An Evaluation of Pile-Raft Interaction in Cohesive Soils using 3D Finite Element Method

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Abstract. This paper presents the results of a numerical study of soil-structure interaction in a piled-raft foundation system in clay soil by reviewing the deformation and load transfer mechanism of the piled-raft foundation system. ABAQUS was used to evaluate the interaction in the system, while a Mohr-Coulomb constitutive model was chosen to model the clay soil. Verification of the model was conducted by comparing the simulation result to an experimental laboratory result. The verification result showed that the model used in this research agreed well with the experimental laboratory research. Subsequently, a parametric study was performed by varying the pile spacing, raft size, pile length, and raft thickness. A parametric study was conducted on very stiff and hard clays. This study concludes that the load transfer mechanism in a piled-raft foundation system between the pile and raft foundation occurs after the pile reaches its ultimate capacity and is in the plastic zone.

Keywords: *ABAQUS; foundation; hard clay; load transfer mechanism; pile; raft; settlement; very stiff clay.*

1 Introduction

The piled-raft foundation system is a combination of a raft foundation and a pile foundation. Piled-raft foundations are commonly used when the bearing capacity of a raft foundation is sufficient to support the load but the differential settlement exceeds the requirement. The addition of a pile foundation is done to reduce the differential settlement by increasing the stiffness of the foundation system.

The total and the differential settlement are two major concerns when the foundation is built in clay soil. They should meet the design criteria. The differential settlement is the main concern because a large differential settlement between the piles will result in construction failure. A pile foundation is usually applied to solve the differential settlement problem. Nevertheless, another problem can arise when hard soil is found deep below the ground surface. At some point it becomes uneconomical to use very long piles

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to overcome this problem. The piled-raft foundation system was introduced to solve this problem.

Traditionally, piled-raft foundation systems were designed by imposing all structural load on the piles without considering the contribution of soil and raft friction. This approach is known to be over-conservative as the raft is in direct contact with the soil. Thus, it contributes significantly to bearing the load. The design philosophy of combined piled-raft foundations marks a progressive change. The concept where the load of the superstructure is partially supported by the piles and the remaining load is supported by the raft is gaining popularity [1-7].

Although significant progress has been made, additional research in this area remains attractive. For instance, many authors are still interested in developing an analysis procedure, investigating uncertainties in the actual load transfer mechanism, performing parametric studies, and evaluating the lateral resistance of the pile-raft foundation system [8-13].

As part of this study, [14] carried out a study for medium stiff clay and stiff clay. In the present study, analysis of a piled-raft foundation system on very stiff clay and hard clay was conducted to complement the previous study and provide more information regarding the application of the piled-raft foundation system in a wide range of soil consistencies. In this research, the effects of pile spacing, raft size, pile length and raft thickness on the total and the differential settlement of the system were studied. Furthermore, this research explains how the load transfer mechanism between the pile and raft foundation in the system works. Thus, additional insight in the optimization of the piled-raft foundation system design could be gained using the results reported in this paper and in [14].

2 Verification of Piled-Raft Foundation Model

Verification of the model was conducted by comparing the load-displacement relationship from numerical modeling with that from the experimental laboratory test conducted by [15]. Numerical modeling was performed with the help of the ABAQUS software [16], utilizing the finite element method (FEM). In this verification, quartz sand with a relative density (Dr) of 50% was used to represent medium dense sand. The model used for the verification was a miniature of a piled-raft foundation system that consists of a single pile. The details of the model were as follows:

1. The raft foundation for the model was made from steel with 16 cm in diameter and a thickness of 0.8 cm. It was considered as a rigid structure.

The diameter of the test tube was 2.5 times the diameter of the raft. The raft was installed with 3 load cell instruments with a capacity of 40 kg to measure the axial stress that occurred on the raft.

2. The pile used for the model was a pipe steel with a diameter of 32 mm, a thickness of 1 mm, and a length of 640 mm. The pile was installed with an axial and lateral strain gauge instrument at the top, middle and bottom of the pile.

The model used for verification is shown Figure 1.

