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Numerical investigation on the performance of Piled Raft Foundation in Soft Clayey Soils

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***Abstract* -** In general high-rise buildings are predominantly supported by piled raft foundations. Deep foundations (piles) are very effective for heavy structures because piles penetrate through the weak or soft soil deposits to the stiff soil or bed rock to support the structure weight. This paper aims to present the performance of piled raft foundation with medium embedment depth in soft clayey soils. A numerical model was developed to simulate the case of a piled raft rigid foundation installed in soft clay. A parametric study is conducted to examine the effect of the geometry of the foundation system (such as piles diameter, length and spacing), and the rigidity ratio between piles material and clay, on the performance of this type of foundation system on soft soils. Moreover, the failure mechanism of such foundation system under loading is examined. Based on the observed failure mechanism, an efficiency factor for the ultimate carrying capacity (q_u) of piled raft foundation is proposed. Furthermore, a semi-empirical model for the determination of improvement factor (*IF)*, for a given soil/pile/geometry conditions, is developed based on the parametric study.

***Keywords*:** Piled raft foundation, performance, carrying capacity, failure mechanism, efficiency factor.

1. Introduction

It is well established that when two columns are near one another and isolated footing for each column would overlap or be excessively close, a combined footing may be used. When the total area of isolated footings would exceed 50% of the area that strip footing would have to support the line of columns, a strip footing is preferable. However, when the ground soil is poor or soft mat foundation is the more appropriate. Nowadays, constructions of medium to high rise buildings are very common due to the expansion and development of urban areas. The foundation system required for such buildings are raft foundations resting on piles. Introducing piles elements with the raft to reduce raft settlement was developed by Burland et al. [1]. According to Sinha and Hanna [2], piled raft foundation was constructed about fifty years ago and the attempt to capture its performance was started in the early eighties, which has intensified in the last few years.

Extensive research has been done so far on the behaviour of piled raft foundations. In order to evaluate the behaviour of piled-raft systems, some researchers carried out laboratory tests (among others, Horikoshi and Randolph, [3], Lee et al., [4], Fattah et al., [5]). In order to understand the design of piled raft foundations, small scale model studies and centrifuge models were carried out (e.g.Turek and Katzenbach, [6]; Balakumar and Ilamparuthi, [7]; Katzenbach et al., [8]; Poulos, [9]). Some others used computational methods to evaluate and predict the performance of piled-raft foundations. Numerical studies have been reported on the settlement and bearing behaviour of these type of foundation systems (among others, Reul, [10]; Sanctis and Mandolini, [11]; Leung et al. [12]; Lee et al., [13]; Cho et al., [14]; Fakharian and Khanmohammadi, [15]; Nakanishi and Takewaki, [16]). Likewise, various analytical modelling were conducted on piled rafts. Furthermore, alternative design and analysis approaches for this type of foundations was investigated by means of modelling the piled raft foundation in the form of plate loaded spring (among others, Clancy and Randolph, [17]; Poulos et al. [18]; Kim K N et al, [19]; Kitiyodom et al., [20]; Poulos, [21]; Ai and Yan, [22]).

Most of the contemporary design practice is based on standard or traditional group pile or block failure theory, which ignores the actual failure mechanism of the piled raft foundation and the interaction between the raft and piles. Moreover, the critical spacing beyond which the contribution of the pile group, on the carrying capacity of piled raft foundation, should be neglected is not defined. The influence of the rigidity of the pile material on the performance of the piled raft foundation installed in soft soils is not well inquired into. The objective of this paper is to investigate the performance of piled raft foundation with medium embedment depth in soft clayey soils. A numerical model was developed to simulate the case of a piled raft rigid foundation installed in soft clay. A parametric study is conducted to examine the effect of the geometry of the foundation system (such as piles diameter, length and spacing), and the rigidity ratio between piles material and clay, on the performance of this type of foundation system on soft soils. Moreover, the failure mechanism of such foundation system under loading is examined. Based on the observed failure mechanism, an efficiency factor for the ultimate carrying capacity (q_u) of piles raft foundation is proposed. Furthermore, a semi-empirical model for the determination of the improvement factor (*IF*), for a given soil/loading/geometry conditions, is developed based on the parametric study.

2. Numerical Model

A numerical model was developed using a nonlinear elastoplastic finite-element technique to simulate the case of a piled raft foundation installed in soft clayey clay. The finite element modeling was performed using PLAXIS 3D. The model consists of 20 m square rigid raft foundation resting on the piled raft or on untreated layer of soft clay underlined by a thick layer of sand.

