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Numerical Analysis of the Carrying Capacity of a Piled Raft Foundation in Soft Clayey Soils

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Abstract

Piled raft foundations are a common type of foundation for high-rise buildings. Unlike shallow foundations, deep foundations (piles) pass through weak or soft soil deposits and can reach stiff soil or bedrock to support the weight of the structure. In this paper, the performance of a medium embedment depth piled raft foundation in soft soil is presented. A numerical model was developed and a parametric study was conducted in order to simulate the case of such a foundation system and to investigate its performance in soft clay. This parametric study investigated the effect of the geometry of a piled raft foundation and the stiffness ratio between the pile material and clay on the performance of the foundation system in soft soil. Additionally, the failure mechanism of such a foundation system under load was examined. An analytical model was developed to predict the ultimate carrying capacity based on the observed failure mechanism. A semi-empirical model is proposed for determining the Improvement Factor (*IF*) of a given soil, pile, and geometric condition. Findings of the study indicate that the performance of piled raft foundations on soft soils is significantly affected by the piles' spacing. As the ratio *S*/*D* increases, the ultimate carrying capacity of a piled raft foundation decreases. However, when this ratio exceeds 10 (*S/D* > 10), piles have little or no effect on the ultimate carrying capacity of this foundation system. A piled raft foundation system fails by bearing at the base of the piles and also by shear at the side of the pile group on hyperbolic plans.

Keywords: Performance; Failure Mechanism; Soft Soil; Piled Raft Foundation; Ultimate Carrying Capacity; Improvement Factor.

1. Introduction

A piled raft foundation system, initially proposed by Burland et al. [1], is the ultimate solution for the foundation of any kind of medium to high-rise structure. This system was developed to provide solutions for two main problems in foundation design faced by geotechnical engineers: load-carrying capacity and excessive settlement of the foundation. Mostly, a raft with piles is used to share the load of the superstructure as a unit to enhance its carrying capacity and protect the safety of the foundation against shear failure and to control the settlement of the foundation as a settlement reducer. A limited number of piles may improve the ultimate carrying capacity, the settlement and differential settlement performance, and reduce the required thickness of the raft. Many researchers have studied this foundation system (piled raft) to assess its bearing capacity and settlement [2-13]. Similarly, many numerical studies have examined the settlement and bearing behavior of these types of foundation systems [14–30]. Other studies have investigated the load sharing behavior of piled rafts, which is considered an important component in designing the piled raft foundation system [31–39].

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Rafts with piles resting in the soil are complex structures to study. The design methods available in the literature are mostly based on block failure theory, which does not consider the complexity of the failure mechanism of this system as a unit. To accurately understand the behavior of a piled raft foundation system, the interaction between the foundation components should be considered. To solve this problem, authors have proposed multiple methods, among others [40–48]. Several methods for analyzing piled raft behavior are suggested in the literature. Some approaches are best suited to preliminary design or checking, while others provide detailed predictions that can be incorporated into complex designs. However, there is limited research available on the failure mechanism of the combined foundation system, carrying capacity prediction models based on this observed failure mechanism, or the configuration that limits the interaction between piles and raft.

The purpose of this paper is to provide an evaluation of the performance of pile raft foundations with medium embedment depths in soft clayey soils. A numerical model was developed to simulate the case of such a foundation system installed in soft clay. In this study, a parametric investigation was performed to examine the effect of the geometry of a piled raft foundation and the stiffness ratio between pile material and clay on the performance of a piled raft foundation on soft soils. In addition, the evolution of the failure mechanism of such a foundation system under a loading change was examined. The actual or observed failure mechanism when the applied load approaches the ultimate load capacity was used to develop a theory to predict the ultimate carrying capacity for this foundation system using the limit equilibrium method of analysis. The authors of this paper assert that a more reliable and trustworthy prediction method should be based on the actual or observed failure mechanism. The safe and cost-effective geotechnical design of a piled raft foundation is critically dependent on the representativeness of the failure mechanism. Additionally, the configuration limiting the interaction between the piles and raft was investigated. A parametric study was used to propose a semi-empirical model for determining the improvement factor (*IF*) for a given soil, pile, and geometry condition. The steps followed for the research are shown in Figure 1.

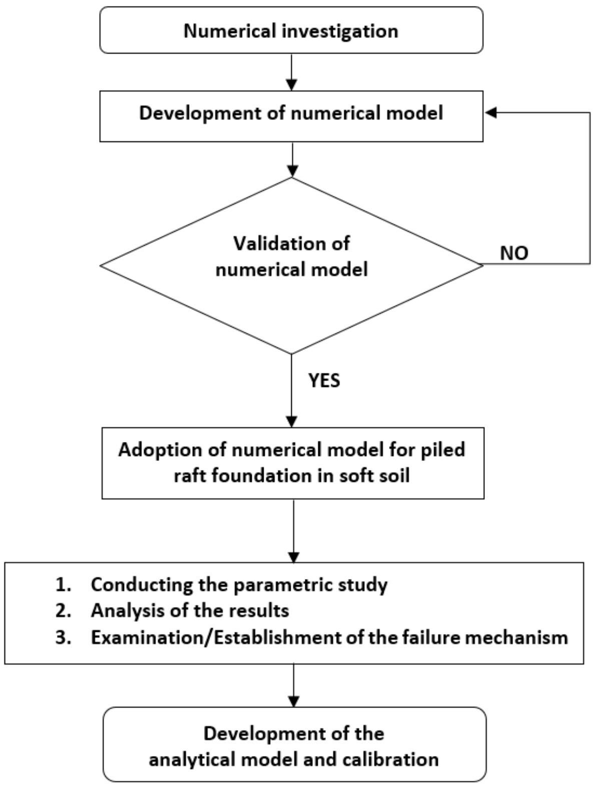

Figure 1. Flowchart for research methodology

2. Numerical Modeling

PLAXIS 3D was used to perform the finite element modeling. The numerical model was developed using a nonlinear elastic-plastic technique to simulate the case of a raft foundation with piles in soft clay. The model consisted of a 20m square rigid raft foundation resting on soft clay (untreated) or on a group of piles underlined by a thick layer of sand.

For all soil elements, three-dimensional meshing was done using tetrahedral elements with 10 nodes. All soil components were modeled using a medium mesh size, and fine to very fine mesh sizes were chosen in areas where higher displacements and stresses were anticipated. For piles, circular steel tube piles were modeled using an embedded pile, which is considered a beam element that interacts and connects with soil with special interface elements (skin resistance and base resistance). Trials were conducted to set the model boundaries to ensure that no horizontal or vertical stress confinement existed in the model. On the horizontal boundaries (bottom of the mesh), a fixed support was assumed, and vertical boundaries were supported by a roller support.

All soil elements were defined based on the constitutive law of Mohr-Coulomb**.** Soft clay and sand were modeled using an elastic perfectly-plastic Mohr-Coulomb model, which works with five basic parameters: Young's modulus (E), Poisson's ratio *(ν)*, cohesion *(c)*, angle of shearing resistance *(φ)*, and angle of dilatancy (ψ).

