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3D Numerical Study of the Behavior of Piled Raft Foundation on Soft Clay with Uniform and Varying Pile Lengths

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Abstract. In the conventional design of a piled raft foundation, piles of uniform lengths are provided underneath the raft. However, it has been observed that in such cases the peripheral piles either carry more loads as compared to central pile for a rigid raft, or central pile undergo more settlements than peripheral piles for a flexible raft. This paper attempts to evaluate the required length of the piles in the group for an optimum design of piled raft foundation with a flexible raft founded on soft clay. Three-dimensional (3D) Finite Element (FE) models having different configurations of pile lengths and pile spacing were analyzed numerically using a general purpose finite element method (FEM) based software *ABAQUS*. Mohr-Coulomb model is used to define the elasto plastic soil behavior. 3 x 3 squared concrete piled raft foundations were designed with three different lengths of the piles used for the centre pile, corner piles and edge piles for models with non-uniform pile lengths. The overall behavior of the piled raft foundation system is evaluated. The results have shown that the model having longest pile at centre, intermediate length of piles at edges, and shortest piles at the corners has the highest improvement in load carrying capacity and maximum reduction in average and differential settlements when compared to the conventional piled raft foundation design.

Keywords: Soft clay; piled raft foundation; load- settlement behavior; varying pile length; *ABAQUS*.

1 Introduction

In the past few decades piled raft foundation has widely been used as a foundation option as it has proven to be an economic and efficient foundation type [9,19]. In this type of foundation the load is shared among the structural elements i.e., piles and the raft. Unlike the traditional foundation design where the loads are assumed to be either carried by the raft or by the piles, the design of the piled raft foundation involves significant contribution of both the raft and the piles in load bearing [4,12]. Taking into account of the relative proportion of load carried by each structural element, different design philosophies were suggested by many researchers [17,18,19,23]. The piled raft foundation consists of three elements; the piles, raft and the soil. The design of such foundation system largely depends on the pile-soil-raft interactions. From the literature many reports can be found where the various soil-structure interactions involved in the load sharing mechanism of piled raft foundation were evaluated to understand the behavior of the foundation system [6,7,19,22,26]. The use of piled raft foundation in soft soils is very much limited mainly due to the low bearing capacities and foundations undergoing settlements beyond the permissible limits [19,20]. In spite of these concerns successful attempts of piled raft foundations on soft clays have been reported in the literature [20,30].

In the conventional design of a piled raft foundation, pile group with uniform pile lengths are provided underneath the raft. However in such cases it is found that the peripheral piles carry majority of the design loads [13,28], resulting in non uniform distribution of loads among the piles for a rigid raft, and in case of a flexible raft, central pile undergoes more settlements compared to peripheral piles [11,23] resulting in higher differential settlements.

From literature it can be observed that most of the reports on piled raft foundations focused on providing piles with similar length underneath the raft [6,7,11,22,23,25,27]. Few literatures were devoted to investigate the behavior of piled raft foundation with varying pile length [16,24,29]. Therefore the effect of varying the lengths of piles distributed underneath the flexible raft with different pile spacing on the ultimate load capacity, load sharing, average and differential settlement of the foundation system needs to be investigated. The results obtained from this study can be used for an effective piled raft foundation design on soft clays.

2 Numerical Model

Three dimensional (3D) numerical model of piled raft foundation was developed using a general purpose FEM based software *ABAQUS*. The model consisted of soil continuum, foundation elements geometry, interface element and load 150 kPa uniformly distributed on raft. Fig. 1 shows the numerical model used for the parametric study. To model the soil and the foundation elements, eight-node hexahedral brick elements were used. The soil mass was considered to be isotropic, homogenous and elasto-plastic in nature. Properties of the soil were simulated in the soil block through the “Mohr-Coulomb” model where failure or yielding is considered to take place when the shear stress mobilized in any plane is equal to the soil shear strength. For modeling the soil, parameters like modulus of elasticity, cohesion, angle of internal friction and Poisson’s ratio was used. The raft and the piles material was considered to be linear elastic as their Young’s modulus is higher than the soil Young’s modulus. Rigid connection between the piles and raft was considered. To stimulate the interactions between the foundation elements and the soil, the master-slave surface option was used. The soil was considered as the slave surface whereas; the piles and the raft were treated as master surface [27]. The soil-structure contact was considered perfectly rough with no relative displacement between structural elements nodes and soil nodes in contact with it [24]. The size of the soil block in *ABAQUS* was evaluated by taking into consideration of the soil at the boundary is not likely to be affected by appreciable amount of stresses and strains generated due to the load on the foundation. Laterally the soil mass was considered five times the foundation width (B_r) and in the vertical direction it was taken as $2B_r$ from the tip of the pile (longest pile, in case of varying pile lengths). For soil in the proximity of the foundation finer mesh was generated that gradually transformed to a coarser mesh at the boundary. The boundary conditions were given such that the movement of bottom portion of the model was restrained in all directions and no rotation. The side faces were restrained in horizontal directions and allowed movement in z-direction [16].

