Chapter 11
Behavior of Combined Piled-Raft Foundation Under Eccentric Loading

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Introduction

For the construction of any structure, raft foundation is generally used to transfer load to soil in the case when a soil layer is available at a near depth with adequate bearing capacity. Sometimes, if raft is placed over a soil with adequate bearing capacity, it also induced an excessive settlement. To minimize this excessive settlement, pile foundation along with this raft foundation can be used. In case of very tall building or structure, wind forces become a considerable design factor and due to this wind forces eccentric load will act on the structure which may result in differential settlement. Various researchers [1, 2] examine the behavior of pile while use as piled raft and pile groups in sand. The interaction behavior between pile and raft is a very important factor while designing piled-raft foundation [3]. Sawwaf [4] has reported the inclusion of short piles and pile arrangements are important factors on enhancing the maneuver of modeled raft loaded at an eccentricity on sand. The raft size, the raft thickness, the piles diameter and lengths are important design parameter of piled-raft foundation and the effect of which are studied by various researchers [5–7]. Soil type has considerable effect on capacity, changing it properties will change the utmost load carrying capacity of any particular foundation [8]. The raft thickness has insignificant effect on distribution of load on both raft and piles [9]. Patil et al. [10] studied addition of piles close to raft edges increase capacity and the settlement. The cushion layer thickness and spacing between piles in pile group effect on the load settlement behavior [11]. Deb and Pal [12] reported the differential settlement may be

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minimized by using raft and pile foundation together as combined foundation. Deb and Pal [13] studied the nonlinear behavior of piled-raft foundation and analyzed the effect of load acting vertically on the response in the lateral direction. Due to limited research work on the effect of eccentric load on piled-raft foundation an attempt has been made to analyze the behavior subjected to eccentric vertical loading. Therefore, the major objectives of this study are:

1. To evaluate the load settlement characteristics of connected piled-raft foundation under eccentric vertical loading.
2. To examine the piled-raft foundation behaviors due to the change of soil's Young's modulus.
3. To examine the load shared by pile under eccentric loading condition.

Numerical Modeling

Modeling of Piled-Raft-Soil System

In this study, ABAQUS/CAE software is used to create the three-dimensional model of pile, raft and soil continuum. Mohr–Coulomb plasticity is chosen for the nonlinear stress–strain characteristics of the soil, raft and pile. Deformable three-dimensional solid element with solid extrude feature is used to model pile and raft. Different datum planes are created in pile, raft and soil which are essential during assemble of all the parts. Material properties of all the parts are created in property module and assigned the properties. Raft is placed over the soil with surface to surface interface in the contact surface between them. Master–slave concept is used while modeling surface interface. For simulating the loading condition, at first geostress may be applied at the soil; at second stage own-weight of the pile and raft is considered and lastly the load is applied in the vertical direction.

Boundary Condition and Mesh Pattern

Boundary conditions are required to confine the soil in any particular direction. For all the bottom nodes, Encastre type of boundary condition is chosen so that translation and rotation movement of soil can be restricted. In the same way, two more boundary conditions are created in X–Y and Z–Y faces by choosing ZSYMM and XSYMM type of boundary condition. Mesh size should be chosen carefully as it has considerable effect on the results. In this modeling, fine meshes are used at the location where load is acting and coarse meshes are used over the remaining part of the soil and throughout same meshes are used in pile and raft. Triangular prism is applied in pile and linear brick element is chosen for soil and raft. The meshing pattern of the pile, soil continuum and raft is shown in Fig. 11.1.