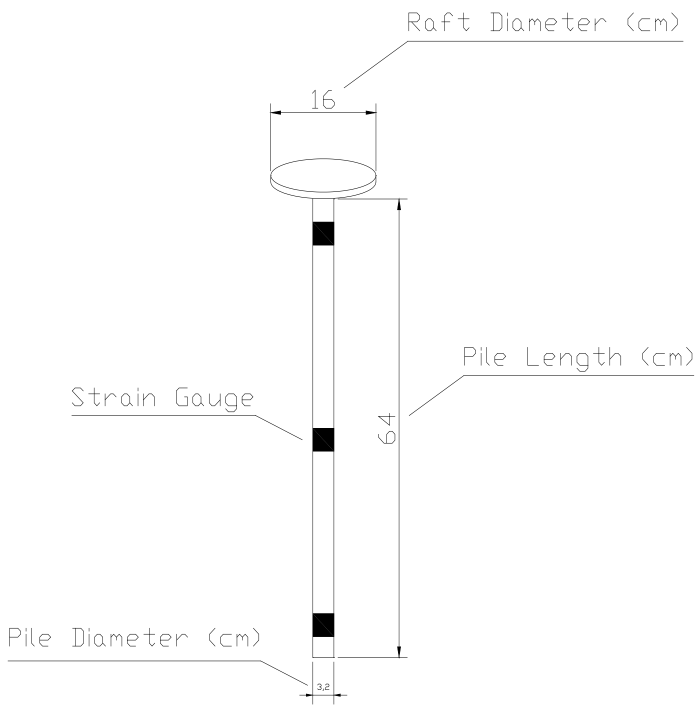


Figure 1 Experimental laboratory test model of a single piled-raft foundation system [15].

Table 1 Input model properties.

Parameter	Unit	Quartz Sand	Raft	Pile
Modulus elasticity, E	kN/m^2	14,500	200,000,000	200,000,000
Poisson's ratio, υ	-	0.2	0.3	0.3
Unit weight, γ	kN/m^3	15	78	78
Friction angle (ϕ)	deg	33.3	-	-
Dilatancy (ψ)	deg	3.3	-	-
Cohesion, c'	kN/m^2	1	-	-

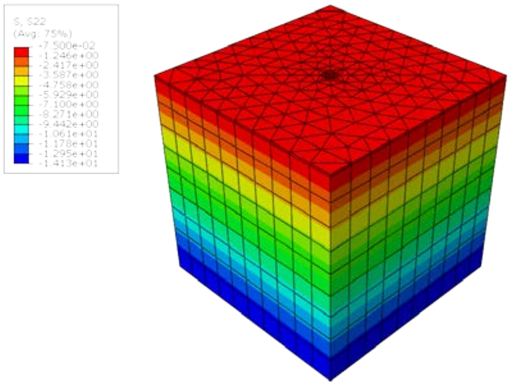


Figure 2 Stresses during the geostatic step (existing condition)**.**

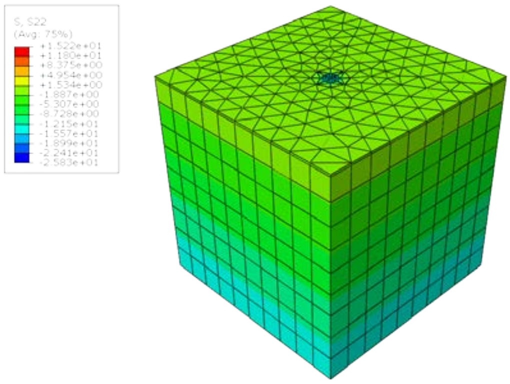


Figure 3 Stresses during pile and raft installation**.**

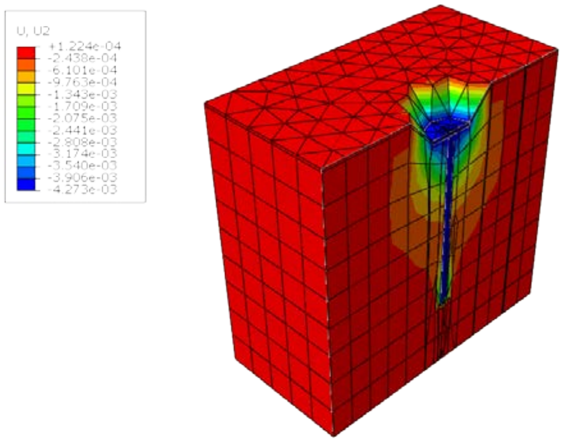


Figure 4 Displacement for applied load 225 kPa (P = 225 kPa).

Figures 2 to 4 illustrate the steps of the numerical modeling. The load and displacement results from the numerical analysis are shown in Table 2 and Figure 5.

Table 2 Load – displacement results from ABAQUS.

