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Research Article

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The behavior of piled rafts in soft clay: Numerical investigation

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Abstract: This research aims to investigate the applicability and performance of piled rafts in soft clay. This aim has been achieved by studying how the pile length, pile number, raft-soil relative stiffness, and presence of a sand cushion beneath the raft would affect piled raft settlement, differential settlement, and load sharing. Piled rafts have been numerically simulated using PLAXIS 3D software. Experimental testing results were used to verify the numerical simulation. The portion of the load carried by the piles to the total applied load was represented by the load sharing ratio (GPR). The results indicated that with increasing pile length and number, settlement and differential settlement decreased. It was also noticed that with increasing raft-soil relative stiffness, the differential settlement decreased. The GPR decreased with increasing thickness and relative density of the sand cushion, whereas it increased with increasing pile length and number. This increase in GPR was 13.7, 36, and 58% with an increase in pile length to diameter ratio from 10 to 30 for the number of piles 4, 9, and 16, respectively. Additionally, the raft-soil relative stiffness was observed to have a marginal effect on the GPR.

Keywords: piled rafts, load sharing ratio, raft-soil relative stiffness, soft clay, sand cushion, numerical modeling

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1 Introduction

In piled rafts, the bearing behavior, pile capacity, total settlement, differential settlement, and load sharing behavior are considered crucial parameters for design. Several researchers have studied the bearing behavior [1,2], pile capacity [3], total settlement [4–6], and differential settlement [7–9] of piled raft foundations. Lee *et al.* [1] found that using a limited number of piles in strategic locations will improve the bearing capacity of the raft. Karkush *et al.* [3] used standard penetration test results and MATLAB software to predict the bearing capacity of driven piles and found there is a 30% difference between the calculated and predicted bearing capacity of driven piles. Cho *et al.* [4] concluded that the total settlement was reduced effectively by increasing the pile spacing at the same pile lengths. El-Garhy *et al.* [7] conducted an experimental program in sandy soil to assess how the raft-soil relative stiffness would affect the behavior of piled rafts. They noticed a major effect on decreasing the differential settlement due to increasing the raft-soil relative stiffness. Elwakil and Azzam [8] found that piles as settlement reducers in sandy soil are very useful in decreasing differential settlement. They also noted that the raft contact pressure increases with decreasing pile length. Mali and Singh [9] studied piled raft behavior using 3D finite element modeling in stiff clay. They found that when the spacing of the piles increases, the differential settlement decreases up to a particular spacing, after which it increases. Thoidingjam and Devi [10] studied how the raft rigidity would affect the ultimate capacity and total settlement of piled rafts in organic clay. They found that higher rigidity gives higher load and lesser settlement of piled raft system. For the term of load sharing, Karkush and Aljorany [11] reanalyzed a piled raft under construction in the Southern part of Iraq using analytical equations and numerically by SAFE 12 software. They noticed a change in the load sharing of the constructed piles due to redistribution of the applied loads on the stiffer piles and the raft. Davids *et al.* [12] indicated that the load carried by the raft is about 20:50% of the total applied load. Leung *et al.* [13] stated that the raft contact pressure changed from 25 to 50% of the building stress. Abdel-Fattah and Hemada [14] indicated that the raft load is about 30:60% of the applied load depending on the soil condition. This portion increases with decreasing pile length and increasing pile spacing. On the other hand, Hoang and Matsumoto [15] reported from experimental tests that the load shared between the raft and piles for spacing 3D is clearly like that for spacing 6D. Hemsley [16] obtained that the soil can carry loads up to 50% of the total load by raft contact pressure. Many contributions to the concept of piled rafts have been conducted in Germany including experiments, field measurements, and numerical studies during the 1980s and 1990s. Piled rafts have been used frequently in Frankfurt stiff clay to support heavy high-rise buildings [17,18]. Although there are enormous studies on piled rafts, there is a scarcity of parametric studies for piled rafts in soft clay. Therefore, the effect of pile length, pile number, raft-soil relative stiffness, and the presence of a sand cushion beneath the raft have been investigated in this study.