As mentioned previously, in this study, piled raft foundation in soft soil was investigated using the finite element modeling software Plaxis-3D. The model consisted of a 20m square and 2m thick raft, rigidly connected and sitting on circular steel tube piles 20m in length and diameter ranging between 0.4, 0.5, and 0.6m. The entire piled raft system was considered to be resting on two layers of soil (soft clay underlined by dense sand), each 20m in depth. The water table was considered to be at ground level, as shown in Figure 2.

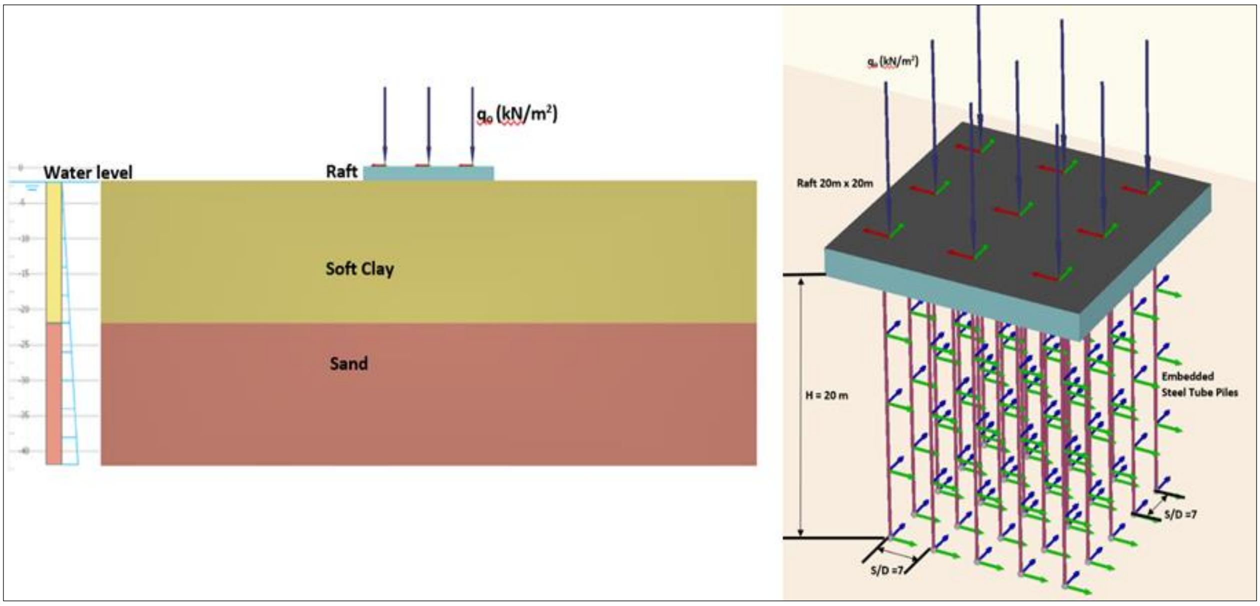

Figure 2. Piled raft foundation system and soil foundation configuration

The raft was modeled as a linear elastic material, whereas the piles were modeled using the embedded pile model, a 3-noded beam element that connected with the soil with special interface elements (skin resistance and foot resistance). On the other hand, the soil structure was modeled as a 10-noded soil element, also known as a tetrahedral soil element.

As indicated previously, the soil was modeled using an elastic, perfectly plastic Mohr-Coulomb model. Overall, a medium mesh size was used for the modeling and analysis of the whole domain, and fine mesh sizes were used in the area where higher stress was expected (Figure 3). The parameters and the properties of the raft, pile, and soil considered in this work are summarized in Table 1.

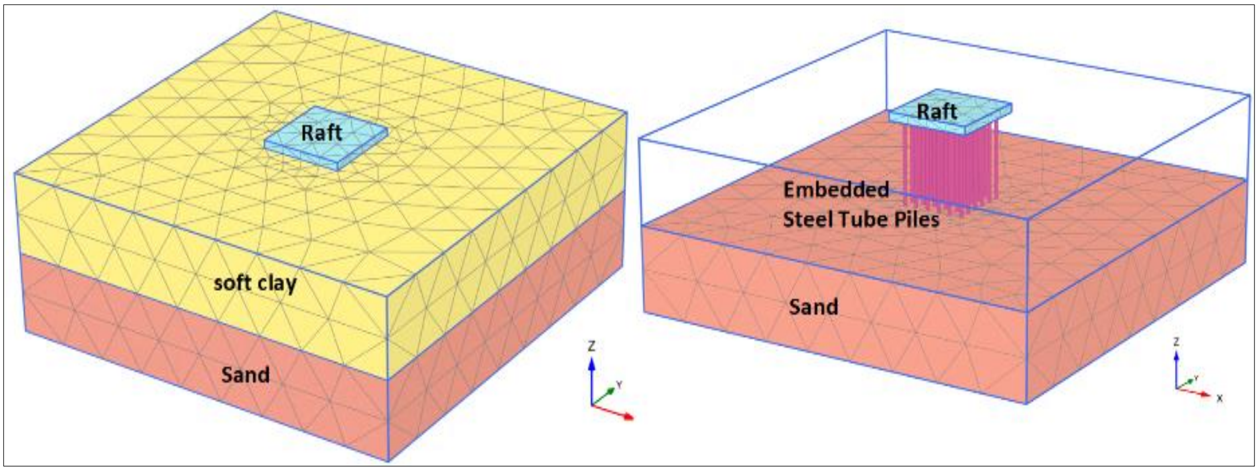

Figure 3. Finite element mesh adopted in the present investigation

Table 1. Validation of the present numerical model with experimental data reported in the literature

References	Parametric Details					Settlements of Piled Raft Foundation (mm)		
	Pile Diameter (m)	Pile Spacing (m)	Pile Length (m)	Raft Area (m^2)	Load Applied (MN)	Previous Works		Present Work
Lee et al. (2010)	0.32	2.5	15	154	12	Numerical Analysis	21	23
						Experimental Work	22	
Cho et al. (2012)	0.9	3	20	429	200	Numerical Analysis	114	131
						Experimental Work	124	

The results obtained from the numerical models were validated against numerical and experimental works available in the literature (Lee et al. [19], Cho et al. [21], and Sinha and Hanna [24]), where alignment was observed (Table 1 and Figure 4). After validation of the numerical model, preliminary tests were performed 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 were similar to each other, indicating that there was good repeatability in these tests.