For all the soil elements 10-noded tetrahedral elements were used for 3D meshing. A medium mesh generation was used for the global coarseness of the model, whereas it was refined two times in areas where higher stresses and displacements were expected. For piles, circular steel tube piles were modelled using embedded pile, which is considered as a beam element which interact and connect with soil with special interface elements (skin resistance and foot resistance). Boundaries of the model were set by trails so that the horizontal and vertical stress confinements were eliminated. Fixed support was assumed at the bottom of the mesh, and roller supports were used on the vertical boundaries (Figures 1 and 2).

The constitutive law of Mohr Coulomb was used to represent the different soils. Soft clay and sand were modelled using elastic perfectly-plastic Mohr-Coulomb model which work with five basic parameters, Young's modulus ($\boldsymbol{E}$), Poisson's ratio (v), cohesion (c), angle of shearing resistance (φ), and angle of dilatancy ($\boldsymbol{\psi}$). The results produced by the present numerical model were validated with the numerical test results available in the literature (Sinha and Hanna, [2]), where good agreement was noted (Figure 3). Moreover, after the validation of the numerical model, some preliminary tests were undertaken in order to ensure the repeatability of the tests and the accuracy of the results. Three identical tests were carried out under the same conditions. It was noted that the obtained results are very close to one another concluding that there was good repeatability in these tests.

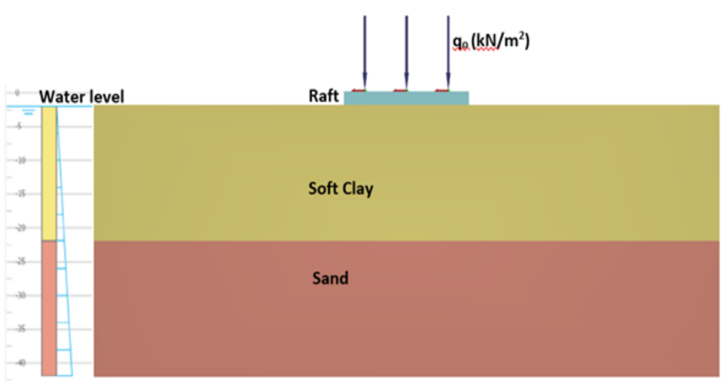

Fig. 1: Layout of the numerical model (side view).

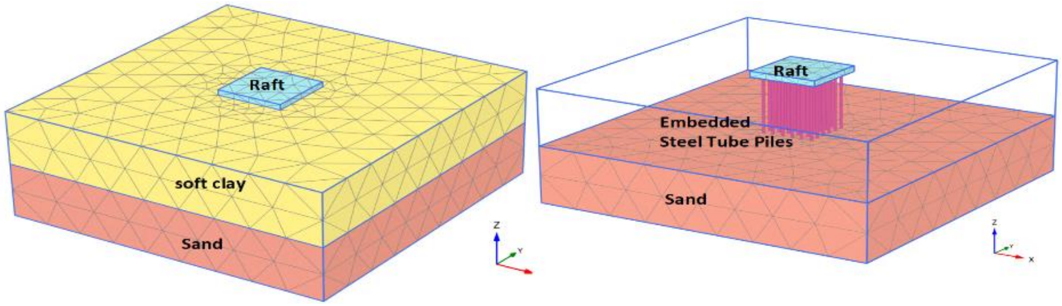

Fig. 2: Layout of the numerical model (perspective).