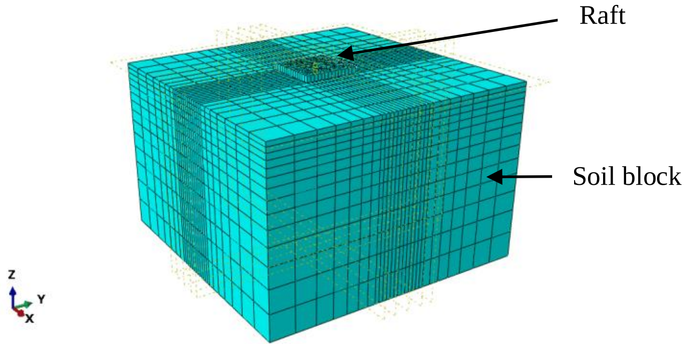

Fig. 1. Finite element mesh of piled raft model used in the parametric study

3 Parametric Study

The ultimate load carrying capacity, load sharing, average and differential settlements of piled raft foundation founded on soft clay under undrained condition were evaluated for both uniform and varying length piles underneath the raft at different pile spacing. For modeling the piled raft foundation on soft clay, the soil, raft and pile properties used are shown in Table 1. The basic parameters used for the design of piled raft are given in Table 2. Raft and pile modulus of elasticity values were taken from [32]. The raft thickness was back calculated corresponding to raft soil stiffness ratio (K_r) value 17.8 where, $K_r = 5.57E_r(1-\mu_s^2)B_r^{0.5}t_r^3/\ E_s(1-\mu_r^2)L_r^{0.5}L_r^3$ for a relatively flexible raft lies in the range of 0.001 (fully flexible) to 1000 (rigid raft) [3]. All the piled raft foundation models were subjected to a uniformly distributed load of 150 kPa. Total nine piles were arranged in a square pattern (3 rows x 3 columns) with a clear distance of 0.5 m from the raft edge to the outermost pile [14]. The piles in the group were termed based on their locations as corner piles labeled ‘1’, edge piles ‘2’, and an interior pile ‘3’ as shown in Fig. 2. Based on those locations the pile lengths were varied while designing piled raft foundations having varying length of piles. The total pile length for all the piled raft foundation models with varying pile length was kept equal to the total pile length as in case of the piled raft foundation model with uniform length piles, i.e., $9L_P$ (L_P = 8 m). Based on the length of pile varied across the pile group, six different piled raft configurations were adopted as shown in Table 3, Type A, B, C, D, E and F; along with the piled raft foundation with uniform pile length, Type U. For each piled raft configuration, four pile length arrangements (A_1, A_2, A_3 and A_4) were taken into consideration. The lengths of piles used for different piled raft configurations are shown in Table 4.

Table 1. Material properties used in the parametric study.

Materials	Properties	Values
Soil	Young's modulus, E_s (MPa)	10
	Poisson's Ratio, μ_s	0.45
	Bulk unit weight, γ_b (kN/m^3)	16
	Undrained cohesion, c_u (kPa)	20 (soft clay)
	Angle of internal friction, ø (°)	0
Raft	Young's modulus, E_r (GPa)	25
	Poisson's Ratio, μ_r	0.2
Pile	Young's modulus, E_p (GPa)	25
	Poisson's Ratio, μ_p	0.2

Table 2. Piled raft geometrical configurations.