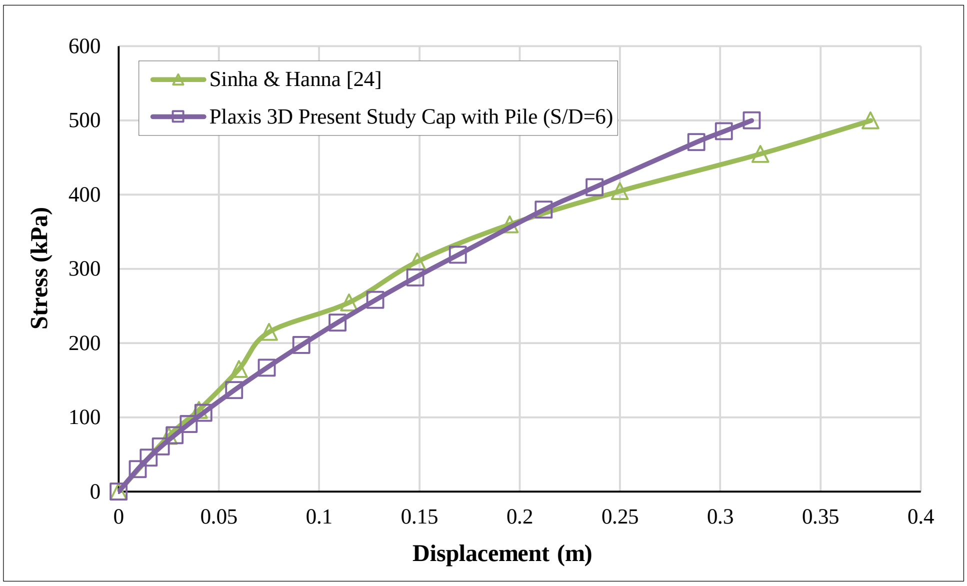

Figure 4. Validation of the present numerical model with numerical results reported in the literature (S/D = 6, H/D = 15, Raft size = 24×24 m^2, number of piles = 16)

3. Results and Analysis

Table 2 summarizes the range of parameters used in this research that are likely to be common in most 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 the raft foundation and piled raft foundation obtained from the present numerical study are presented in Figure 5.

Table 2. Properties of soils, raft, and piles foundation used in this investigation

Materials	Properties	Unit	Value
Soft Clay	Saturated unit weight, γ_{sat}	kN/m^3	18
	Unsaturated unit weight, γ_{unsat}	kN/m^3	17
	Young's modulus, E_s	MPa	4, 6, 8
	Poisson's ratio, ν_s	-	0.4
	Angle of shearing resistance, φ	°	0
	Cohesion	kPa	25
Sand	Saturated unit weight, γ_{sat}	kN/m^3	19.5
	Unsaturated unit weight, γ_{unsat}	kN/m^3	17.5
	Young's modulus, *Es*	MPa	28
	Poisson's ratio, ν_s	-	0.3
	Angle of shearing resistance, φ	°	42
	Cohesion	kPa	0

Raft	Young's modulus, E_r	GPa	27.8
	Poisson's ratio, v_r	-	0.15
Pile	Young's modulus, E_p	GPa	210

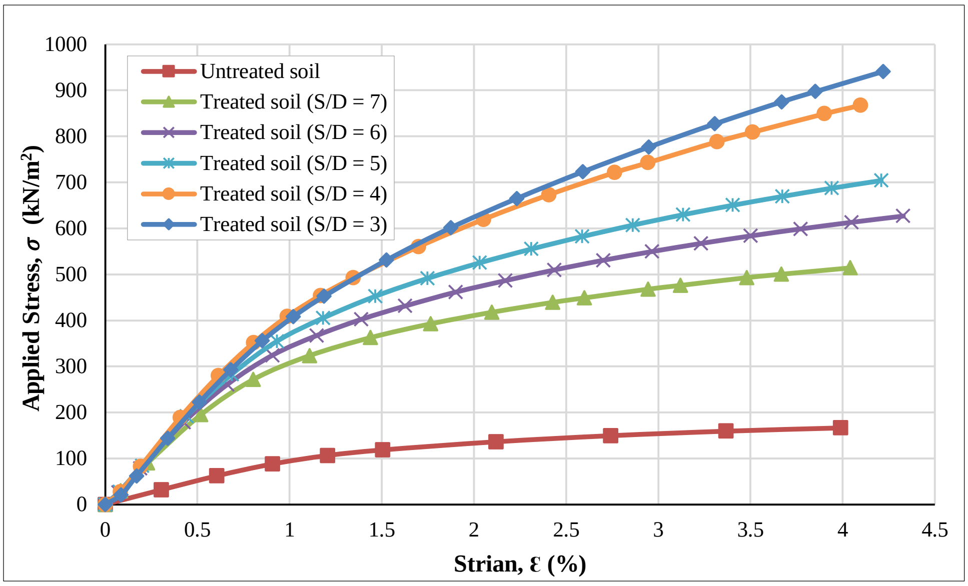

Figure 5. Stress-strain curves for the case of H/D= 40, and E_p/E_s= 52500

The curves of Figure 5 show that a decrease in the spacing to pile diameter ratio (*S/D*) led to an increase in the linearity of these parts, which indicates an increase in the shaft friction or skin friction along the side of the pile group. The slopes of the load displacement curves for different foundation systems tended to become steeper as the ratio of spacing to pile diameter (*S/D*) decreased, compared with the case of raft foundation alone. The behavior of the raft foundation gradually evolved from the load-displacement trend of a bearing footing to that of a bearing and friction foundation system in which greater amounts of settlements were required to mobilize the total carrying load.

Generally, these curves do not show any obvious differences except the strain rate, which decreases with an increase in the spacing to diameter ratio (*S/D*) of piles for a given stress as the foundation system approaches its ultimate stress. Because these graphs showed no distinct failure indication, Chin's stability method [49] was employed to calculate the ultimate carrying capacity of the foundation system under different conditions. For all these curves, the ultimate carrying capacity of the piles was determined by Chin's stability plot [49]. In this method, the ratio of strain over applied stress (ε/σ) is plotted against the strain (ε) from the stress-strain curves of piled raft foundation. The plotted values of this relation (ε/σ against ε) will fall in a straight line, as shown in Figure 6. Based on this line's inverse slope, the ultimate carrying capacity of a piled raft foundation can be computed.

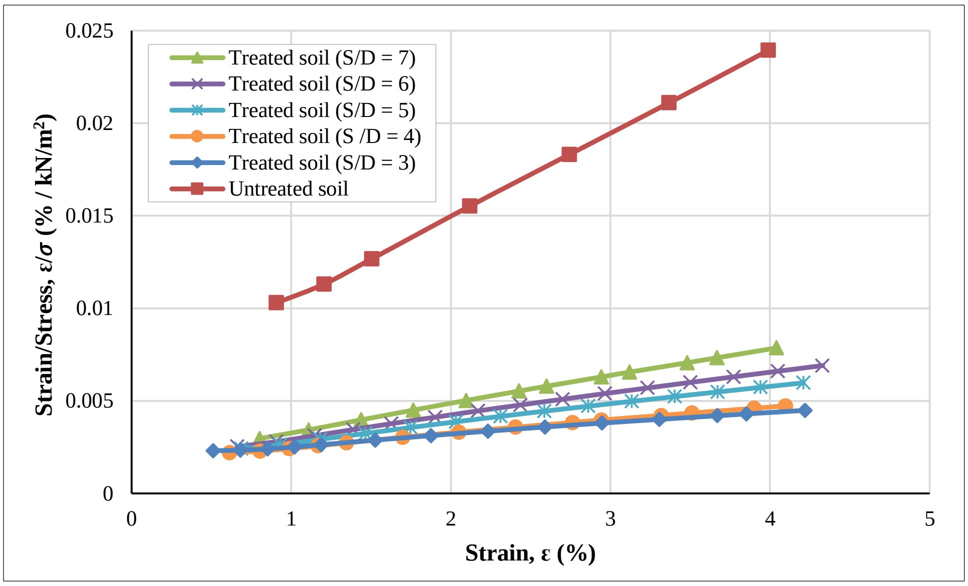

Figure 6. Stain/stress against strain for the case of H/D = 40, and E_p/E_s = 52500

It is obvious from Figure 6 that with the decrease in pile spacing, the ultimate carrying capacities of pile raft foundations increased. The results of all the tested piled raft foundations showed a considerable improvement in ultimate carrying capacities when compared with the results of raft foundation alone (with a minimum of 27% for a piled raft foundation with the ratio S/D = 7). However, it is important to note that the increase in carrying capacities between the different piled raft foundations is relatively low in comparison to the raft foundation alone. By installing the piles within a ration S/D of less than 3, the best improvement in load capacity was achieved. This finding aligns with those of Elwakil and Azzam [50].