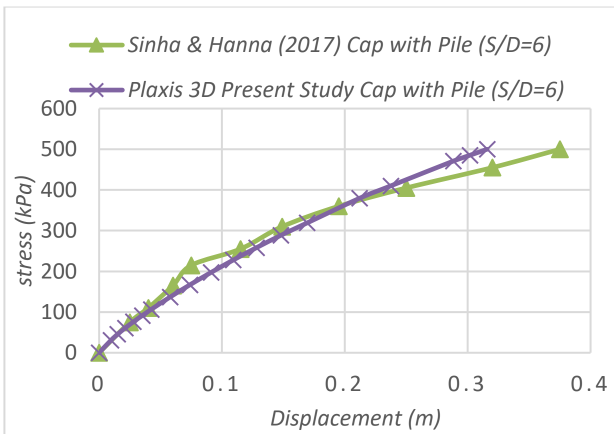

Fig. 3: Validation of the present numerical model

3. Parametric Study

Table 1 presents the range of parameters that is believed to govern the cases encountered in practice. In this investigation, each parameter was isolated and individually examined to determine its effects on the ultimate carrying capacity of raft or piled raft foundation on soft soil. The stress-strain characteristics of raft foundation and piled raft foundation obtained from the present numerical study are presented in Figure 4(*a*). Based on this figure, there is no significant difference in the general trend of these curves apart from the decreasing rate of strain for a given stress with the increase of the ratio of spacing to pile diameter (*S/D*) as the foundation system approaches its ultimate stress. Since no distinct indication of failure could be observed from these graphs, Chin's stability method was used to predict the ultimate carrying capacity of the foundation system under different conditions. For all these curves Chin's stability plot [23] was used to determine the ultimate carrying capacity of the piles. This method assumes that the stress-strain curve of the piled raft foundation when the load approaches the failure stress is of a hyperbolic form, and the plot of ratio of strain of the piled raft foundation to the applied stress on its top (ε/σ) against an abscissa of the strain of the piled foundation (ε) is linear. The inverse slope of this line would therefore give the ultimate carrying capacity of the piled raft foundation (Figure 4*b*). The variation of the obtained values of the ultimate carrying capacity of the piled raft foundation with the ration *S/D* is presented in Figures 5(*a*) and 5(*b*). It is clear from these figures that the ultimate carrying capacities of these piled raft foundation decreased with increase in the ratio (*S/D*).

Table 1: Range of Parameters Used in the Numerical Model.

Material	Properties	
Soft Clay	Unit weight, γ_{unsat}, γ_{sat}	17, 18 kN/m^3
	Young's modulus, E_s	4, 6 and 8 MPa
	Poisson's ratio, v_s	0.5
	Angle of friction, φ	0°
	Cohesion, c	25 kPa
Sand	Unit weight, γ_{unsat}, γ_{sat}	17.5, 19.5 kN/m^3
	Young's modulus, E_s	28 MPa
	Poisson's ratio, v_s	0.3
	Angle of friction, φ	42°
	Cohesion, c	0
Raft	Young's modulus, E_r	27.8 GPa
	Poisson's ratio, v_r	0.15
Pile	Young's modulus, E_p	210 GPa

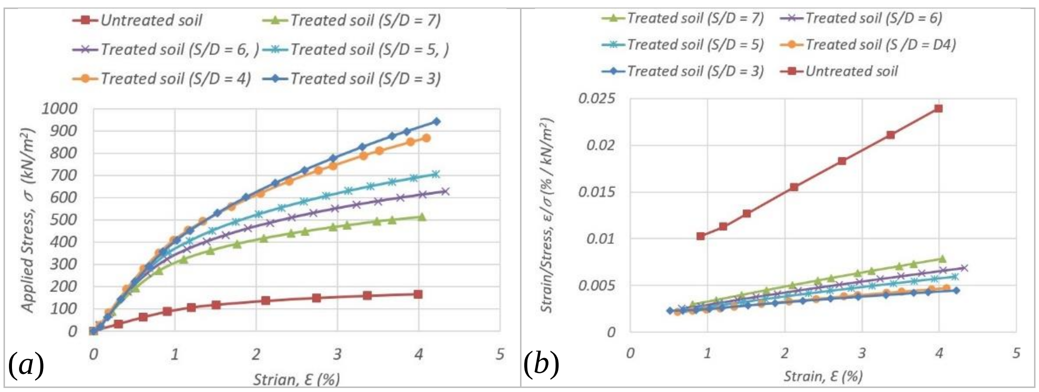

Fig. 4: (*a*)Stress against Strain for the cased of *H/D* = 40, *Ep/Es* = 52500 & (*b*) Strain/Stress against Strain (Chin [23]) for raft and piled raft foundation for the cased of *H/D* = 40, *Ep/Es* =52500.

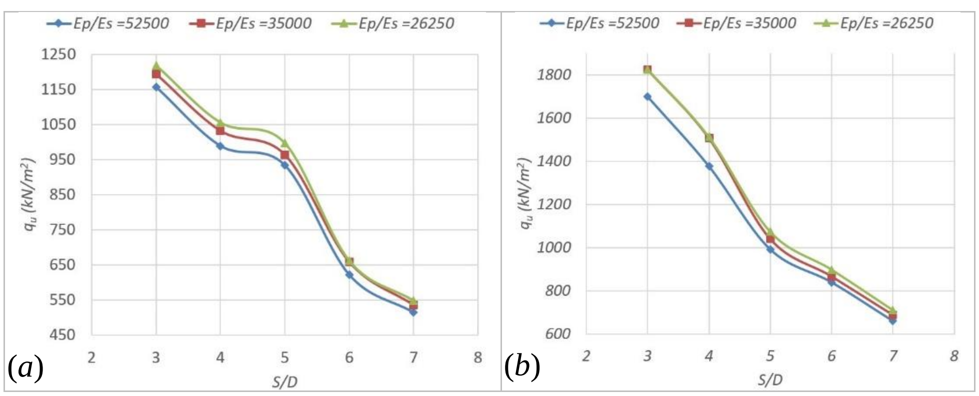

Fig. 5: (*a*)Variation of the ultimate carrying capacity (q_u) with the ration *S*/*D* for *H*/*D* = 50 & (*b*)Variation of the ultimate carrying capacity (q_u) with the ration *S*/*D* for *H*/*D* = 40.