Parameters	Value
Raft width (B_r)	6.5 m
Raft width (L_r)	6.5 m
Raft thickness (t_r)	0.75 m
Pile length (L_P)	8 m*
Pile diameter (d_P)	0.45 m
Pile spacing (s_P)	4, 6
Number of piles	9

*Standard value for uniform length piled raft founndation

These 24 piled raft foundation models with varying lengths of piles along with the piled raft foundation model with uniform length piles (Table 4) were analyzed with pile spacing (s_P) to pile diameter (d_P) ratio equal to 4 and 6 i.e., s_P/d_P ratio of 4 and 6

[32]. The ultimate load carrying capacity values for all the piled raft foundation models were evaluated by using double tangent method [31] for the respective load settlements curves obtained after the analysis. The average settlement (s_{avg}) of the piled raft foundation was evaluated using Eqn. 1 [24] and the differential settlement (s_{diff}) was calculated using Eqn. 2 [3]

$$s_{avg} = (2s_{centre} + s_{corner})/3 \tag{1}$$

$$s_{diff} = (s_{centre} - s_{corner}) \tag{2}$$

where s_{centre} is the settlement at the raft centre and s_{corner} is the settlement at the raft corner. The load sharing between the structural elements can be represented in term of a coefficient α_{pr} known as pile raft coefficient [8]. α_{pr} can be defined as the ratio of total design load carried by the piles (Q_g) to the load applied on the foundation (Q).

$$\alpha_{pr} = Q_g / Q \tag{3}$$

α_{pr} = 0 represents a foundation with no piles i.e., a shallow foundation; α_{pr} = 1 represents a fully piled foundation, with the raft having no contact with the ground; and in the range of $0 < \alpha_{pr} < 1$ represents the case of piled raft foundation.

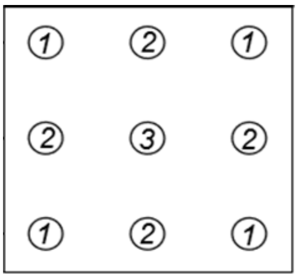

Fig. 2. Plan of piled raft foundation.

Table 3. Different Piled raft configurations adopted based on pile length varied across the pile group.

Type	Centre pile	Edge pile	Corner pile
A	Shortest	Intermediate	Longest
B	Shortest	Longest	Intermediate
C	Longest	Intermediate	Shortest
D	Longest	Shortest	Intermediate
E	Intermediate	Longest	Shortest
F	Intermediate	Shortest	Longest
U	Uniform	Uniform	Uniform

Table 4. Pile lengths based on the location of piles used for different piled raft configurations

Type	A_1	A_2	A_3	A_4
A	1: 1.25 L_P 2: 0.875 L_P 3: 0.85 L_P	1: 1.3125 L_P 2: 0.8125 L_P 3: 0.5 L_P	1: 1.25 L_P 2: 0.8125 L_P 3: 0.75 L_P	1: 1.125 L_P 2: 0.9375 L_P 3: 0.75 L_P
B	1: 1.25 L_P 2: 0.85 L_P 3: 0.875 L_P	1: 1.3125 L_P 2: 0.5 L_P 3: 0.8125 L_P	1: 1.25 L_P 2: 0.75 L_P 3: 0.8125 L_P	1: 1.125 L_P 2: 0.75 L_P 3: 0.9375 L_P
C	1: 0.8125 L 2: 1.125 L_P 3: 1.25 L_P	1: 0.875 L_P 2: L_P 3: 1.5 L_P	1: 0.8125 L_P 2: L_P 3: 1.75 L_P	1: 0.75 L_P 2: L_P 3: 2 L_P
D	1: 1.125 L_P 2: 0.8125 L_P 3: 1.25 L_P	1: L_P 2: 0.875 L_P 3: 1.5 L_P	1: L_P 2: 0.8125 L_P 3: 1.75 L_P	1: L_P 2: 0.75 L_P 3: 2 L_P
E	1: 0.5 L_P 2: 1.5 L_P 3: L_P	1: 0.75 L_P 2: 1.25 L_P 3: L_P	1: 0.875 L_P 2: 1.125 L_P 3: L_P	1: 0.8125 L_P 2: 1.15625 L_P 3: 1.125 L_P
F	1: 1.5 L_P 2: 0.5 L_P 3: L_P	1:1.25 L_P 2: 0.75 L_P 3: L_P	1: 1.125 L_P 2: 0.875 L_P 3: L_P	1: 1.15625 L_P 2: 0.8125 L_P 3: 1.125 L_P
U	1: L_P 2: L_P 3: L_P			