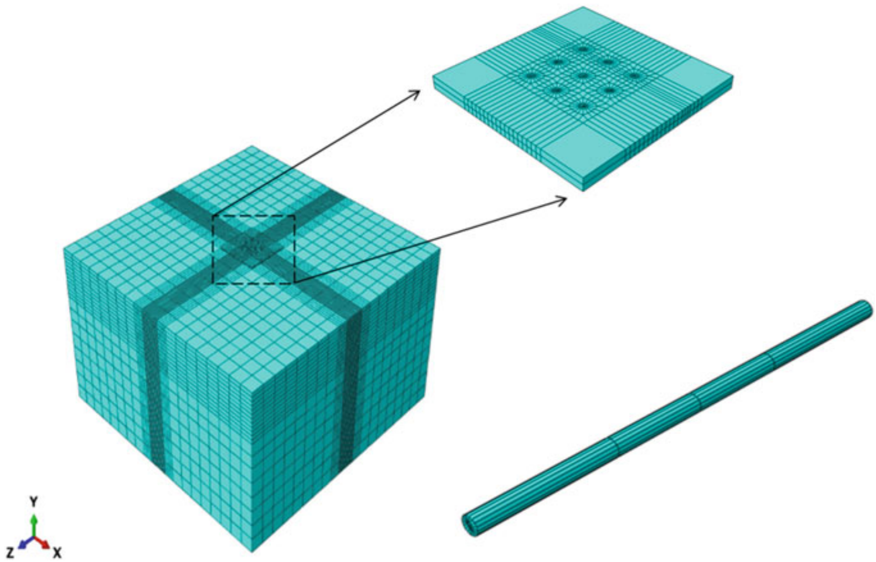

Fig. 11.1 Meshing pattern of the pile, raft and soil continuum

Test Program and Material Properties

Raft size of 14 m × 14 m × 1 m and pile of 15 m length and 0.6 m diameter is considered in this numerical modeling. Different spacing to dia. ratio (s/d) of pile such as 3, 4 and 5 is chosen for this analysis. Three type of pile group such as 3 × 3, 4 × 4 and 5 × 5 configuration are modeled for the analysis. For the effective analysis of settlement and load, the ultimate load is taken at 10% settlement of raft width, i.e., $w = 0.1B$ (where, w is settlement and B is raft width). Specifications of the piled-raft element and general properties of dry sand used for numerical modeling are presented in Table 11.1.

Table 11.1 Specifications of the piled-raft element and general properties of dry sand used for numerical modeling

Parameters	Prototype dimension	Properties of dry sand	Value
Width of raft (B)	14 m	Dry density (kN/m^3)	16.50
Thickness of raft (t)	1 m	Specific gravity	2.63
Dia. of pile (d)	0.6 m	Poisson's ratio	0.3
Length of concrete pile (L)	15 m	Friction angle	30°
Length to dia. ratio (L/d) of pile	25	Relative density	60%
Eccentricity to width ratio (e/B)	0, 0.1, 0.25, 0.4	E_P/E_S	1000

Note E_P = Young's modulus of pile = 22.4 GPa, E_S = Young's modulus of sand

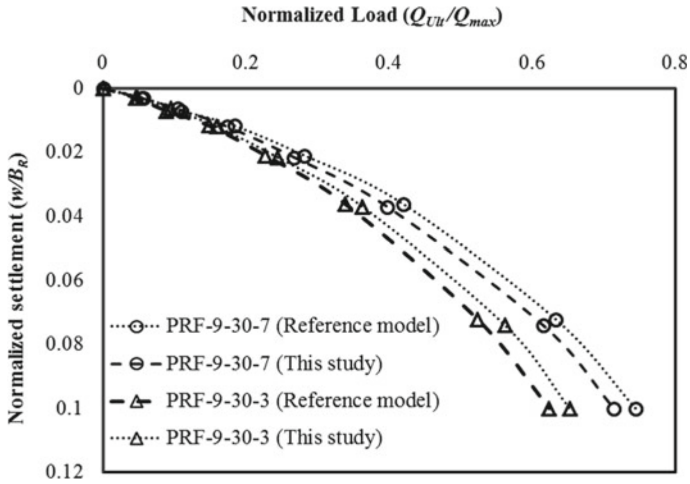

Fig. 11.2 Comparison of this model with the numerical model of Deb and Pal [12]

Validation

Better accuracy of any numerical model can be check by comparing it with other published numerical model. For the validation of the numerical model prepared in this study, the analysis is compared with the publish work of Deb and Pal [12]. A 3 × 3 pile configuration similar to reference model with raft width of 30 m and pile spacing to diameter ratio of 3 and 7 are prepared for comparison purpose. The load settlement response obtained from numerical analysis is compared with reference model and presented in Fig. 11.2. From the below figure, it can be ensured as load settlement responses obtained from this study matches very close to load settlement responses obtained from reference model.

Result and Discussion

Effect of Number of Pile and Young's Modulus of Sand on Vertically Loaded Piled-Raft Foundation

Each model is analyzed for eccentric load with eccentricity of $e/B = 0, 0.1, 0.25, 0.4$ and the responses are recorded. The utmost load carrying capacity of all the configurations is obtained for the settlement of the foundation equal to 10% of raft width as per Deb and Pal [14]. The variation of normalized load settlement response for different pile configurations and Young's modulus of dry sand in case of e/B of 0.1 are shown in Fig. 11.3. Figure reveals that with increase of number of pile