1.1 Research significance

Soft soils are found in many regions in Egypt such as the industrial zone in Port Said, in which the soft clay extends up to the depth of 60 m. As reaching the bearing layers in very deep soft soils is difficult and uneconomic, the floating piles would be appealing to reduce settlement and enhance the bearing capacity. Hence, the main objective of this research is to investigate the applicability and performance of using piled rafts in soft clay.

1.2 Testing equipment

Remolded kaolinite was used to prepare the soft clay deposit. Kaolinite clay is usually applied in laboratory investigations and physical model testing, as well as in fundamental studies of soil behavior as mentioned by Abdelrahman and Elragi [19]. The soft clay was prepared according to Ilyas *et al.* [20]. The raft was a square steel plate with a length of 200 mm and the piles were steel hollow tubes with a length of 250 mm, an outer diameter of 10 mm, and a thickness of 1.3 mm. The plate had nine holes with 10 mm diameters. The top head of each pile was provided with a solid tube with a sufficient length to achieve a 10 mm length inserted into the hollow tube and a screwed length to connect the pile to the raft through a nut to ensure a rigid connection. The test chamber was a cube with edges of 600 mm and made from steel plates. The test chamber and raft dimensions were selected to ensure no effect on the failure mechanism of soft soils according to Prandtl [21]. A load cell was used to measure the applied load. To measure the settlement, four linear variable differential transformers (LVDTs) with 0.001 mm accuracy were placed on raft corners. The LVDTs average value was calculated to represent the total settlement of the piled raft. Strain gauges were attached to pile heads to measure the elastic strains developed and hence the axial forces of piles were calculated. The test chamber and instrumentations used in the present study are presented in Figures 1 and 2.

2 Finite element modeling

2.1 Meshing and boundaries

In the present study, the foundation was loaded by a uniform load (q) of 80 kPa. As shown in Figure 3, the soil mass dimensions were the same as the dimensions of the test chamber. The model lateral soil domain limits were constrained against horizontal translation but allowed vertical soil translation. The bottom soil boundary was selected to be three times the raft width according to Yılmaz [22]. The model mesh size was fine but around the working zone it was very fine to ensure solution accuracy.

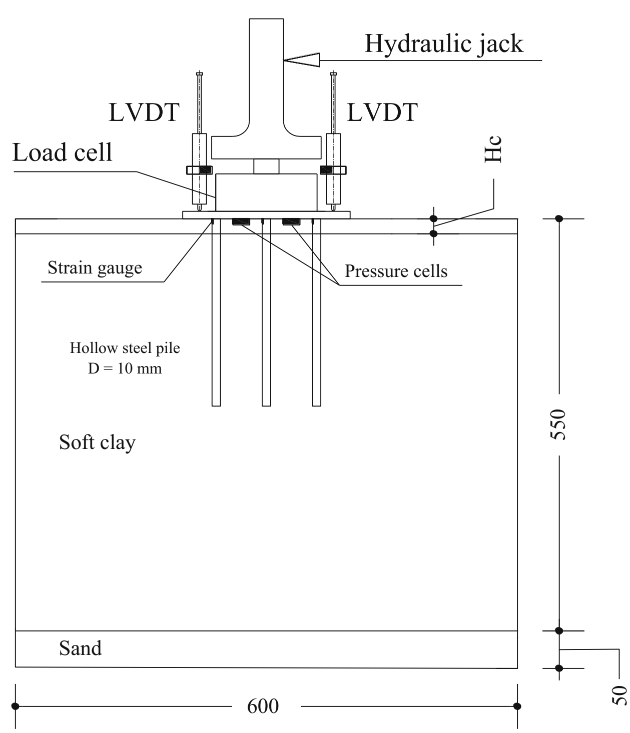

Figure 1: Test chamber and instrumentations (dimensions in mm).

Figure 2: The driving process and instrumentation locations.