The variation of the obtained values of the ultimate carrying capacity of the piled raft foundation with the ratios (*S/D*) and (*H/D*) are presented in Figures 7 and 8, respectively. It is clear from these figures that with an increase in the ratios (*S/D*) and (*H/D*), these foundation systems (piles with raft) showed a reduction in their ultimate load carrying capacity.

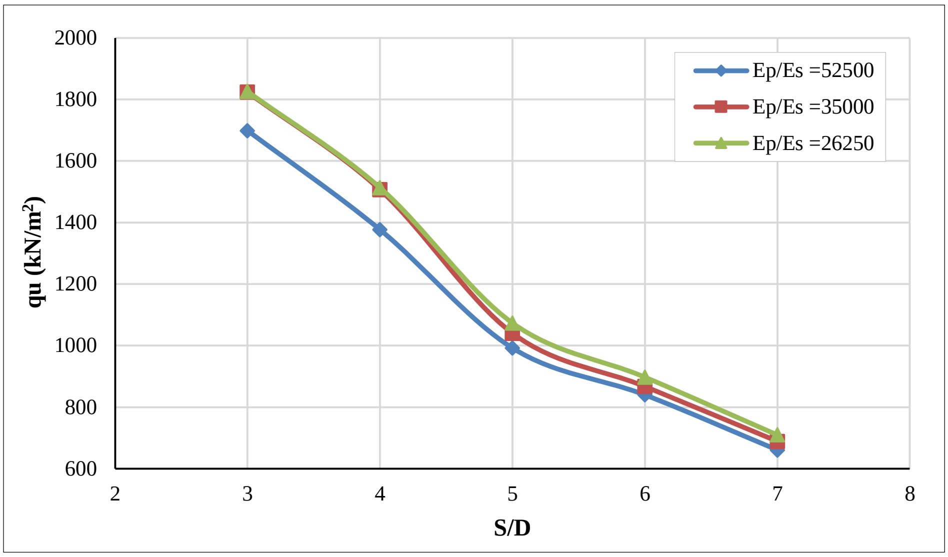

Figure 7. Variation of the ultimate carrying capacity (q_u) with the ratio S/D for H/D = 40

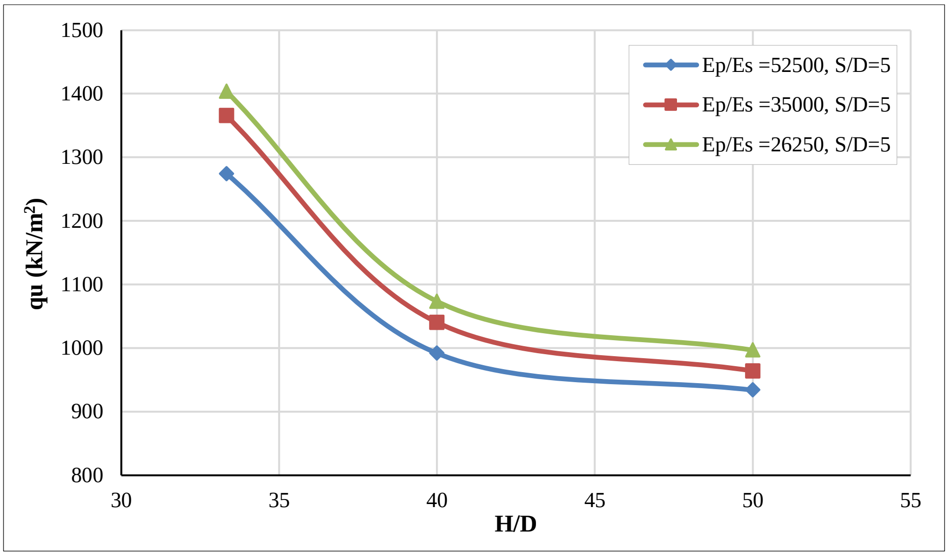

Figure 8. Variation of the ultimate carrying capacity (q_u) with the ratio H/D for S/D = 5

To clearly show the effect of pile spacing and its 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 alone. The variation of this improvement factor (*IF*) with the ratios (*S/D*) and (*H/D*) are presented in Figures 9 and 10, respectively. It is clearly indicated that the performance of piled raft foundation on soft soil is significantly impacted by the pile spacing. The relationship between (*IF*) and (*S/D*) can be considered linear. Furthermore, it can be deduced from these figures that, when the spacing to diameter ratio exceeds 10 (*S/D*> 10), piles have little or no effect on the ultimate carrying capacity of this foundation system. In this case, the raft can be considered as acting alone on the soft soil. Accordingly:

When *S/D*>10: Raft foundation can be considered as acting alone.

When *S/D*<10: Carrying capacity of piled raft = Capacity of raft foundation × *IF*

This finding indicates that when the ratio *S/D* is less than 10, the piled raft foundation concept is a better alternative than the raft foundation alone. Banerjee [51] concluded that piles interact even beyond distances of 8 diameters. Moreover, the results obtained illustrate that the load carried by a raft increases with a reduction in the pile length and the number of piles, which is in accordance with Elwakil and Azzam [50]. The improvement factor is reduced from 5.25 for *S/D* = 3 to 2.25 for *S/D* = 7, which corresponds to a reduction of about 60%.