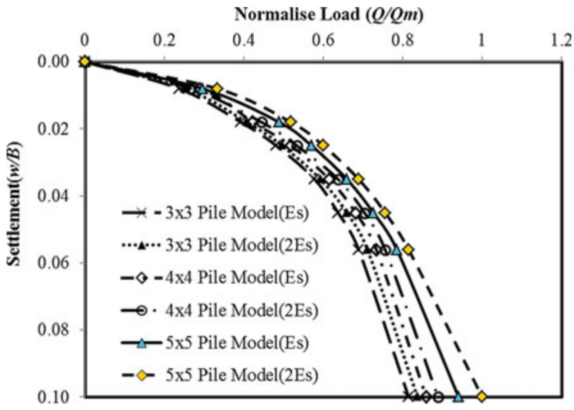

Fig. 11.3 **Variation** of load versus settlement curve for $e/B = 0.1$

from 9 to 25 in piled-raft foundation, the utmost load carrying capacity of foundation increases by 16%. With number of pile increases, contact surface between the pile and dry sand also increases which leads to enhance in capacity. It may also be found that the ultimate load carrying capacity increases with higher values of soil's Young's modulus as the stiffness of soil increases with increase in Young's modulus. Load carrying capacity can be increases by 3–4% by changing the values of soil's Young's modulus from 1 to 2 E_S.

Eccentric Vertical Load Carried by the Each Row Pile

Vertical load settlement curves are shown in Fig. 11.4 for different rows of pile group for s/d ratio of 4 and e/B ratio of 0.1. The capacity under eccentric vertical load subsequently reduces from row 3 to 1. From the figure, it is found that due to eccentric loading around 24%, more load is developed in the 3rd row of pile group as compare to the 1st raw.

Variation of the Vertical Eccentric Load for the Different E_S Values

The normalized vertical eccentric load carrying capacity of different pile groups varies with Young's modulus of dry sand used in this modeling. The variation of 3 × 3 pile group for different e/B ratios has shown in Fig. 11.5. It is found that the normalized vertical eccentric load carrying capacity increases with increase values of E_S and decreases when the e/B ratio increases. In case of eccentric load, the nearby piles take the maximum amount of load initially and get mobilized first, and after mobilization of nearby piles, the additional load takes by adjacent piles but in

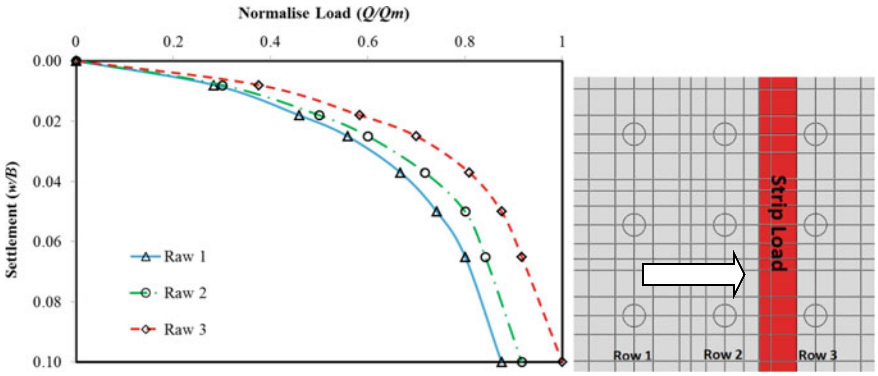

Fig. 11.4 Eccentric vertical load carried by the each row pile

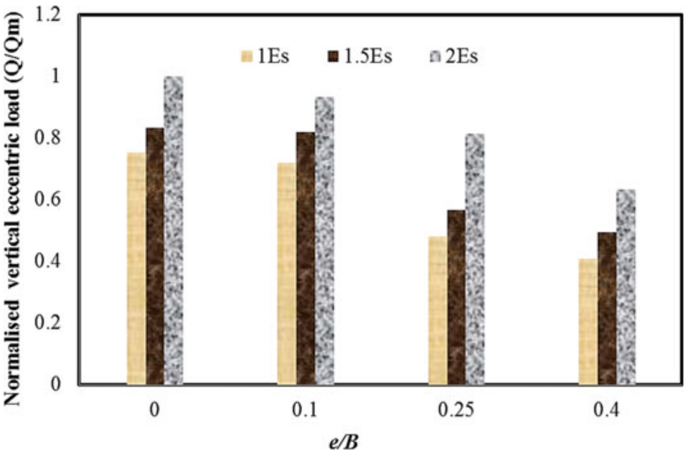

Fig. 11.5 Variation of vertical eccentric load for different E_S values

vertical load, all the piles mobilizes together. It is further observed that when the *e*/*B* ratio increases, the pile numbers which take the initial load become less and the normalized vertical eccentric load carrying capacity decreases.