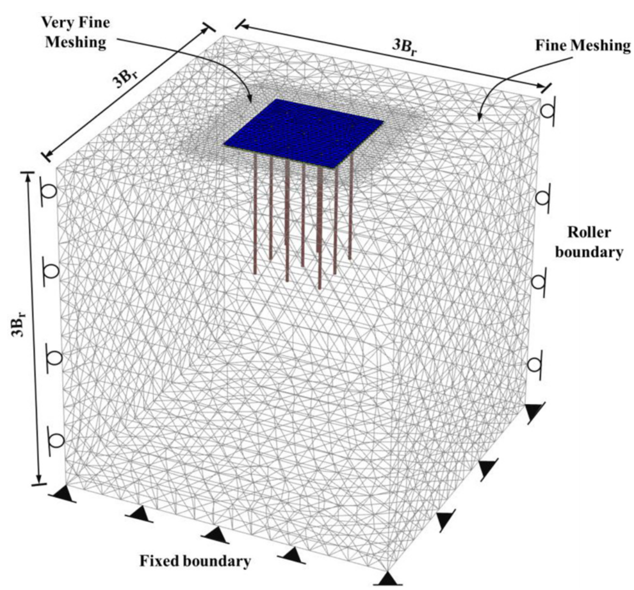

Figure 3: Meshing and boundaries.

2.2 Constitutive modeling

The hardening soil (HS) model used in this study is a sophisticated constitutive model that can simulate both stiff and soft clays. The HS is a development of Duncan and Chang's hyperbolic model [23]. HS model depends on plasticity theory with soil dilatancy, and a yield cap behavior modeled. The HS model employs a work-hardening plasticity technique to represent soil loading in shear. As the plastic shear strain increases, the inner yield surface expands to meet a Mohr–Coulomb failure surface on the outside. As the HS model uses the hyperbolic stress–strain curve and controls stress level dependency, it offers an advantage over the Mohr–Coulomb model. The raft was modeled as a plate element and the piles as embedded beams. The embedded beam was defined as a circular tube and the connection with the raft was rigid. The analysis included four stages, the initial stage, pile installation stage, raft stage, and loading stage. In the past numerical research, the stress change because of pile installation was neglected [24,25]; however, the installation method of piles affects the condition of stress. The pile installation method (driving or boring), type of soil (sand or clay), and condition of the soil (soft clay or stiff clay) affect the stress change in the soil, so driven piles were used in the present study to match the experimental work.

2.3 Model validation

The ability to validate the experimental model is a key feature of employing numerical software to create simulations. The properties of soft clay and sand at different relative densities were obtained from experimental testing except for dilatancy angles and the Poisson's ratios. The dilatancy angles (ψ) were calculated using the equation given by Schanz and Vermeer [26] and the Poisson's ratios (υ_s) of the used sand at different relative densities were obtained using the charts given by Dutta and Saride [27]. The clay secant stiffness (E_{50}^{ref}) and unloading/reloading stiffness ($E_{\mathrm{ur}}^{\mathrm{ref}}$) were obtained from the stress–strain curve (Figure 4a), whereas tangent stiffness for oedometer loading ($E_{\mathrm{oed}}^{\mathrm{ref}}$) was obtained from the stress–strain curve of odometer test. For the sand cushion, (E_{50}^{ref}) was obtained from the triaxial test results (Figure 4b), whereas the ($E_{\mathrm{ur}}^{\mathrm{ref}}$) and ($E_{\mathrm{oed}}^{\mathrm{ref}}$) were obtained from Eqs. (1) and (2), the program default. The material properties of the soft clay and sand are summarized in Table 1. The Young's modulus and unit weight of raft and piles, obtained from the datasheet of the manufacturing company, are summarized in Table 2. Figure 5 shows the present study results in comparison with the results of the experimental model. As shown, the results of the present study were in a reasonable level of agreement with the experimental stress-settlement curve of the piled raft and represent the variation of pile load (Pp) with the settlement.