ABAQUS modelling			
Load (kg)	**Disp (mm)**	**Load (kg)**	**Disp (mm)**
0	0.01	307	2.40
28	0.10	327	2.62
57	0.21	358	2.96
99	0.48	388	3.32
163	0.96	418	3.70
258	1.87	452	4.14
294	2.26	-	-

Figure 5 illustrates the excellent agreement between the numerical analysis and the experimental laboratory test result. The loading simulation on the single-pile model showed a displacement of 4 mm for a load of 438 kg. The results of the laboratory test showed that a displacement of 4 mm was the result of a load of 428 kg. This was 3% lower than the numerical analysis result. In general, this indicates that simulation using a finite element program can represent the experimental laboratory test.

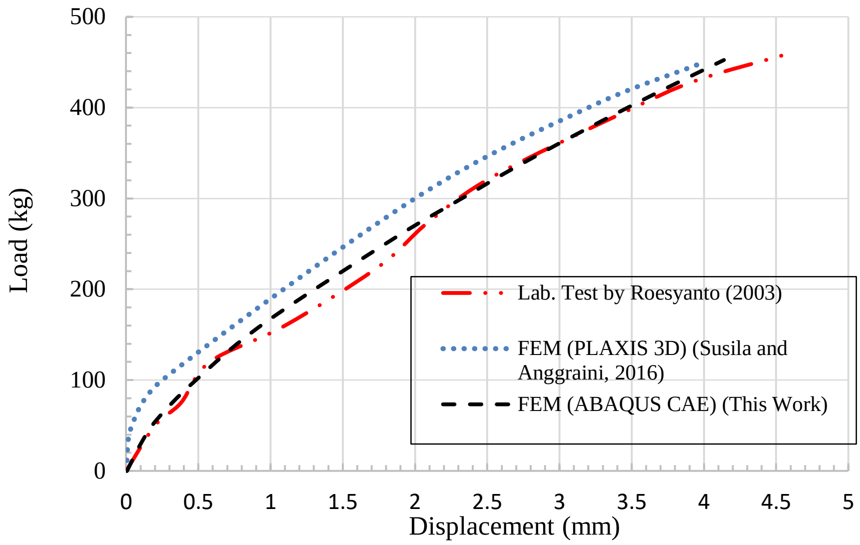


Figure 5 Comparison between numerical analysis results and experimental laboratory test results.

3 Analysis and Discussion

3.1 Parametric Studies

Parametric studies were conducted to determine the behavior of the raft and piles in a piled-raft foundation system. The main concern of this study was the effect of load variation on displacement. In addition, this paper also discusses the load transfer mechanism between the raft and piles. This mechanism is presented as a percentage of the applied total load.

This study was conducted using two clay soil consistencies, i.e. very stiff clay and hard clay. In addition to complementing previous study [14], these consistencies were selected in this study because, to the authors' knowledge, they are within the common range of pile-raft foundations used in Indonesia, particularly for 10-story buildings or higher. A Mohr-Coulomb constitutive model was chosen to model the clay soil. The soil parameters used for numerical modeling were obtained from empirical correlations. The parameters of very stiff clay and hard clay soil are shown in Table 3. The piles and rafts were modeled as K-300 concrete with a compression strength of 25 MPa. The piles had a diameter of 1.0 m, while the raft area and thickness were varied according to the specified case study. The parameters for the piles and rafts are shown in Table 4.

Table 3 Soil material parameters.

Parameter	**Unit**	***Very Stiff Clay***	***Hard Clay***
Material model	-	Mohr-Coulomb	Mohr-Coulomb
Elastic modulus, E	kN/m^2	24,000	36,000
Poisson's ratio, υ	-	0.3	0.3
Unit weight, γ	kN/m^3	17.5	18.0
Cohesion, c_u	kN/m^2	120	180

Table 4 Bored pile and raft parameters.

Parameter	**Unit**	***Bored Pile***	***Raft***
Elastic modulus, E	kN/m^2	23,500,000	23,500,000
Poisson's ratio, υ	-	0.2	0.2
Unit weight, γ	kN/m^3	24	24

3.1.1 Effects of Pile Spacing

In this study, the dimensions of the raft used for the analysis were 20 x 20 m^2 with a thickness of 2 m. The length of the piles used for this study case was 10 m. The independent variable in this case study was the spacing between the piles. The piled-raft foundation system consisted of nine piles with a 3 x 3 configuration. The load applied to the system for both types of soil was 1,000 kPa (see Figure 6).