To show clearly the effect of piles spacing and their rigidity on the carrying capacity of the piled raft foundation system, the term improvement factor (*IF*) was introduced. It is defined as the ratio between the ultimate carrying capacity of piled raft foundation to that of raft foundation only. The variation of this improvement factor (*IF*) with the ratio (*S/D*) is presented in Figure 6(*a*) and 6(*b*). It is clearly indicated that the piles spacing significantly affect the performance of the piled raft foundation on soft soil. The relationship between (*IF*) and (*S/D*) can be considered as linear. Furthermore, it can be deduced from these figures that, when the ratio *S/D* is greater than 10 (*S/D* > 10), the influence of piles on the ultimate carrying capacity of the piled raft foundation is not significant. The raft can be considered in this case as single acting alone on the soft soil.

Figures 6(*a*) and 6(*b*) show also the effect of the ratio between the modulus of elasticity of piles and soft soil (E_p/E_s) on the improvement factor. It can be noted from these figures that, the improvement factor is lower for piles with higher modulus of elasticity (higher rigidity). Commonly, this ratio is a governing parameter for piles settlement rather than for the carrying capacity. However, the effect of the ratio (E_p/E_s) on the improvement factor (IF), noted on this investigation, can be explained by the fact that for rigid piles, the settlement of pile under load at the pile tip, and the settlement caused by the load transmitted along the pile shaft, is higher.

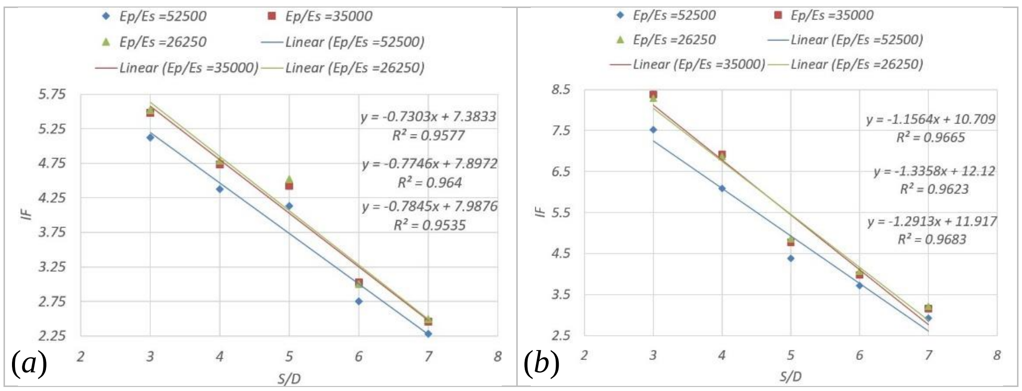

Fig. 6: (*a*)Variation of the improvement factor (*IF*) with the ration *S*/*D* for *H*/*D* = 50 & (*b*)Variation of the improvement factor (*IF*) with the ration *S*/*D* for *H*/*D* = 40.

The present numerical model was used to examine the failure mechanism of the piled raft foundation under loading. It was deduced that the foundation system fails by bearing at the tip of the piles and also by shear along the side of the piles group (Figure 7). In 2-D plan, the failure by shear has a trapezoidal form. When the width of the raft foundation is larger than the width of the piles group, the shear failure along the side of the observed trapezoid can be presented by a straight line. This line passes from the corner edge of the raft to the tip corner of the pile group with and angle to the vertical (θ), Eq. (1):

$$\tan(\theta) = \frac{B - B_g}{2H} \tag{1}$$

Where:
B = Width of raft foundation,
B_g = Width of piles group,
H = High or length of piles group

4. Analytical Developments

As stated previously, depending on their spacing within the group, the piles are generally considered as block, ignoring the effect of the raft. Based on that, several equations for the group efficiency were proposed. They were based on the assumption that when the piles are placed close to each other, the stress transmitted by the piles to the soil will overlap, reducing the carrying capacity of the piles. However, Based on the observed failure mechanism, it is clear that there is an interaction between the raft and pile group. To take into account this interaction a new expression for the efficiency factor (η) for piled raft foundation is defined (Eq. 2):

$$\eta = \frac{q_{g(u)}}{\Sigma q_u} \tag{2}$$

Where:
η = group efficiency,
$q_{g(u)}$ = ultimate carrying capacity of the group pile,
q_u = ultimate carrying capacity of each pile without the group effect.