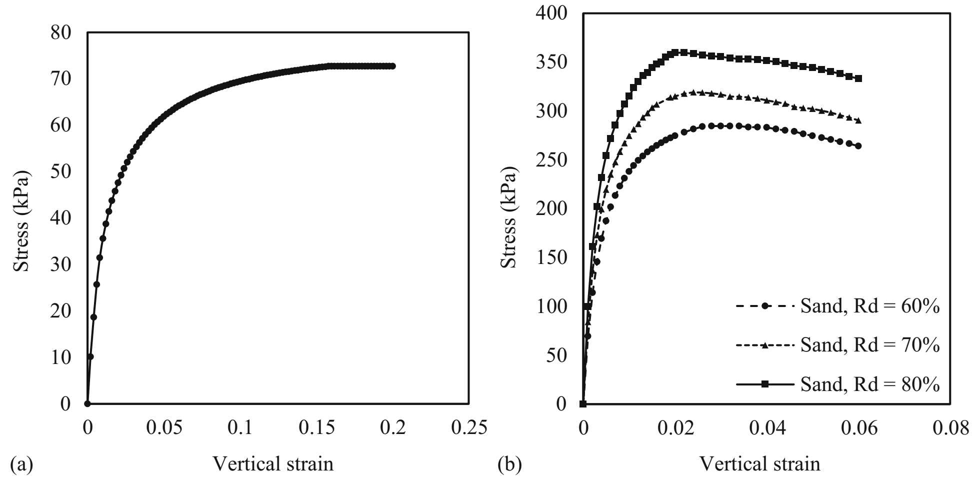

Figure 4: Stress–strain curves for used materials. (a) Stress-strain curve of soft clay, and (b) stress-strain curve for sand.

$$E_{ur}^{ref} = 3E_{50}^{ref}, \quad (1)$$

$$E_{oed}^{ref} = E_{50}^{ref}. \quad (2)$$

2.4 Parametric study

The total settlement, differential settlement, and load sharing behavior of the piled rafts were studied with the variation of pile length, pile number, raft-soil relative stiffness, thickness, and relative density of the sand cushion (Table 3). The pile arrangement is presented in Figure 6.

The results were plotted to indicate the effect of studied parameters on the settlement reduction ratio (SR), differential settlement reduction ratio (Sdiff), and load sharing ratio (GPR). The SR is the ratio of maximum settlement of piled raft to the maximum settlement of raft. The differential settlement is expressed in Eq. (3). The SR and Sdiff are calculated by Eqs. (4) and (5). The GPR is the proportion of total pile load (Pp) to total applied load (Ppr). GPR is introduced to obtain the percentage of load carried by piles and raft individually. The load carried by piles (Pp) is calculated by summing the load at their heads. The expression for GPR is given in Eq. (6). The raft-soil relative stiffness (K_{rs}) is calculated using Eq. (7), which has been given by Brown [28], where E_r is the modulus of elasticity of the raft, υ_s is the Poisson's ratio of soil, G_s is the shear modulus of soil, t is the raft thickness, and B_r and L_r are the raft dimensions.

Table 2: Raft and pile properties

	Raft	Pile
Material model	Plate	Embedded beam
Unit weight (kN/m^3)	78.5	78.5
Young's modulus (kN/m^2)	200.0×10^6	200.0×10^6

Table 1: Soft clay and sand cushion properties

Soil parameter	Soft clay	Sand cushion
Material model	HS model	HS model
Drainage type	Undrained	Drained
Saturated bulk density (kN/m^3)	18.65	18.80, 19.30, 19.50
E_{50}^{ref} (kN/m^2)	1,600	50,000, 62,000, 75,000
E_{oed}^{ref} (kN/m^2)	1,500	50,000, 62,000, 75,000
E_{ur}^{ref} (kN/m^2)	4,200	150,000, 182,000, 225,000
Power (m)	1.0	0.5
Undrained cohesion (kN/m^2)	16	–
Angle of internal friction, ϕ°	–	36, 38, 40
Relative density, Rd	–	60%, 70%, 80%
P_{ref} (kN/m^2)	100	100

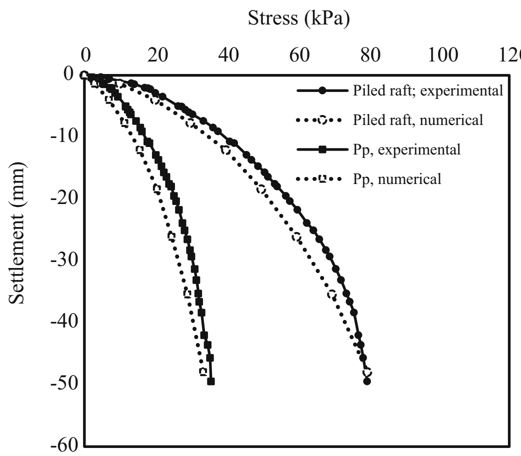

Figure 5: Comparison of numerical and experimental results for piled raft system.