According to the results presented in Figures 9 and 10, and using a least square regression, the following expression was established for the estimation of the improvement factor of such a foundation system:

$$IF = -a \times \frac{S}{D} - b \times \frac{H}{D} + c a, b, \text{and } c = f\left(\frac{E_p}{E_s}\right) \quad (1)$$

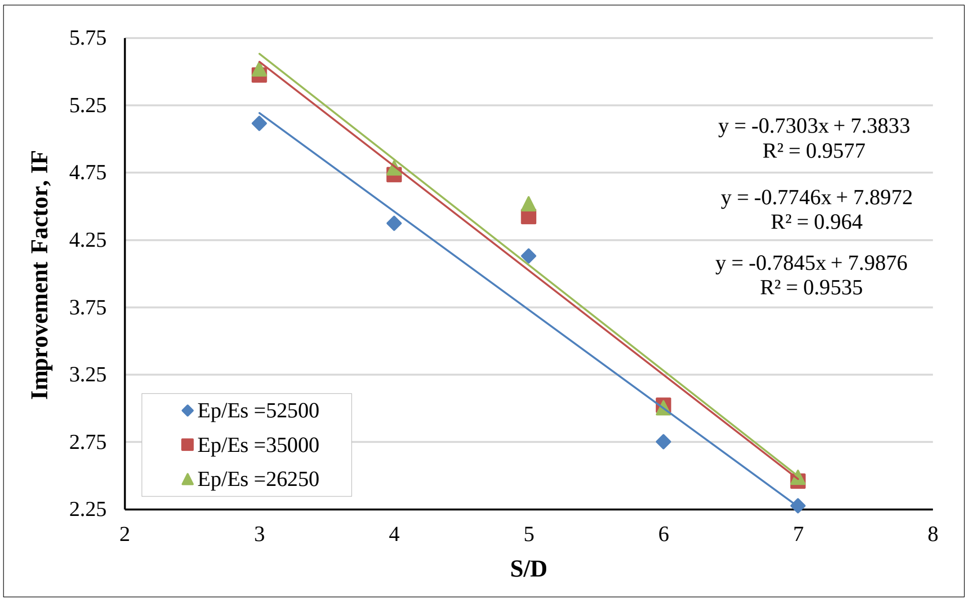

Figure 9. Variation of the improvement factor (IF) with the ration S/D for H/D = 50

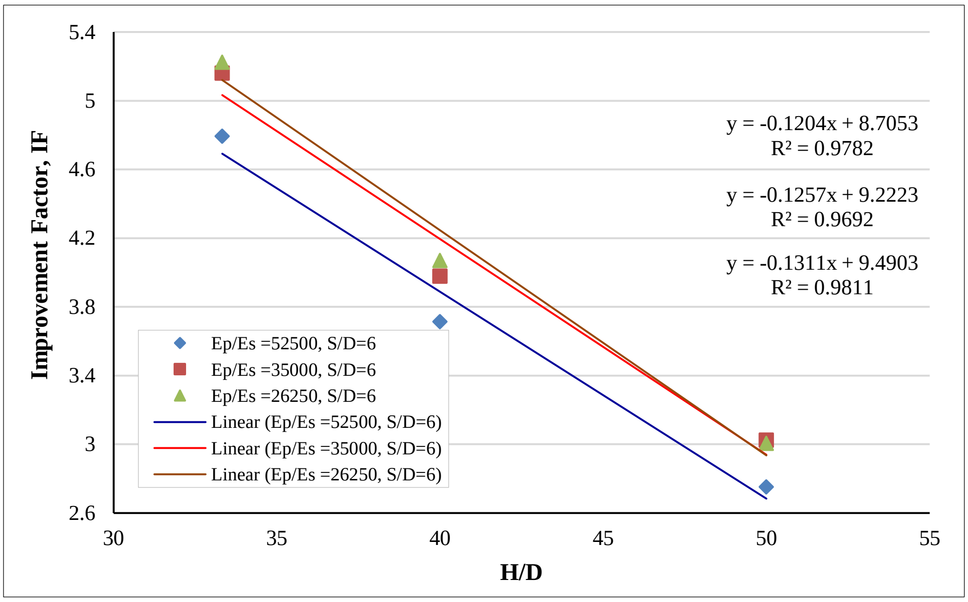

Figure 10. Variation of the improvement factor (IF) with the ration H/D for S/D = 6

Figures 11 and 12 show the effect of the ratio between the modulus of elasticity of piles and soft soil (E_p/E_s) on the improvement factor (*IF*). It can be noted from these figures that the improvement factor is lower for piles with higher modulus of elasticity (higher rigidity). This can be explained by the fact that rigid piles penetrate more easily in the layer of sand situated beneath the layer of soft soil. However, it is worth noting that this ratio is commonly applied as a governing parameter for pile settlement analysis rather than for carrying capacity.

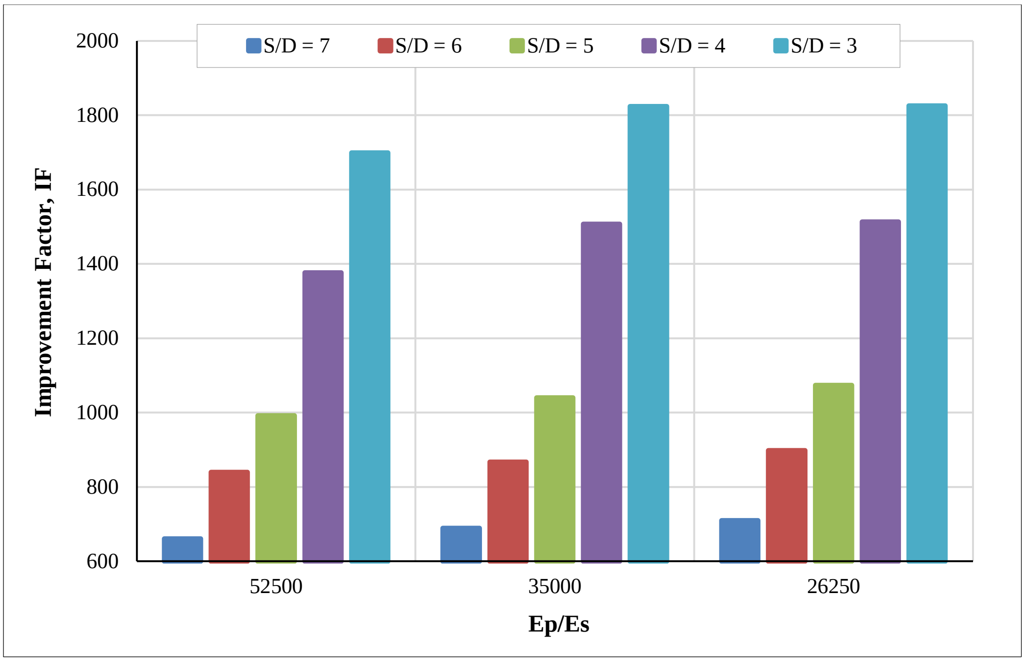

Figure 11. Variation of the improvement factor (IF) with the ration E_p/E_s for H/D = 40

