Studies on the Piled Raft Foundation for a High-Rise Building Using Finite Element Modeling

Pratish Kannaujiya, Sagar Jaiswal, and Vinay Bhushan Chauhan

Abstract Piled raft foundations (PRFs) are essential for improving the load-bearing capacity of the foundation and for controlling the total and differential settlements. For an efficient design of the foundation for high-rise buildings, components of PRF such as length, diameter, and raft thickness are important factors. This study aims to examine the interaction behavior of pile–soil foundations for various parameters, namely the diameter and the length of the pile and also the raft thickness, which plays an important role in improving the behavior of piled raft foundation. The important aspects that must be taken into account to achieve a reliable design and strategies for the optimized design of PRF that is subjected to load–settlement with regard to the distribution of shear force and bending moment are also analyzed. In order to understand the behavior of piled raft foundation subjected to uniform loading, numerical simulations are carried out in this study by using a numerical tool based on the finite element method (FEM), ELPLA. This study reveals that proper pile arrangement can result in a significant reduction in the total and differential settlements, as well as induced shear force and bending moments on the raft.

Keywords Piled raft foundation · Pile configuration · Numerical analysis · Pile settlement · FEM

1 Introduction

High-rise buildings are often built on piled raft foundations (PRF) that must withstand vertical, lateral, and overturning loads. The consideration of wind and seismic loads is also important while designing high-rise buildings. In such buildings, the foundation impacts a strong axial load on the ground. In the case of such structures, it is therefore important that the foundation is designed in such a way that it can resist the load of the superstructure and can also adequately transfer these loads to the ground. In previous

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studies, conventional methods were used to design the pile group to withstand the heavy loads acting on the pile foundations [1–3].

In the PRF, the load is distributed between the piles and the raft, so that the load from the superstructure can be partially taken over by the piles and the raft [4]. The analysis of the PRF is also performed by a hybrid method to analyze the total and differential settlement [5]. The simplified analysis based on the stiffness of the pile group and raft stiffness had been presented by many researchers for analyzing the load–settlement behavior of the PRF [6, 7]. In addition, the behavior of piled rafts has been analyzed with a pile of different lengths subjected to horizontal and vertical loadings by using the finite layer method [8]. It is noted from the available literature that the earlier researchers had developed three broad classes of different methods to analyze the behavior of PRF, such as simplified calculation methods, approximate computational methods, and more rigorous computational methods [6, 9–12].

Horikoshi et al. [13] adopted a centrifuge model to examine the behavior of a combined PRF under static horizontal and vertical–horizontal load and concluded that different results were obtained when the response of a single isolated pile is compared with the PRF of the same size. Also, the researchers had reported that the proportion of vertical load supported by the piles in a piled raft remains unchanged, whereas in the case of pile foundation, the proportion of horizontal load supported by the pile upsurges as the horizontal displacement decreases.

Rabiei [14] had conducted a numerical study to examine the effect of loading type on pile configuration and PRF using the FEM. The results showed that the piled raft foundation is economical foundation systems. Moreover, the study suggested that the design philosophy of a pile raft configuration should be based on both ultimate load and settlement responses.

From the previous studies, it has been found that the provision of the piled raft foundation improves the overall stability of the structures. Besides, the stability is controlled by many important parameters such as raft thickness, pile length, and pile diameter. These factors not only govern the overall stability of the structure but also contribute to an optimum selection of the aforementioned parameters, which leads to an economical design of the PRF.

Given the above, a comprehensive numerical study has been carried out to investigate the influence of pile length, pile diameter, pile spacing, numbers of piles, pile configuration, and raft thickness on the performance of the PRF by using a numerical tool based on the finite element method (FEM). Moreover, the detailed design of PRF system with optimum pile raft design and pile configuration scheme for a building of 20 storeys having a height of 60 m is carried out, and the total load (133 MN) of the building is calculated manually by using the codes of Indian Standards [15–18].

2 Numerical Modeling and Analysis

In the present paper, the designing of the piled raft foundation is performed by considering two configurations and their factor of safety as well, by using the finite element computational tool ELPLA [19]. A parametric study is performed to evaluate the behavior of PRF and also to analyze the parameters of different types of subsoil models. The thickness of layers of soil that are available for piling in case of loose, medium dense, and dense soils is 0–4 m, 4–15 m, and 15–35 m, respectively. The raft is modeled as an elastic element, and the size of the piled raft is 20 × 20 m, with a uniform load applied over the raft to investigate the maximum settlement and bending moment of piled raft foundations. In order to create a better understanding, two configurations of pile raft are considered for designing of foundation with an optimum selection of the pile length (L_p), pile diameter (d_p), and the raft thickness (t_R) which leads to an economical design. The details of the model configuration that are used in this study are shown in Fig. 1. The width (B) of the raft and the spacing between piles (s) are shown in Fig. 1. The properties of the soil and the foundation that are considered in this study are presented in Table 1. A comprehensive numerical study has been carried out to investigate the effect of length, diameter, and spacing between the piles on a pile group, and the raft thickness on the behavior of PRF using curves obtained from the numerical analysis.