Since the piles group is embedded in soft clayey soil, it is reasonably to believe that the piled raft foundation fails more rapidly by shear rather than by bearing. According, a simplified analysis is performed to obtain the group efficiency for pile group in soft soil, as follows, Eq. (3):

$$q_{g(u)} = P_g H f_{av} \tag{3}$$

Where:
P_g = the average the perimeter of the cross-section raft/piles group P_g = [2(n_1+n_2 -2) S + 4D +2(B + L)]
n_1 and n_2 = number of piles in both directions
S = Spacing
D = Diameter of piles
L = Length of raft foundation
f_{av} = average unit frictional resistance.

Similarly, for each pile acting individually Eq. (4)

$$q_u = P_i H f_{av} \tag{4}$$

Where:
P_i = the perimeter of the individual pile
Thus: Eqs. (5) & (6)

$$\boldsymbol{\eta = \frac{q_{g(u)}}{\Sigma q_u} = \frac{f_{av}\left[\frac{2(n_1+n_2-2)S+4D+2(B+L)}{2}\right]H}{\pi n_1 n_2 D H f_{av}}} \tag{5}$$

$$\eta = \frac{(n_1+n_2-2)S+(B+L)+2D}{\pi n_1 n_2 D} \tag{6}$$

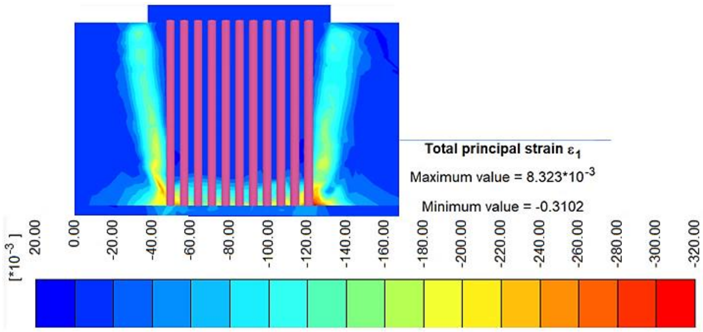

Fig. 7: The observed failure mechanism for the case of H/D = 40, S/D = 3, E_p/E_s =52500).

It is worthy to note that this expression of (η) is valid only when the ratio $8 \geq S/D \geq 2$. Moreover, when $S/D > 10$, the raft is considered as acting alone and the effect of piles is neglected. This factor is greater than 1 ($\eta > 1$).

As mentioned previously, the results of the parametric study were also used to develop a semi-empirical model to predict the Improvement Factor *(IF)* of the piled raft foundation. Based on the results presented in Figure 6(*a*) and 6(*b*), and using a least square regression, the following expression Eq. (7) was established for the estimation of the improvement factor of such foundation system:

$$IF = \left(4.3 \times 10^{-6}\ \frac{E_p}{E_s} - 1.1\right)\frac{S}{D} - \left(4 \times 10^{-5}\ \frac{E_p}{E_s} - 8.2\right) \tag{7}$$

5. Conclusion

A numerical model was developed to investigate the performance of group piles installed in soft soils under a raft foundation. A parametric study was conducted on the parameters believed to govern this complex behavior. The following conclusions were drawn:

1. There is no significant difference in the general trend of the stress-strain curves of the piled raft foundation on soft soils apart from the decreasing rate of strain for a given stress with the increase of the ratio of spacing to pile diameter (S/*D*), as the foundation system approaches its ultimate stress.
2. The ultimate carrying capacities of the piled raft foundation decreased with increase in the ratio (S/D).
3. The piles spacing significantly affect the performance of the piled raft foundation on soft soil. The relationship between the improvement factor (*IF*) and (S/D) can be considered as linear. Moreover, when the ratio S/D is greater than 10 ($S/D > 10$), the influence of piles on the ultimate carrying capacity of piled raft foundation is not significant.
4. The improvement factor (*IF*) is lower for the more rigid piles. This can be explained by the fact that the rigid piles penetrate more easily in the layer of sand situated beneath the layer of the soft soil.
5. The piled raft foundation system fails by bearing at the tip of the piles and also by shear along the side of the piles group. The failure by shear has a trapezoidal form, which can be considered in 2-D plan as straight line.
6. Based on the observed failure mechanism, an efficiency factor of the ultimate carrying capacity of a piled raft foundation was defined.
7. Based on the parametric study, a semi-empirical model to predict the ultimate carrying capacity of the piled raft foundation was developed.

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