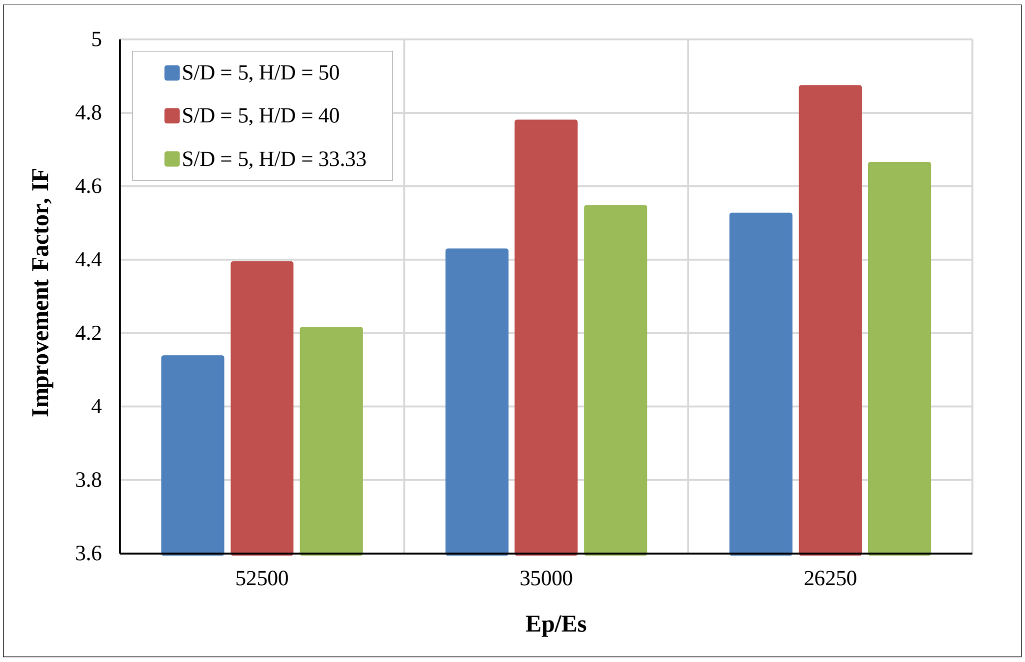

Figure 12. Variation of the improvement factor (IF) with the ration E_p/E_s for S/D = 5

For the range of parameters considered in this investigation, the improvement factor (*IF*) can be expressed by:

$$IF = \left(4.3 \times 10^{-6}\frac{E_p}{E_s} - 1.1\right)\frac{S}{D} - \left(4 \times 10^{-5}\frac{E_p}{E_s} - 8.2\right) \quad (2)$$

Numerical models were used to study the failure mechanism of raft with piles in soft clayey soil under loading. It was deduced that foundation failure occurs at the base of piles by bearing as well as by shear on inclined/curved plans near the side of the pile group (Figures 13 and 14). In the 2-D plan, the failure by shear of the foundation system was observed at the beginning of the failure to have a trapezoidal form (i.e., linear, or straight line from the edge of the raft to the edge of the base of the pile group). However, when the applied load approached the ultimate load capacity of this foundation system, the shape of the failure mechanism was observed to take the form of a hyperbolic curve, which can be expressed by the following equation (Figure 15):

$$Z = -aX^2 + b \quad (3)$$

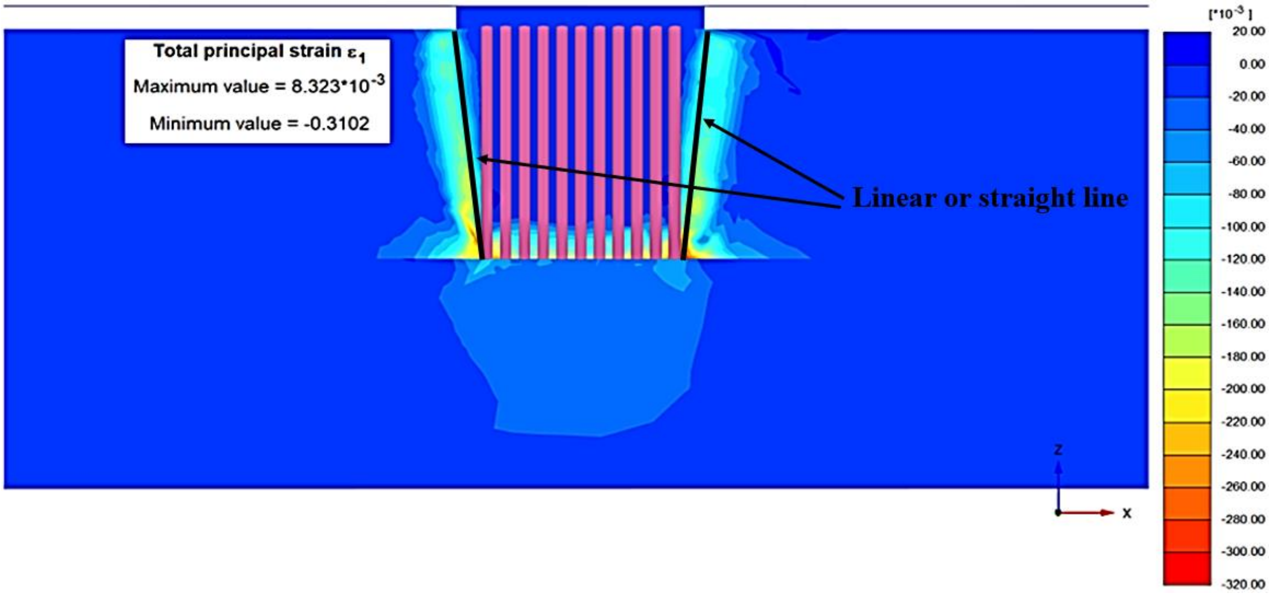

Figure 13. Shape of the shear failure at the beginning of the failure mechanism

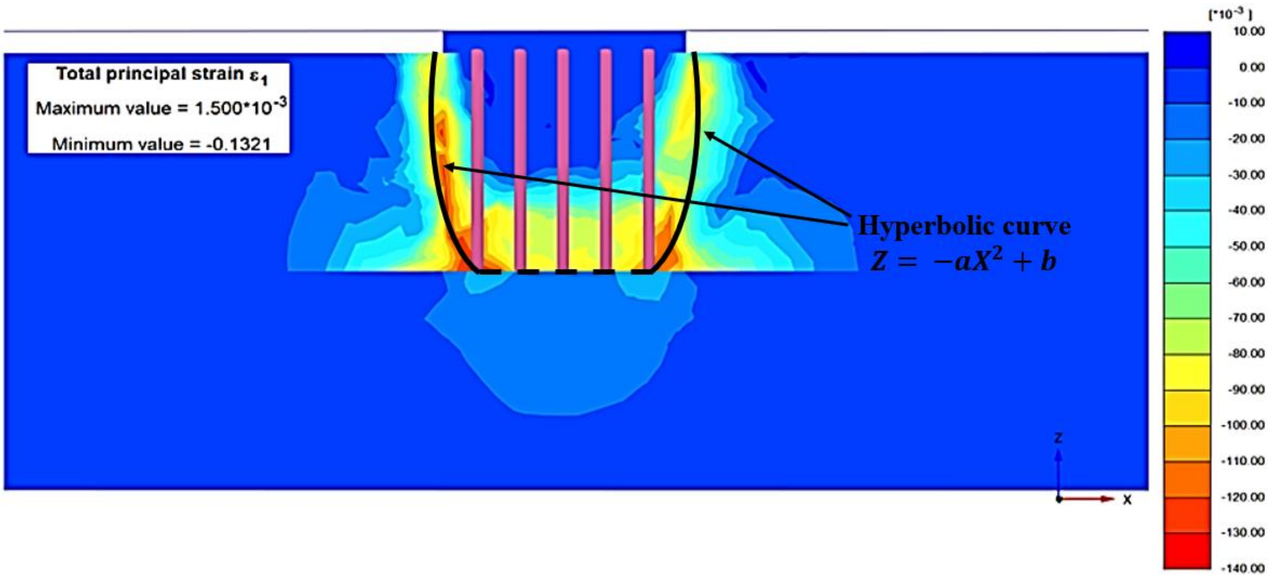

Figure 14. Shape of the shear failure mechanism when the applied load approaches the ultimate load capacity