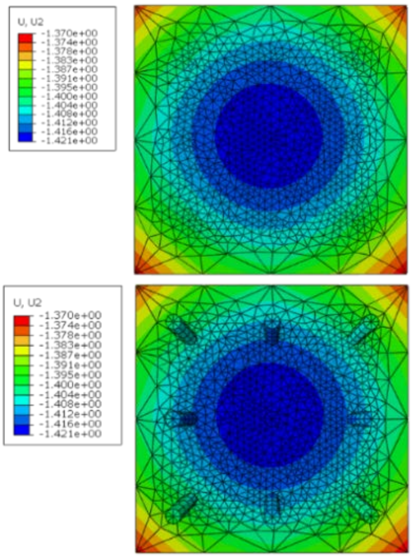


Figure 6 Differential settlement of piled-raft foundation system.

The settlement of the foundation for the piled-raft foundation system with various pile spacings was quite uniform, as shown in Figure 7. This means that pile spacing has no significant effect on the settlement of the foundation. The differential settlement of the system obtained by comparing the settlement of foundation at the center and the edge of the raft is shown in Figure 8.

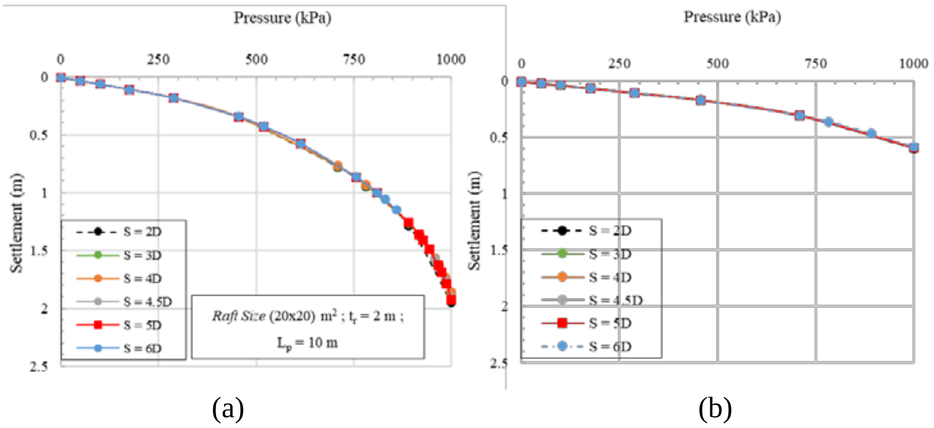


Figure 7 Load settlement on clay soil with spacing variation between the piles: (a) very stiff clay, (b) hard clay.

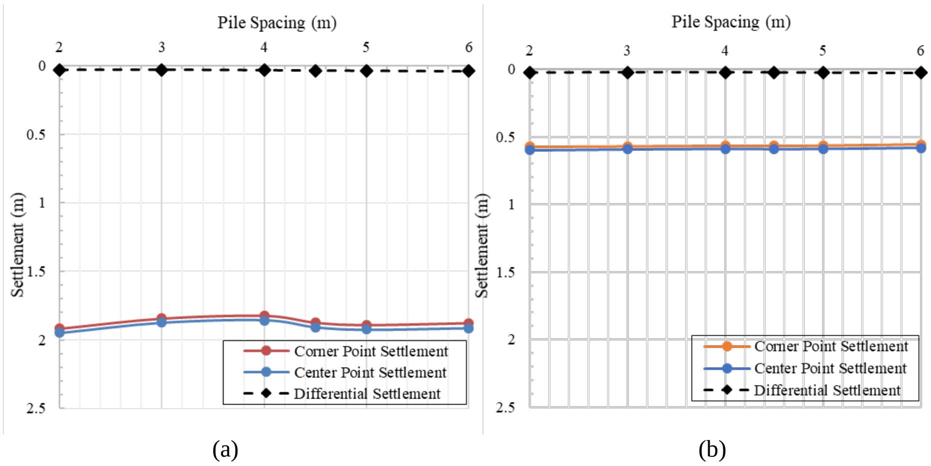


Figure 8 Differential settlement on clay soil with spacing variation between the piles: (a) very stiff clay, (b) hard clay.