4 Results and Discussion

4.1 Ultimate load carrying capacity of piled raft foundation

This section discusses the effect of pile spacing and varying the pile lengths across the pile group on the ultimate load carrying capacities of all the piled raft foundation models. The ultimate load carrying capacities of all the models with s_P/d_P ratio of 4 and 6 are in Fig. 3 and Fig. 4, respectively. It can be noted that the load carrying capacity decreased as the pile spacing increased for all the piled raft foundation models. Similar results were observed previously by [5,27]. This decrease in capacity of the piled raft system can be attributed to the reduction in the pile group effect with increased pile spacing. However it should be noted that in order to make up for the reduction in the capacity of the piled raft system the raft contribution increases with increased pile spacing.

It can also be seen that for both s_P/d_P ratio of 4 and 6, in comparison to the piled raft foundation with uniform length piles (Type U), the piled raft configuration with longest pile at the centre, intermediate length piles at the edges and shortest pile at the corners (Type C) with A4 arrangement, showed the highest improvement in ultimate load carrying. This is in accordance with the practical implication of the piled raft foundation design of Messe Trum Tower in Frankfurt [19], where longer length piles were provided at the central region of the raft and pile lengths gradually decreased towards the raft edges. For both the pile spacing considered, Type A and Type F showed relatively lesser values of ultimate load carrying capacities in comparison to other piled raft configuration models.

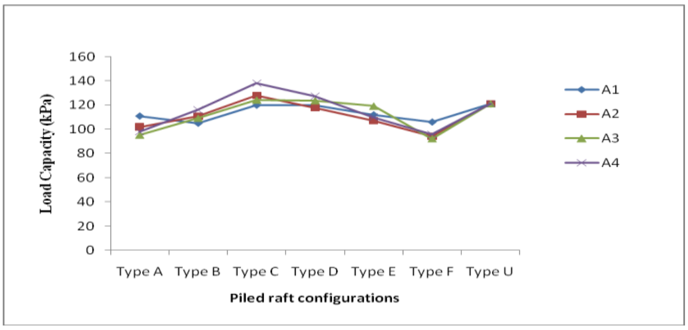

Fig. 3. Ultimate load carrying capacities of piled raft foundation models (s_P/d_P ratio 4)

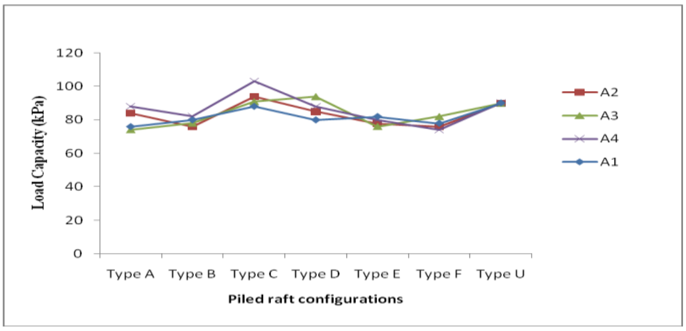

Fig. 4. Ultimate load carrying capacities of piled raft foundation models (s_P/d_P ratio 6)

4.2 Load sharing of piled raft foundation

For the safe and economic design of piled raft foundation it is very essential to determine the relative proportion of the design load carried by each structural component, i.e., the raft and the pile group [19]. Pile raft coefficient (α_{pr}) indicates the portion of load carried by the piles in piled raft foundation system. The remaining load is considered to be carried by the raft in contact with the soil underneath. The total load carried by the piles is evaluated by determining the summation of the loads on different pile heads. From Fig. 5 and Fig. 6 it can be seen that with the increase in pile spacing α_{pr} decreases i.e., the proportion of total load carried by the raft increases. This is due to the fact that with the increase in pile spacing the raft-soil contact stresses increases, thus rafts contribution in load sharing increases [27]. The results are similar to those observed by [2]. For both s_P/d_P ratio of 4 and 6, α_{pr} was observed to be higher in case of Type A and Type F configuration piled raft models in comparison to Type U configuration model. On the other hand, Type C configuration piled raft models showed the lowest α_{pr} values compared to other piled raft foundation models, indicating more contribution of raft in load sharing.