Table 3: Parametric analysis

Parameter	Value
Pile length, Lp/pile diameter, dp	10, 15, 20, 25, 30
Pile number	4, 9, 16
Raft thickness	2, 4, 10 mm
Corresponding raft-soil relative stiffness	0.08, 0.70, 10.43
Sand cushion thickness, Hc/pile diameter, dp	1, 2, 3, 4, 5

$$\text{Differential settlement} = \text{Max. settlement of the raft} - \text{Min. settlement of the raft}, \quad (3)$$

$$\text{SR} = \frac{\text{Maximum settlement of piled raft}}{\text{Minimum settlement of raft}}, \quad (4)$$

$$\text{Sdiff} = \frac{\text{Differential settlement of piled raft}}{\text{Differentail settlement of raft}}, \quad (5)$$

$$\text{GPR} = \frac{\text{Pp}}{\text{Ppr}}, \quad (6)$$

$$K_{\text{rs}} = \frac{(1 - \upsilon_{\text{s}}) \times E_{\text{r}}}{2\,G_{\text{s}}} \times \frac{4\,B_{\text{r}}}{3\pi L_{\text{r}}}\left(\frac{t}{L_{\text{r}}}\right)^3. \quad (7)$$

3 Results and discussion

3.1 Effect of pile length (Lp) and number (Np)

To analyze the effect of Lp and Np, simulations were carried out on piled rafts with Lp/dp of 10, 15, 20, 25, and 30, for Np of 4, 9, and 16, and piles were spaced at Sp = 6dp. Figures 7–9 present the effect of Lp/dp and Np on SR and Sdiff at different K_{rs} values. The results show that SR and Sdiff decreased with increasing Lp/dp and Np for every K_{rs} value. The decrease in SR and Sdiff was a result of increasing the skin friction of piles by increasing

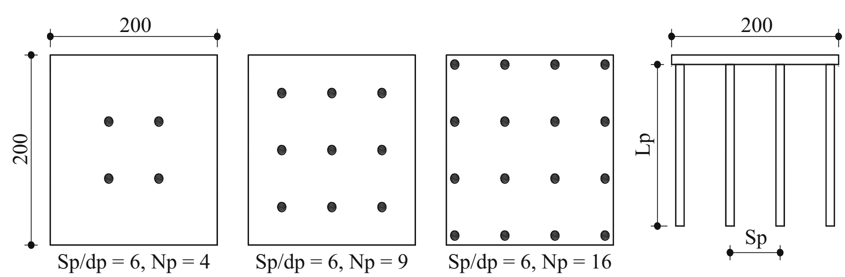

Figure 6: Pile arrangements (dimensions in mm).

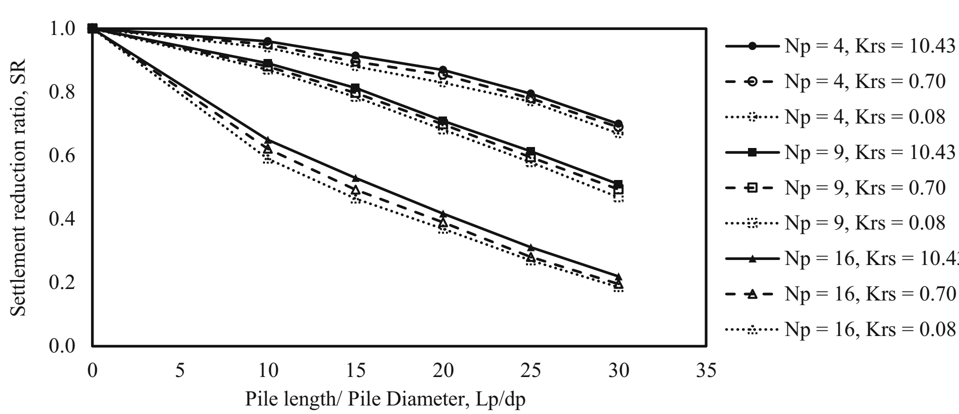

Figure 7: Effect of pile length on SR for different piled raft cases.