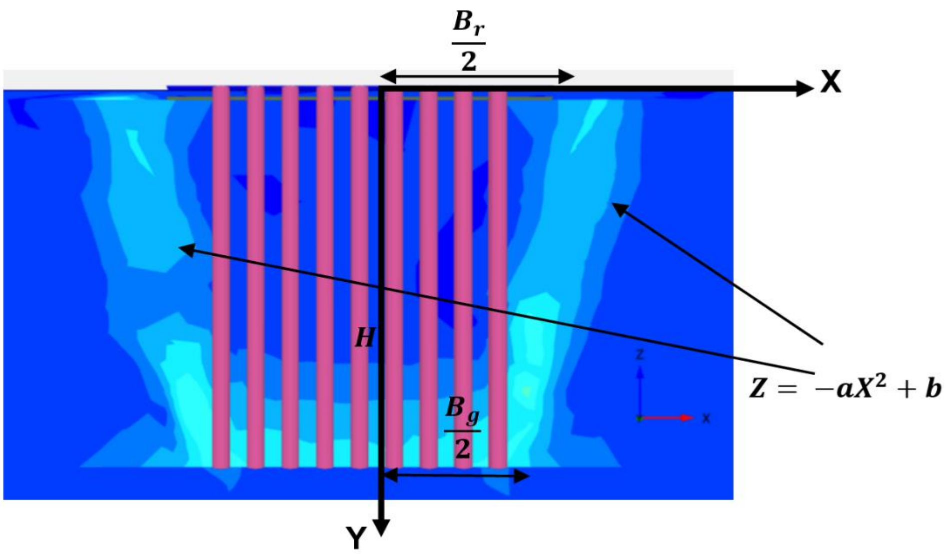

Figure 15. Geometry/configuration of the shear failure mechanism of the piled raft foundation in soft soils

The proposed Equation 3 represents the function of the failure contour caused by shear around the piled raft foundation. It represents the function of the delineations or delimits caused by the shaft only. Concerning the beginning of the failure mechanism of the foundation system, it is worth noting that when the width of the raft foundation is larger than the width of the pile 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 base corner of the pile group with an angle to the vertical (θ):

$$\tan(\theta) = \frac{B_r - B_g}{2H} \tag{4}$$

where B_r is Width of raft foundation, B_g is Width of pile group, and H is Height or length of pile group.

Several research works (experiments and modeling) have been carried out to understand the effect of geometry and the failure mechanism of pile raft foundation in soft soils (e.g., El-Mossallamy et al. [32]). However, the novelty of this research is that it examined the evolution of the failure mechanism of such a foundation system under loading and observed a distinctive shape and form of failure pattern. Recent studies have shown that there is a major concentration of stress shading at the bottom of piles, which indicates a significant amount of stress (among others, El-Mossallamy, et al. [32]; Horikoshi and Randolph [52]). According to their failure diagram, the load transfer mechanism begins at the lower third of the pile length. The system behaves as if embedded blocks are equivalent to pier-one units. The present numerical analysis provided a better understanding of the failure patterns of the piled raft soil system. This confirmed that the transmitted stresses concentrated at the bottom of piles lead to failure by bearing. However, the failure extends by a shearing process at the side of the pile group, from the bottom edge of the pile group to the edge of the raft, on hyperbolic plans.

4. Theoretical Development

An analytical model was developed to predict the ultimate carrying capacity of this foundation system based on the observed failure mechanism. As mentioned previously, the final shape of the failure mechanism can be expressed by Equation 3 (Figure 15).

By considering the boundary conditions:

$$Z = 0 \qquad X = \frac{B_r}{2} \tag{5}$$

$$Z = H \qquad X = \frac{B_g}{2} \tag{6}$$

We obtain:

$$a = \frac{H}{\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2} \tag{7}$$

$$b = \left(\frac{B_r}{2}\right)^2 \left[\frac{H}{\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2}\right] \tag{8}$$

From Equation 3:

$$X = \left(\frac{b-Z}{a}\right)^{1/2} = f(Z) \tag{9}$$

The side area of the curved shear failure plane can be computed by:

$$A_1 = \int_0^H f(Z)\, dZ = \int_0^H \left(\frac{b-Z}{a}\right)^{1/n} dZ \tag{10}$$

Let's consider $m = \frac{1}{2}$, $\frac{Z}{a} = Y$, and $\frac{b}{a} = C$. Therefore when $Z = 0 \Rightarrow \; Y = 0$, and when $Z = H \Rightarrow \; Y = \frac{H}{a}$.

Also $dZ = a\, dY$.

By replacing in Equation 10, we get:

$$A_1 = \int_0^{\frac{H}{a}} (C - Y)^m\, a\, dY = a \int_0^{\frac{H}{a}} (C - Y)^m\, dY \tag{11}$$

$$\Rightarrow A_1 = -\left[a\,\frac{(C-Y)^{m+1}}{m+1}\right]_0^{\frac{H}{a}} = -a\,\frac{\left(c - \frac{H}{a}\right)^{m+1}}{m+1} + \frac{aC^{m+1}}{m+1} \tag{12}$$

Therefore $\overline{A_1} = \frac{A_1}{cos\theta}$ where $cos\theta = \frac{H}{\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}}$

$$\overline{A_1} = \frac{-a}{(m+1)H}\left(C - \frac{H}{a}\right)^{m+1}\left[\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}\right] + \frac{a}{(m+1)H}C^{m+1}\left[\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}\right] \quad (13)$$

From Equations 7 and 8:

$$C = \frac{b}{a} = \left(\frac{B_r}{2}\right)^2$$

Therefore:

$$\overline{A_1} = -\frac{\frac{H}{\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2}}{\left(\frac{1}{2}+1\right)H}\left[\left(\frac{B_r}{2}\right)^2 - \frac{H}{\frac{H}{\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2}}\right]^{\frac{1}{2}+1}\left[\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}\right] + \frac{\frac{H}{\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2}}{\left(\frac{1}{2}+1\right)H}\left(\frac{B_r}{2}\right)^{2\left(\frac{1}{2}+1\right)}\left[\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}\right] \quad (14)$$

So:

$$\overline{A_1} = \frac{1}{\left[\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2\right]\left(\frac{1}{2}+1\right)}\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}\left[-\left(\frac{B_g}{2}\right)^{2\left(\frac{1}{2}+1\right)} + \left(\frac{B_r}{2}\right)^{2\left(\frac{1}{2}+1\right)}\right] \quad (15)$$

i.e.

$$\overline{A_1} = \frac{\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}}{\left(\frac{3}{2}\right)\left[\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2\right]}\left[\left(\frac{B_r}{2}\right)^3 - \left(\frac{B_g}{2}\right)^3\right] \quad (16)$$