Load Sharing Mechanism Under Eccentric Loading

The load transfer system of raft and piles as combined foundation is quite different from the individual raft and pile. In case of combined foundation of pile and raft, the total applied load is carried by both raft and pile. Eccentric load carried by pile group with different *e/B* ratios is shown in Fig. 11.6. Under eccentric loading, all the pile

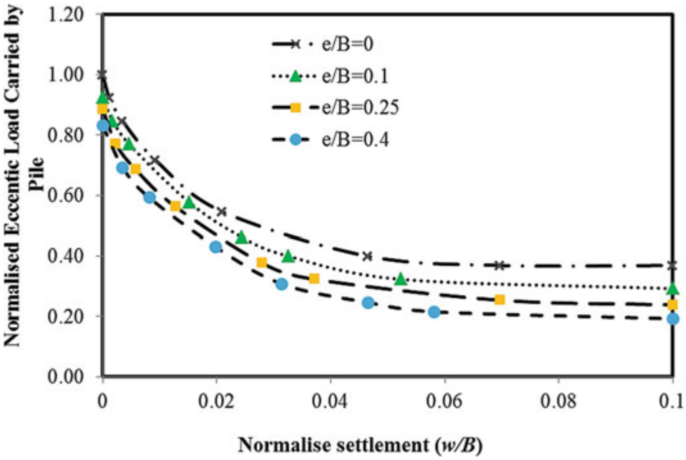

Fig. 11.6 Vertical eccentric load carried by 4 × 4 pile group with different *e/b* ratio

do not take equal load. Therefore, the maximum amount of loads are taken by nearby piles, where eccentric load is developed and the average load share by all the piles in case of eccentric loading becomes lower as compare to uniform vertical loading. After some period of eccentric loading, the piles near the vicinity of the eccentric loading get mobilized, and the remaining amount of loads are shared by raft. Due to this, the load shared by piles becomes lower with the eccentricity increases.

The normalized vertical eccentric load is carried by each pile group varies with Young's modulus of dry sand. Figure 11.7 shows such variation of 4 × 4 pile group. From the below figure, it is noticed that load which is carried by pile decreases with increase of *e*/*B* ratio, and with increase in soil's Young's modulus, the load carried by the pile increases. Stiffness of soil increases with Young's modulus, so the same pile can take higher load in the soil as the pile–soil interface becomes stiffer with higher value of soil's Young's modulus.

Effect of the s/d *Ratio on Ultimate Load Carrying Capacity*

For modeling of the foundation, different pile spacing in group pile to diameter ratio, i.e., 3, 4, 5 is used in this modeling, and the effect of the *s*/*d* ratio on ultimate load carrying capacity with eccentricity $e/B = 0.25$ is shown in Fig. 11.8. From the analysis, it is noticed that with lower *s*/*d* ratio, the stress field generated around each pile overlaps each other, and as *s*/*d* ratio increases, overlap stress field zone reduces. So, the load carrying capacity increases with increase in *s*/*d* ratio.

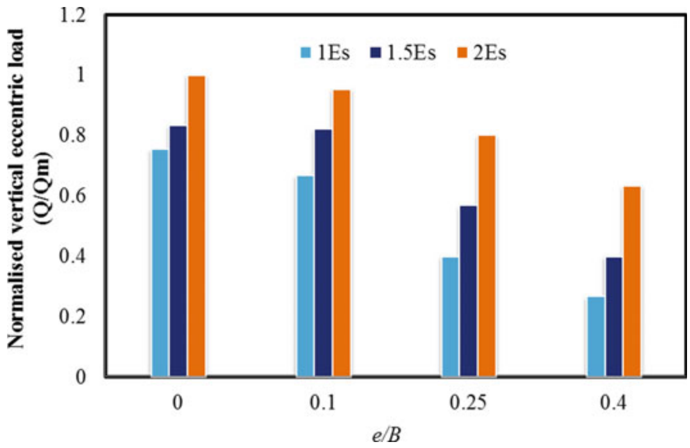

Fig. 11.7 Variation of normalized vertical eccentric load carried by 4 × 4 pile group with different E_S values