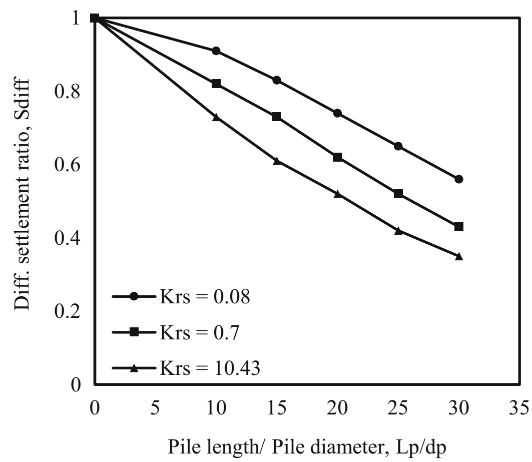

Figure 8: Effect of pile length on SR (Np = 9 and Sp/dp = 6).

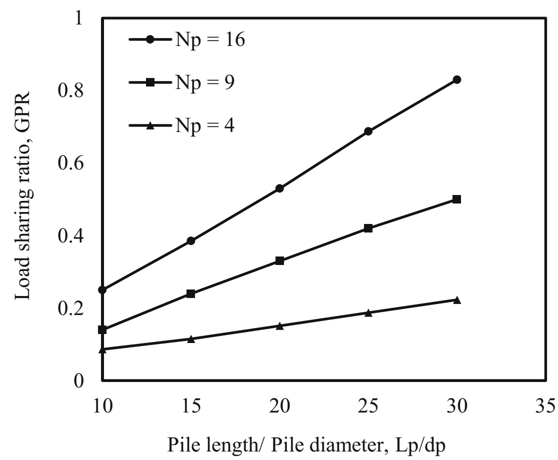

Figure 10: Effect of pile length on GPR at different pile numbers.

Lp/dp and Np. Additionally, the decrease of SR was obtained to be similar at the same Np and Lp/dp for different K_{rs} values (e.g., piled raft with Lp/dp of 25 and Np of 9 at K_{rs} of 10.43 caused SR equal to 0.614 and piled raft with the same Lp/dp and Np at K_{rs} of 0.7 caused SR of 0.58). In comparison with the Sdiff, with increasing K_{rs}, Sdiff decreased (Figures 8 and 9). As a result, it is clear that K_{rs} had a significant effect on the differential settlement but marginal on the total settlement. Therefore, the most effective way to reduce SR is to use a larger number of piles with longer lengths. To minimize Sdiff, in addition to increasing Lp/dp and Np, increasing K_{rs} would be more effective. Figure 10 presents the Lp/dp *versus* GPR at different pile numbers. As expected, the GPR increased with increasing Lp/dp and Np. For example, the increase in GPR was 13.7, 36, and 58% with increasing Lp/dp from 10 to 30 for the number of piles 4, 9, and 16, respectively.

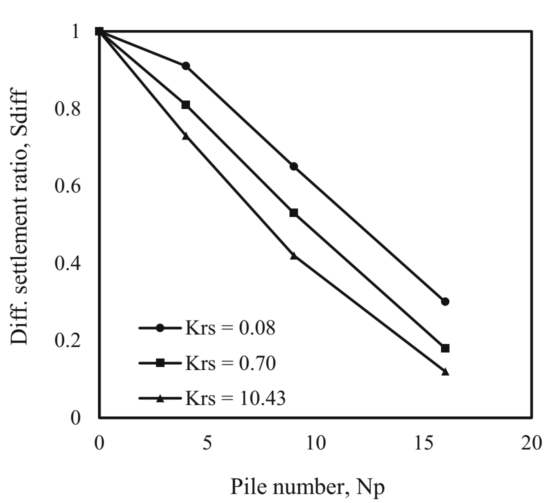

Figure 9: Effect of pile number on Sdiff (Lp/dp = 25 and Sp/dp = 6).