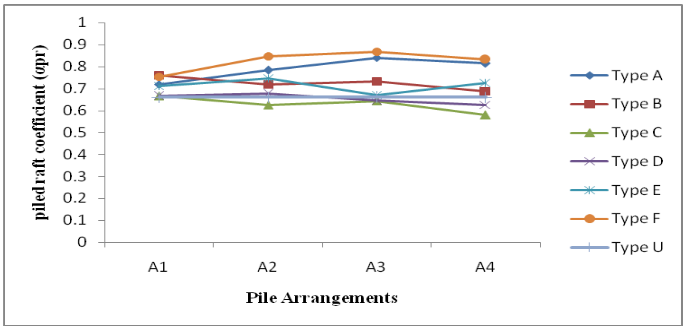

Fig. 5. Pile raft coefficients of piled raft foundation models (s_P/d_P ratio 4)

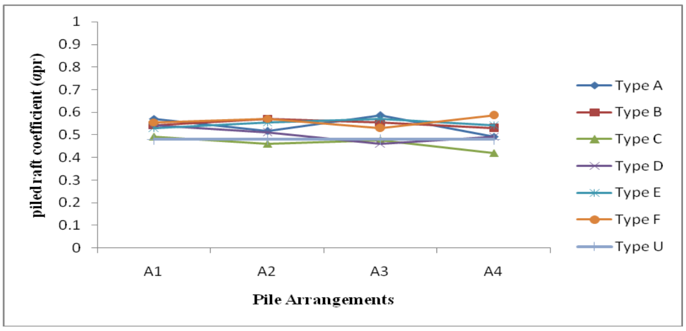

Fig. 6. Pile raft coefficients of piled raft foundation models (s_P/d_P ratio 6)

4.3 Average settlements

The average settlement of all the piled raft foundation models with different pile spacing is shown in Fig. 7 and Fig. 8. It is evident from the figures that the average settlement reduced with increased pile spacing. Similar results were encountered by [3,25]. This is due to the fact that with the increase in pile spacing the area covered by the piles underneath the raft increases and the load gets uniformly distributed, resulting in decrease in average settlements. Type A and Type B configuration piled raft models shows higher values of average settlements whereas, Type C piled raft foundation models show lower average settlement values compared to Type U piled raft foundations.

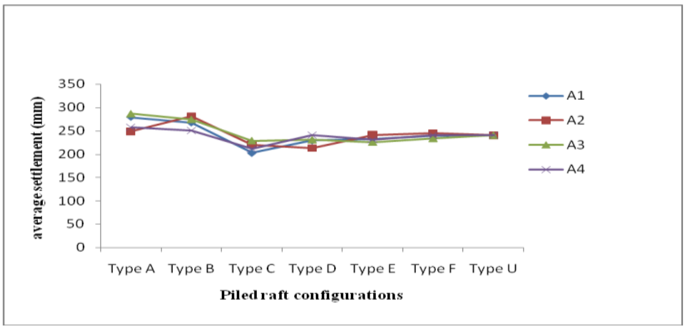

Fig. 7. Averge settlements of piled raft foundation models (s_P/d_P ratio 4)

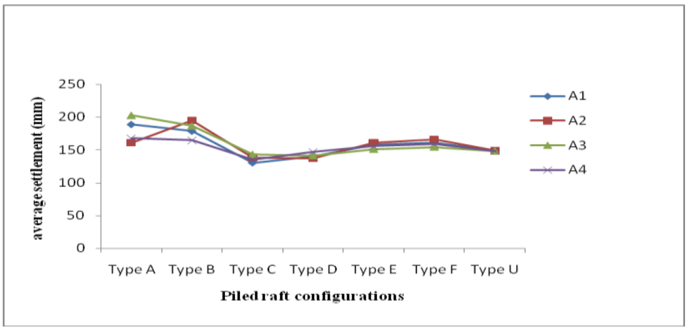

Fig. 8. Averge settlements of piled raft foundation models (s_P/d_P ratio 6)