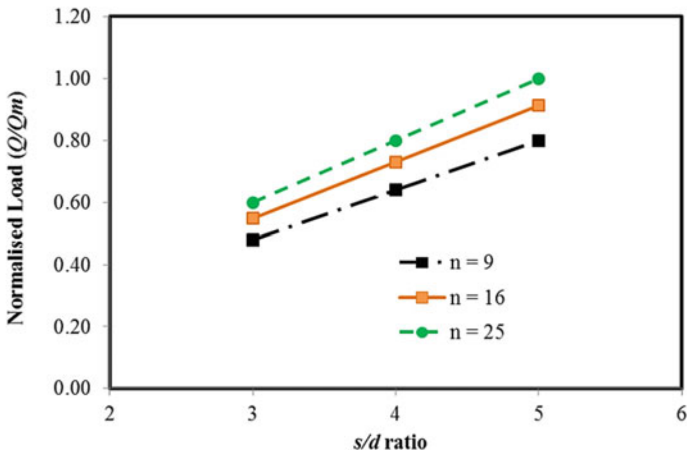

Fig. 11.8 Normalized eccentric load carried by the piled-raft with different values of *s*/*d* ratio

Stress in Soil and Piled-Raft

Stress in soil due to vertical eccentric load is represented in Fig. 11.9. In vertical load test, all the piles mobilized together, whereas under eccentric loading, the nearby piles of eccentric loading are mobilized first as the stress concentration occurs around those piles and the adjacent piles are mobilized later. The stress which is developed in piled-raft is analyzed for vertical loading and eccentric loading. Figure 11.10 is showing the stress which is developed in piled-raft foundation under the vertical load and vertical eccentric loading situation. The maximum amount of stress developed

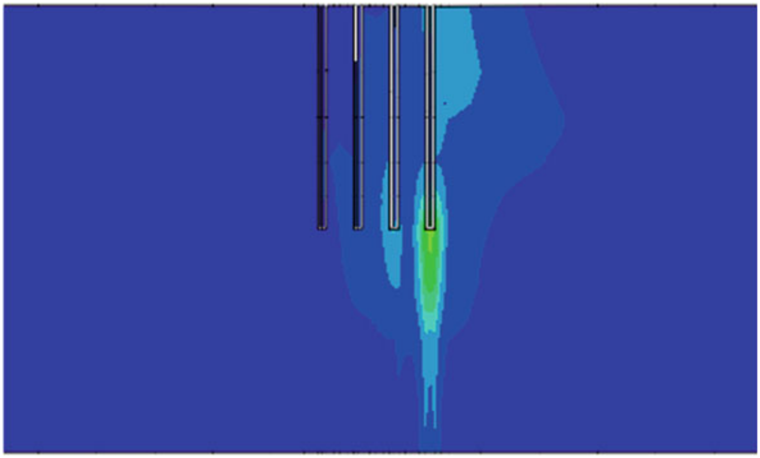

Fig. 11.9 Stress in soil due to vertical eccentric load

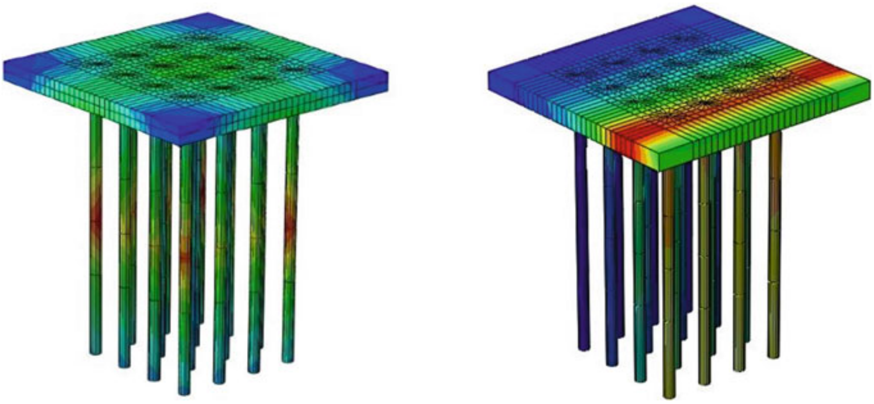

Fig. 11.10 Stress in piled-raft system under the vertical and eccentric loading situation

in piles and the raft experiences a very little amount of stress, and under eccentric loading, the maximum stress is developed in nearby pile row where the eccentricity occurs.

Conclusion

A series numerical model has been made and analyzed in this study. Based on numerical investigations, the conclusions are as follows:

1. In eccentric loading, the maximum amount of eccentric load is carried by the nearby row of group of pile where the eccentric load applied and this eccentric load is gradually decreases in successive rows.
2. The load carrying capacity of the piled-raft foundation increases about 3–4% when the value of Young's modulus increases from E_S to $2E_S$.
3. When the value of *e/B* ratio changes from 0 to 0.4, the load carrying capacity of the piled-raft foundation decreases up to 46%.
4. In vertical loading, the stress is developed almost equally in all the piles, whereas in vertical eccentric loading, the maximum stress develops in the nearby piles where eccentricity develops.

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