3.2 Effect of raft-soil relative stiffness (K_{rs})

Table 4 presents the loads carried by the center, edge, and corner piles for the case of the piled raft with Np = 9, Lp/dp = 20, and spaced 6dp. As shown, the corner pile carried the maximum load, followed by the edge pile, and finally the center pile. In addition, the piled raft with high K_{rs} improved the distribution of load between the piles. Also, the total pile loads increased marginally with increasing K_{rs}. Figure 11 shows the K_{rs} *versus* GPR for different Np and Lp/dp. As shown, the effect of K_{rs} on the GPR was marginal. Similar conclusions were obtained by Singh and Singh [29], Poulos [30] from numerical analysis, and El-Garhy *et al.* [7] from experimental analysis of piled rafts.

3.3 Effect of the presence of the sand cushion

In a trial to improve the contact layer, simulations were carried out on piled rafts with the presence of a sand cushion beneath the raft with a thickness (Hc/dp) of 1, 2, 3, 4, and 5. Figures 12 and 13 show the effect of Hc/dp on SR and GPR for piled raft with Lp/dp = 25, Np = 9, and Sp = 6dp at different Rd values. Although the effect of placing a sand cushion on the shear strength of soft clay

Table 4: Pile loads (N) for piled raft (Np = 9, Lp/dp = 20, and Sp/dp = 6)

K_{rs}	Center pile	Edge pile	Corner pile	Total pile loads (Pp), *N*
0.08	88	119	123	1,056
0.70	112	127	133	1,152
10.43	120	131	135	1,184

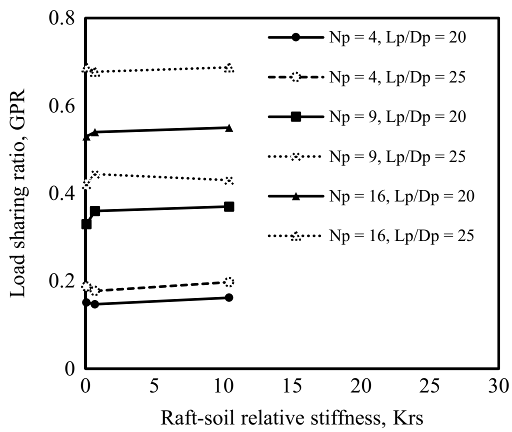

Figure 11: Effect of raft-soil relative stiffness on the GPR.

was neglected, the SR decreased with increasing Hc/dp at different relative densities (Figure 12). This decrease in the settlement occurred as a result of increasing the bearing capacity of the contact layer with increasing Hc/dp and Rd. The GPR decreased slowly as the Hc/dp and Rd increased (Figure 13) as a result of the load redistribution between raft and piles due to the presence of the sand cushion. For example, the GPR decreased by 8.1% with Hc/dp = 5 and Rd of 70% when compared to piled raft without the presence of the sand cushion. Therefore, to minimize SR and increase the load carried by the raft, using a sand cushion with reasonable thickness and a high Rd is a perfect solution.

3.4 Negative skin friction

It was found that the negative skin friction has a minor effect on pile geotechnical capacity. As the raft was subjected to vertical loads, it pushed the soil beneath the raft and the piles to settle together. So, there was no relative movement between the pile and soil beneath the raft. Polous [31] observed that it is prudent to design the piles to settle with the ground rather than attempt to restrain them from the settlement.