4.4 Differential Settlements

Fig. 9 and Fig. 10 show the effect of pile spacing and varying the pile lengths across the pile group on the differential settlements of all the piled raft foundation models. It can be seen that with the decrease in pile spacing the differential settlement decreases. Similar results were observed by [11,16,23]. This may be due to increase in central raft sagging, having lesser pile support with increased pile spacing [23]. It can also be seen that the differential settlements were lowest in Type C, A4 arrangement piled raft model in comparison to Type U piled raft model.

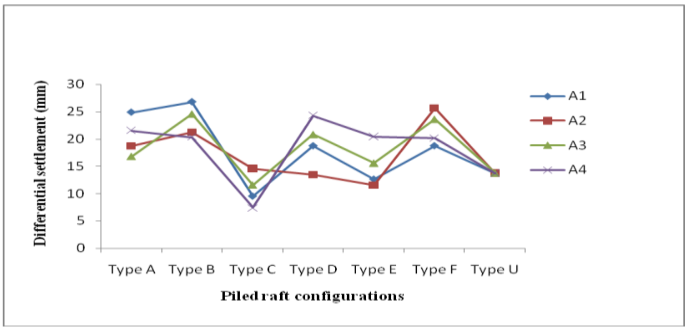

Fig. 9. Differential settlements of piled raft foundation models (s_P/d_P ratio 4)

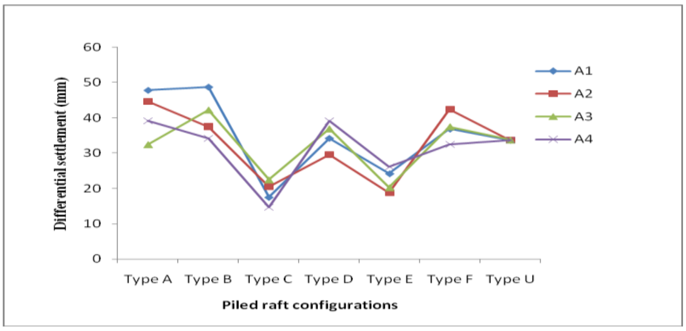

Fig. 10. Differential settlements of piled raft foundation models (s_P/d_P ratio 6)

5 Conclusions

The conclusions that can be drawn from the 3D finite element analysis carried out on piled raft foundations founded on soft clay are as follows:

1. The ultimate load carrying capacity of piled raft foundation system for any piled raft configuration with uniform and varying length of piles decreases with the increase in pile spacing. This is due to the decrease in pile-pile interaction effects in the pile group with the increased pile spacing.
2. Reduction in average settlement and increment in differential settlement with increase in pile spacing was observed for all piled raft configurations. The decrease in average settlement is due to the uniform distribution of piles covering a larger area underneath the raft whereas; the increase in the differential settlement can be attributed to lesser pile support than required to resist sagging at the central portion of the raft with increased pile spacing.
3. Proportion of the design load carried by the piles decreases with the increase in pile spacing due to the increase in raft-soil contact pressure.
4. For both s_P/d_P ratios of 4 and 6, Type C, A4 arrangement piled raft foundation model, having maximum length of pile at the centre ($2L_P$), intermediate length (L_P) at edge and shortest pile length ($0.75L_P$) at corner showed the highest im-

provement in the load carrying capacity and decrease in differential settlement when compared with Type U, uniform pile length piled raft foundation model.

5. The average settlement was noted to be minimum for Type C, A1 arrangement piled raft foundation model with longest pile ($1.25L_P$) at the centre, intermediate length pile ($1.125L_P$) at the edge and shortest pile ($0.8125L_P$) at the corner in comparison with Type U, uniform pile length piled raft foundation.
6. Hence in soft clay instead of providing a conventional piled raft foundation with uniform length piles underneath the raft, a piled raft foundation with Type C pile raft configuration can be suggested to get better performance with the same volume of pile material.

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