In this study, two pile configurations are considered, namely pile configuration A and B, respectively. The pile configuration A has 34 and B has 25 piles, respectively, out of which the 25 piles of configuration A are of type P1 and 9 piles are of type P2, whereas the pile configuration B has 16 piles of type P3 and 9 piles of type P4. The

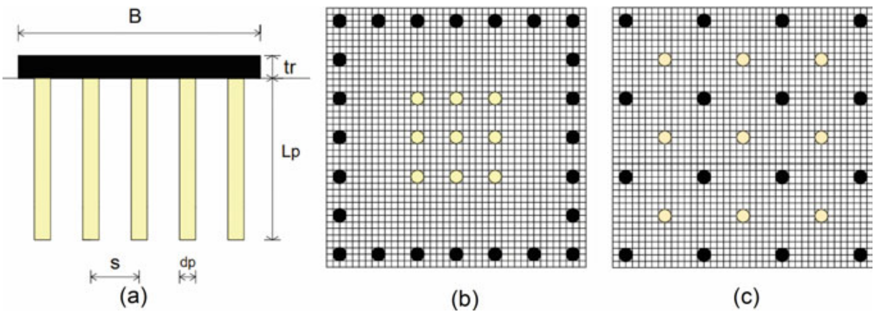

Fig. 1 Model configurations, **a** model condition, **b** pile configuration A, and **c** pile configuration B

Table 1 Properties used in the present study

Parameter	Soil type			Pile	Raft
	Loose	Medium dense	Dense		
Young's modulus, E (MPa)	10	18	22	3×10^4	2×10^4
Unit weight (kN/m^3)	18	19	20	25	25
Friction angle, ϕ(°)	22	31	38	–	–
Cohesion, c (kN/m^3)	1	2	2	–	–
Poisson's ratio, μ	0.3	0.3	0.3	0.18	0.25

pile configuration A having pile type P2 and B having pile type P4 has a constant length of 10 m, whereas the length of pile type P1 and P3 is varied to examine the behavior of pile length on the settlement of the foundation.

To analyze the behavior of pile raft, the length of pile type P1 and P3 is varied from 10 to 30 m, and the diameter of the pile and the raft thickness is kept constant at 1 m. Also, the embedded length of the piles (L_1/L_2) is varied from 1 to 3 in an interval of 0.5, for the selection of optimum depth of embedded pile length. Furthermore, for the ease of understanding, the length of pile and raft thickness are normalized with the pile diameter, i.e., L_p/d_p and t_R/d_p, and have been varied from 5.2 to 1.7 and from 0.5 to 1.5 in an interval of 0.2, respectively, to obtain the optimum dimensions.

3 Results and Discussion

To examine the behavior of the piled raft foundation, a parametric study is done for two configurations of PRF by varying the pile length, pile diameter, and raft thickness by using a finite element method-based numerical computational tool, ELPLA. The numerical results obtained from the present study are demonstrated in the form of curves and discussed in the following section.

Moreover, to validate the current numerical model, a numerical analysis is done for 9 identical piles placed at a spacing of 2 m vertical and 4 m horizontal concerning each other, and response of raft thickness versus the maximum bending moment and the differential settlement have been calculated (as shown in Fig. 2). The results obtained from the present study are in good comparison with those reported by Van Impe and Lungu [20]. Therefore, the current model can be described as well-validated and suitable for further analysis.