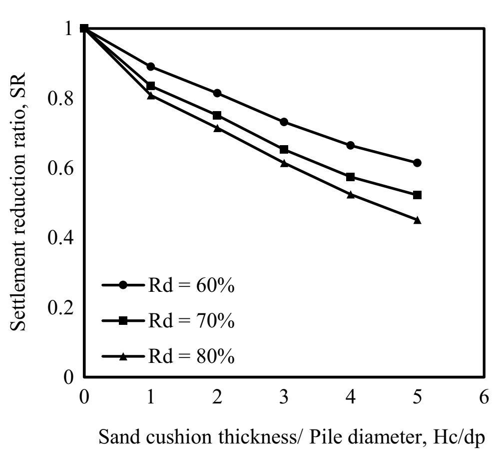

Figure 12: Effect of the presence of a sand cushion on the SR.

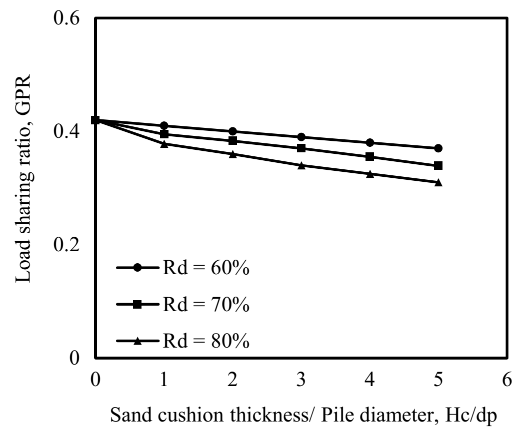

Figure 13: Effect of the presence of a sand cushion on the GPR.

3.5 Scale effect and boundary conditions

According to Bezuijen [32], there is no scale effect of clay particle size in experimental tests. The clay particles are very small compared to the pile diameter. For the term of boundary conditions, Figure 14 shows the settlement shading of the piled raft with Np/dp = 9, Sp/dp = 6, and Lp/dp = 30 which represented the longest pile used in this study. It was observed that the selected

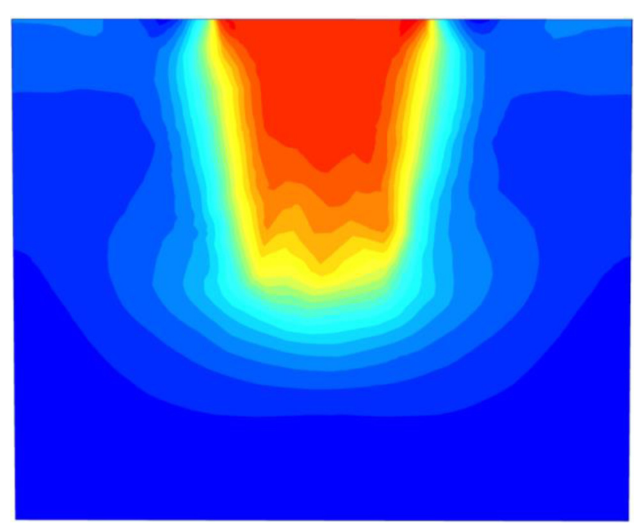

Figure 14: Effect of boundary conditions.

boundaries effect could be neglected as the settlement shading showed only a minor effect.

4 Conclusions

The numerical study was performed to investigate the applicability and performance of piled rafts in soft clay. The effect of pile length (Lp), pile number (Np), raft-soil relative stiffness (K_{rs}), and the presence of a sand cushion beneath the raft on the total settlement, differential settlement, and load sharing were studied. The following conclusions were given:

- Piled rafts are effective and applicable in soft clay due to piles‘ efficiency in decreasing the total settlement and differential settlement.
- With increasing pile number and pile length, total settlement and differential settlement decrease.
- The increase in GPR is 13.7, 36, and 58% with increasing Lp/dp from 10 to 30 for the number of piles 4, 9, and 16, respectively.
- The raft-soil relative stiffness has an important role in decreasing the differential settlement, whereas it has a marginal effect on the GPR.
- The presence of a sand cushion beneath the raft decreases the total settlement efficiently and leads to a significant decrease in the total settlement.
- The GPR decreases by 8.1% with Hc/dp = 5 and Rd of 70% when compared to piled raft without the presence of the sand cushion.

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