Similarly, for the other side of the curved shear failure plan:

$$\overline{A_2} = \frac{\sqrt{\left(\frac{L_r}{2} - \frac{L_g}{2}\right)^2 + H^2}}{\left(\frac{3}{2}\right)\left[\left(\frac{L_r}{2}\right)^2 - \left(\frac{L_g}{2}\right)^2\right]}\left[\left(\frac{L_r}{2}\right)^3 - \left(\frac{L_g}{2}\right)^3\right] \quad (17)$$

Therefore:

$$A_{Total} = 2(\overline{A_1} + \overline{A_2}) \quad (18)$$

So:

$$A_{Total} = 2\frac{\sqrt{\left(\frac{B_r}{2} - \frac{B_g}{2}\right)^2 + H^2}}{\left(\frac{3}{2}\right)\left[\left(\frac{B_r}{2}\right)^2 - \left(\frac{B_g}{2}\right)^2\right]}\left[\left(\frac{B_r}{2}\right)^3 - \left(\frac{B_g}{2}\right)^3\right] + 2\frac{\sqrt{\left(\frac{L_r}{2} - \frac{L_g}{2}\right)^2 + H^2}}{\left(\frac{3}{2}\right)\left[\left(\frac{L_r}{2}\right)^2 - \left(\frac{L_g}{2}\right)^2\right]}\left[\left(\frac{L_r}{2}\right)^3 - \left(\frac{L_g}{2}\right)^3\right] \quad (19)$$

As observed from the piled raft foundation failure mechanism, the ultimate carrying capacity (Q_u) can be computed as:

$$Q_u = Q_p + Q_s \quad (20)$$

Based on the formula of Meyerhof for foundation on sand:

$$Q_p = 0.5\gamma B_r \overline{N_\gamma} A_g \quad (21)$$

And by taking (Q_s) as:

$$Q_s = \sum_{i=0}^{n} A_i f_i = A_{total} \times C_u \quad (22)$$

Finally:

$$Q_u = 0.5\gamma B_r \overline{N_\gamma} A_g + A_{total} \times C_u \quad (23)$$

where A_g = Actual area of the pile group ($A_g = (m \times n) \times \left(\frac{\pi}{4} \times D^2\right)$), $m \times n$ = Number of piles, $\overline{N_\gamma} = N_\gamma F_{\gamma s} F_{\gamma d} F_{\gamma i}$, $F_{\gamma s} = 1 - 0.4\left(\frac{B_g}{L_g}\right)$, $F_{\gamma d} = 1$, $F_{\gamma i} = 1$.

So:

$$\overline{N_\gamma} = N_\gamma \left[1 - 0.4\left(\frac{B_g}{L_g}\right)\right] \tag{24}$$

The results of this numerical investigation and data previously reported in the literature were used to validate the proposed analytical model (Equation 23). A comparison between the measured and calculated values of the ultimate carrying capacity (Equation 23) of raft foundations with piles in soft soils was undertaken. The results of this comparison are shown in Table 3, where acceptable agreement is apparent. The calculated values for the mean and the standard deviation of the results grouped in Table 3 are 10.45 and 7.52, respectively. Furthermore, the coefficient of variation, defined as the ratio of the standard deviation to the mean (which is a measure of the dispersion of a dataset), was less than 1, indicating a relatively low variation in the results.

Table 3. Validation of the present analytical model (Equation 23)

	D **(m)**	***LS*****(m)**	***S/D***	**Q_u (kN/m^2) Plaxis 3D**	**Q_u (kN/m^2) Analytical Model (Eq. 23)**	**Difference (%)**
Current study	0.40	20.00	3.00	1156.65	1450.47	(25.40)
	0.40	20.00	4.00	988.99	1074.85	(8.68)
	0.40	20.00	5.00	934.04	916.85	1.84
	0.40	20.00	6.00	622.20	649.29	(4.35)
	0.40	20.00	7.00	514.79	544.27	(5.73)

	D **(m)**	***L*** **(m)**	***S/D***	**Q_u (kN) Experimental Work**	**Q_u (kN) Analytical Model (Eq. 23)**	**Difference (%)**
Elwakil, and Azzam,.[50]	0.01	0.40	3.13	1.70	1.37	19.45
	0.01	0.20	3.13	1.50	1.26	16.04
	0.01	0.10	3.13	1.30	1.20	7.35

	D **(m)**	***L*** **(m)**	***S/D***	**Q_u (kN) Experimental Work**	**Q_u (kN) Analytical Model (Eq. 23)**	**Difference (%)**
Basuony El-Garhy et al. [53]	0.01	0.50	3.00	15.50	14.69	5.26

5. Conclusion

The performance of the pile group under a raft foundation installed in soft soils was examined using a numerical model. A parametric study was also conducted on the parameters thought to govern this complex behavior. The results obtained indicate that the stress-strain curves of the piled raft foundation on soft soils show no significant differences in the general trend other than a decreasing rate of strain for a given stress with an increase in the ratio of spacing to pile diameter (*S*/*D*) as the foundation system approaches its ultimate stress. In soft soils, pile spacing has a significant effect on piled raft foundation performance. When the ratio (*S*/*D*) increased, the ultimate loads carried by the piled raft foundation decreased. Based on the parametric analysis, an improvement factor (*IF*) of the ultimate carrying capacity of a piled raft foundation was determined. A linear relationship can be assumed between the improvement factor (*IF*) and the ratio (*S*/*D*). Additionally, when the ratio *S*/*D* is greater than 10 (S/D > 10), the influence of piles on the ultimate carrying capacity of piled raft foundations is negligible. More rigid piles have a lower improvement factor (*IF*). This can be explained by the fact that rigid piles penetrate the sand layer beneath soft clayey soil more easily.

According to the observed failure mechanism, the foundation system fails through bearing at the base of the pile group and also through shearing on inclined/curved plans near the sides of the pile group. It was observed in two-dimensional planes that failure of the foundation system by shear began to have a trapezoidal form (that is, a linear or straight line from the edge of the raft to the bottom edge of the pile group). The failure mechanism, however, takes the form of a hyperbolic curve when the applied load approaches the ultimate capacity of the foundation system. Furthermore, based on the observed failure mechanism, an analytical model to predict the ultimate carrying capacity of the piled raft foundation was developed (Equation 23).A more reliable and trustworthy prediction method should be based on the actual or observed failure mechanism. The safe and cost-effective geotechnical design of a piled raft foundation is critically dependent on the representativeness of the failure mechanism.

6. Declarations

6.1. Author Contributions

Conceptualization, D.A., S.N.L.T. and T.A.; methodology, D.A. and T.A.; software, D.A.; validation, D.A.; formal analysis, D.A., S.N.L.T. and T.A.; investigation, D.A.; resources, D.A., S.N.L.T. and T.A.; data curation, D.A.; writing—original draft preparation, D.A.; writing—review and editing, D.A., S.N.L.T., T.A. and A.H.; visualization, S.N.L.T., T.A. and A.H.; supervision, S.N.L.T., T.A., and A.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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