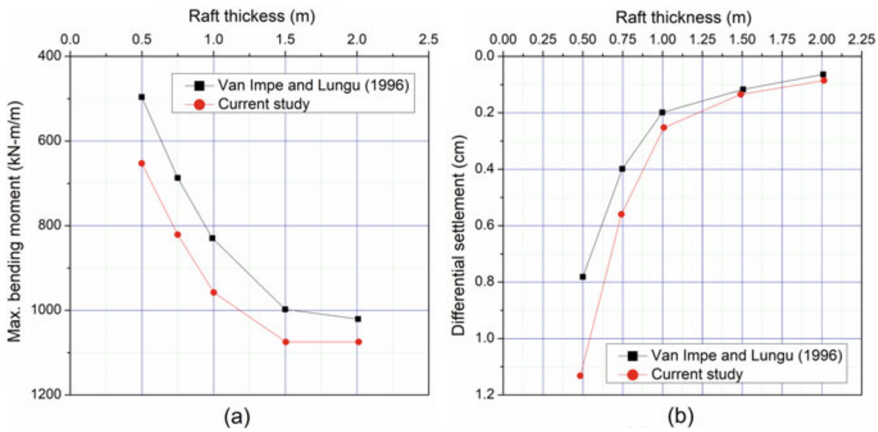

Fig. 2 Validation of the current numerical model

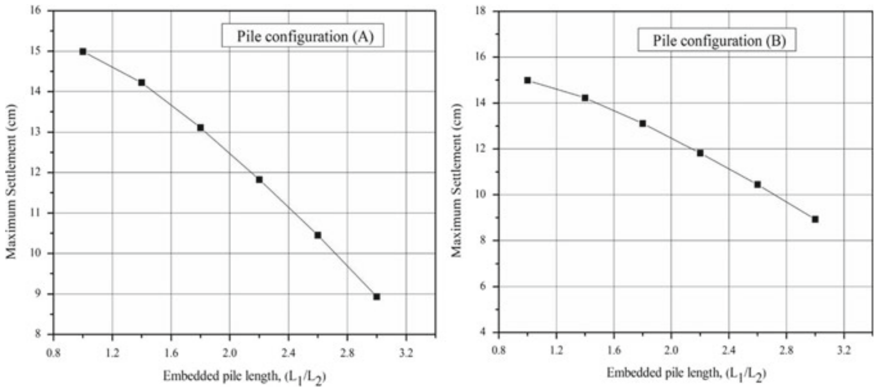

Fig. 3 Variation of maximum settlement with the embedded pile length (L_1/L_2) for pile configuration A and B

The variation of maximum settlement with the embedded pile length (L_1/L_2) is shown in Fig. 3. It can be noted from Fig. 3 that for the pile configuration (i.e., A and B), the settlement decreases with the increase in pile length. Moreover, the decrement in the settlement of configuration A and B is almost similar despite a greater number of piles present in A (i.e., 34). The settlement in both the configurations is reduced by 66.67%, as the embedded length is increased from 1 to 3. It is observed from both the configurations that the determinations of the proportional load carried by the piles are insensitive to the embedded length of the piles and there is no major difference in the settlement observed.

Furthermore, keeping constant the embedded pile length (L_1/L_2) as 2.6 and raft thickness 1 m, the diameter of the pile is varied for the procurement of optimum diameter which tends to enhance the load-bearing capacity and overall stability of the foundations. The interaction factor applied to the raft for a vertically loaded pile is 332 kN/m^2. The curve between maximum settlement versus normalized diameter of the pile is obtained on the application of load over the raft and shown in Fig. 4. It can be noted from Fig. 4, as the L_p/d_p ratio changes from 5.2 to 3.5, there is a sudden decrease of 6.6, and 13% in the maximum settlement is observed in configurations A and B, respectively. However, after $L_p/d_p = 2.8$, the change in the settlement is not very significant, and therefore, for keeping the design more economic, the diameter corresponding to $L_p/d_p = 2.8$ is kept constant for further analysis.

In a piled raft foundation, the design of the raft thickness is an important factor which also results in improving the ultimate load-bearing capacity and settlement behavior of the system. In the present study, the normalized raft thickness, i.e., (t_R/d_p) has been varied from 0.4 to 1.2 to obtain the optimum thickness of the raft. The variation of the maximum settlement versus normalized raft thickness is shown in Fig. 5.

The result indicates that the maximum settlement decreases linearly with the t_R/d_p ratio for both the configurations A and B, respectively. The maximum settlement at

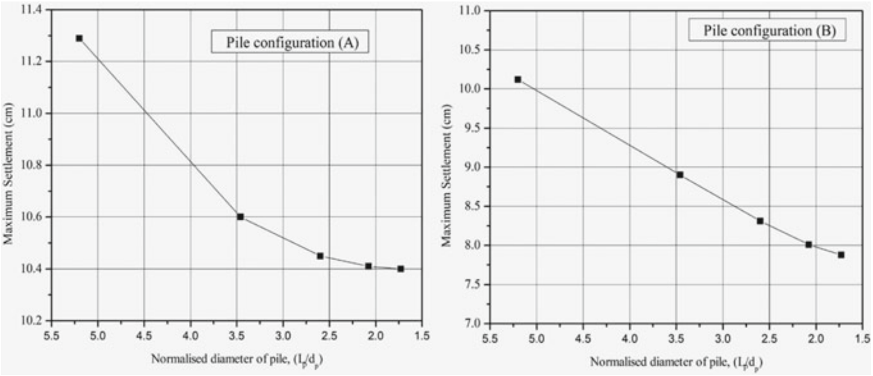

Fig. 4 Variation of maximum settlement with the normalized diameter of pile (L_p/d_p) in pile configuration A and B

