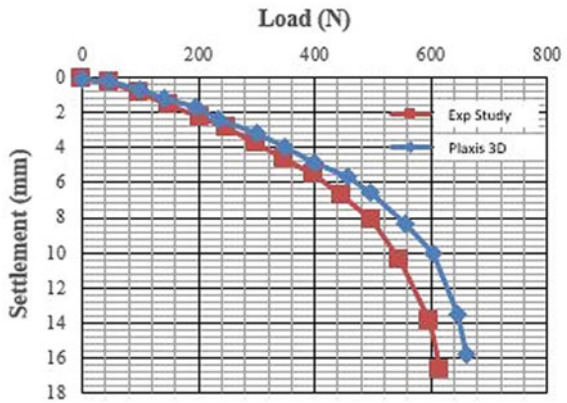


Fig. 11 PRF 3×3 load versus settlement curve

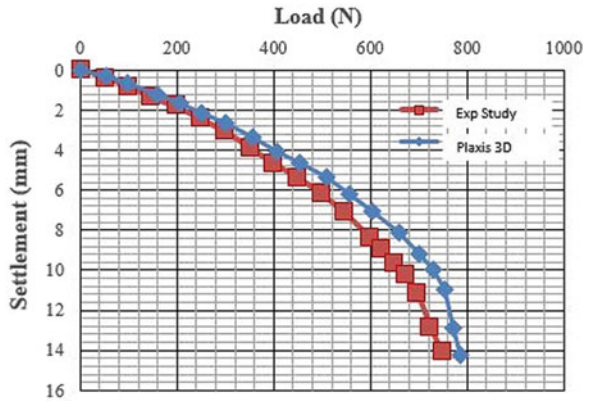
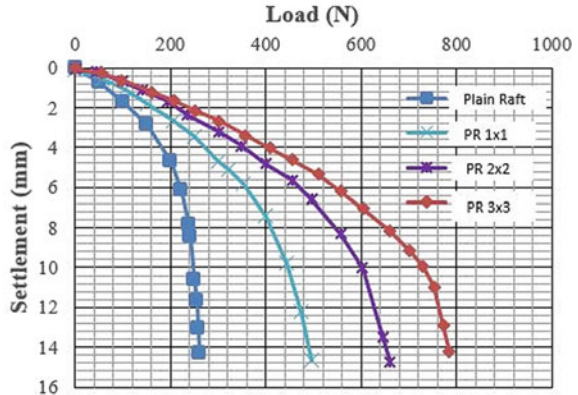


Fig. 12 PRF load versus settlement (Plaxis 3D Study)



raft raised to 57% as the number of piles decreased. With the settlement ratio S/B below or equivalent to 0.9, the load carried by piled raft is greater than the sum of raft's load and the pile load for each settlement ratio. The use of the piled raft as a settlement reducer is very helpful. For the best results, the piled raft at $S/B = 0.9$ should be designed. For pile rafts with 9 piles and the total load of piles raft with 4 piles is 27% higher. In this analysis, the computational model appears to work in a fairly reasonable direction, including the settlement magnitude. It reveals that the PLAXIS 3D model can be an efficient time tool for an advanced 3D model. The study of finite elements helped to better understand the piled-raft soil system's failure pattern.

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