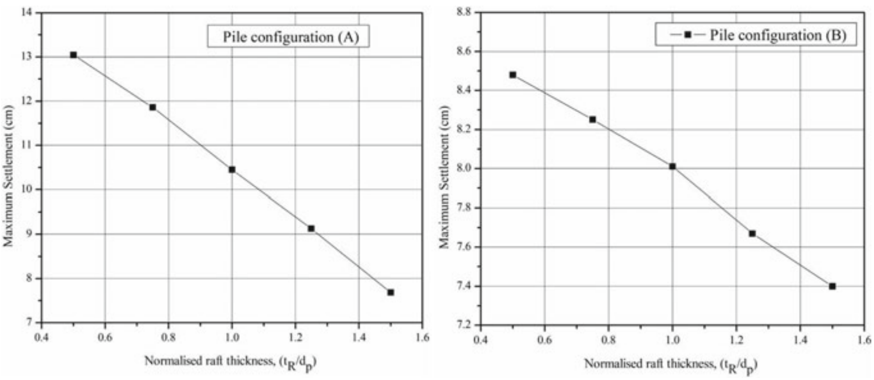

Fig. 5 Variation of maximum settlement with the normalized raft thickness (t_R/d_p) in pile configuration A and B

$t_R/d_p = 0.5$ is greater in case of configuration A than the configuration B, and this can be attributed to the fact that the arrangement of piles while the construction of a high-rise building affects the load-bearing capacity of the foundation immensely. For the same maximum settlement level, configuration B is far better than configuration A, despite having a greater number of piles.

Moreover, the variation between the maximum moment and the normalized thickness (t_R/d_p) is also investigated for the pile configuration (as shown in Fig. 6). The maximum moment in $x(M_x)$ and $y(M_y)$ direction is calculated, and also, their average values are evaluated for better accuracy. For both the pile configurations, it is noticed that the maximum moment resisted by the raft, in this case, increases with the increase in normalized thickness, and also, for all the corresponding values of t_R/d_p, the moment that the pile configuration A withstands is higher than the pile configuration B.

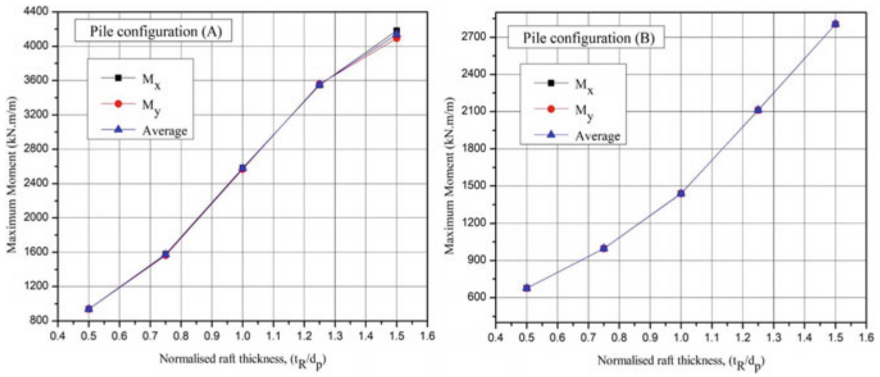

Fig. 6 Variation of the maximum moment with the normalized raft thickness (t_R/d_p) in pile configuration A and B

4 Conclusion

A numerical study is conducted to analyze the behavior of piled raft foundation by varying the length of the pile (L_p), pile diameter (d_p), and the raft thickness (t_R), by using a finite element numerical tool, ELPLA. This paper aims to determine the suitability of the PRF for the construction of high-rise building by examining the settlement behavior of the foundation. To analyze the effect of the number of piles on the settlement and maximum moment that the foundation can withstand, two different configurations of the piles are taken into account. The optimum length of piles, optimum diameter, and raft thickness have been calculated by performing a parametric study. The results showed that the arrangement of piles in the piled raft foundation plays a decisive role in improving the load-bearing capacity and also the maximum settlement of the foundation. The result obtained in the above numerical analysis is discussed below.

1. It would be a more efficient design strategy for improving the piled raft foundation. This can be observed that the embedded length of the pile ($L_1/L_2 = 2.6$) is a governing factor in improving the bearing capacity of the foundations and also improving the overall stability of the structures.
2. The pile configuration (B) is more effective than configuration (A) for the reduction of the overall settlement as it reduces 30% of the overall settlement at the corner and edges of the PRF.
3. It is observed that the raft thickness (t_R) has a great influence on the total and differential settlement of the foundation, and based on the present study, an optimum normalized raft thickness, t_R/d_p, of 1 is recommended.
4. Based on settlement and bearing capacity comparison, it is recommended to use the piled raft configuration B, as it is found as an economical configuration for the piled raft foundation.

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