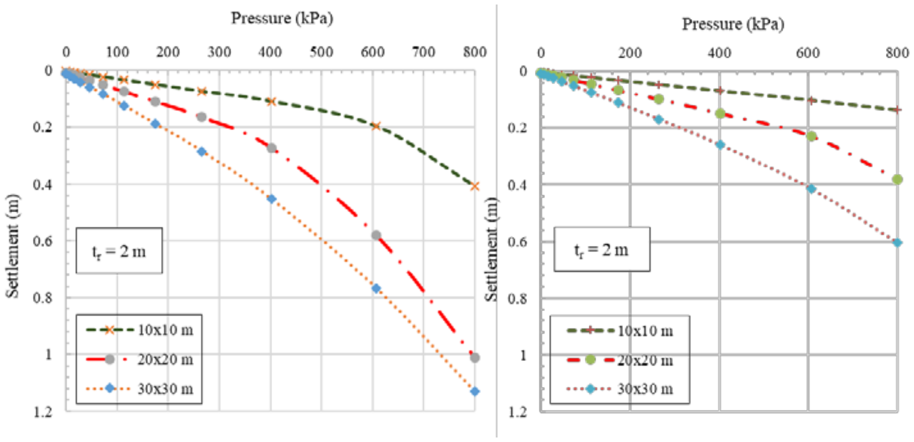
The differential settlement of a system in very stiff clay is slightly larger than in hard clay. Based on Figure 8, differential settlement for very stiff clay was generally about 3 cm, while for hard clay it was about 2 cm. Based on this result, it is obvious that harder soil consistency results in lower differential settlement. The differential settlement of the system increases as the pile spacing increases, but the effect of pile spacing on differential settlement is not significant.

3.1.2 Effect of Raft Size

This case study looked at the effect of raft size on foundation settlement. Three sizes of raft were used in the analysis: 10 x 10 m^2, 20 x 20 m^2, and 30 x 30 m^2 with a thickness of 2 m. The research interest in this case study was the margin of settlement as the raft size increases at the same applied load. The load applied to the raft for both types of soil was 800 kPa. The results of the analysis are shown in Figure 9.

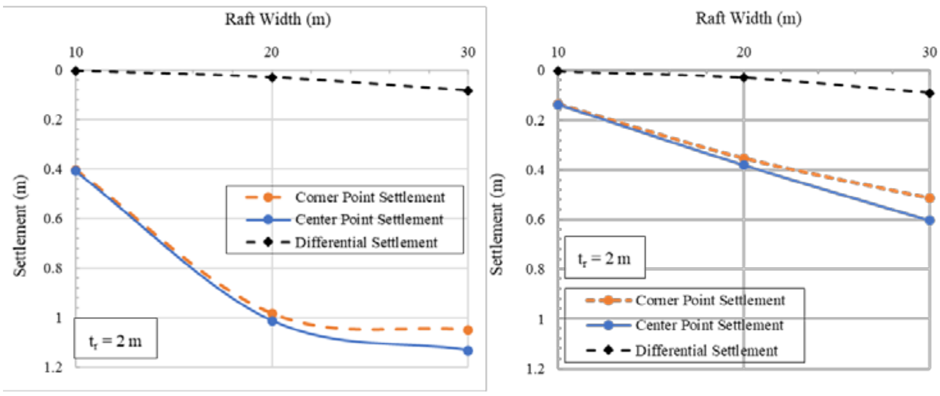
In general, at the same applied load, the larger the raft size, the greater the load received. Based on the results of the analysis, it was proven that the larger the raft size, the greater the settlement of the foundation. Soil consistency also affected the settlement, namely the settlement of the foundation in hard clay was smaller than in very stiff clay. It shows that harder soil consistency results in smaller settlement. As stated by [3], the introduction of piles results in a decrease in the maximum settlement. In general, the settlement decreases with an increasing number of piles, however, it becomes almost constant for 20 or more piles. Additionally, [3] also states that for a small number of piles, the maximum settlement for concentrated loading is larger than for uniform loading, but the difference becomes very small for 10 or more piles.

In the authors' experience, the most common acceptable maximum settlement in high-rise buildings up to approximately 30 stories is within a range of 10 to 20 cm. As shown in Figure 9, the corresponding load pressures for this settlement range were about 180 to 400 kPa and 300 kPa to 800 kPa for very stiff and hard clay, respectively. It is observed that within these ranges, the relationship between settlement and load pressure is still relatively linear, consistent with the results of other researchers, such as [17].



(a) (b)

Figure 9 Load settlement on clay soil with raft size variation: (a) very stiff clay, (b) hard clay.



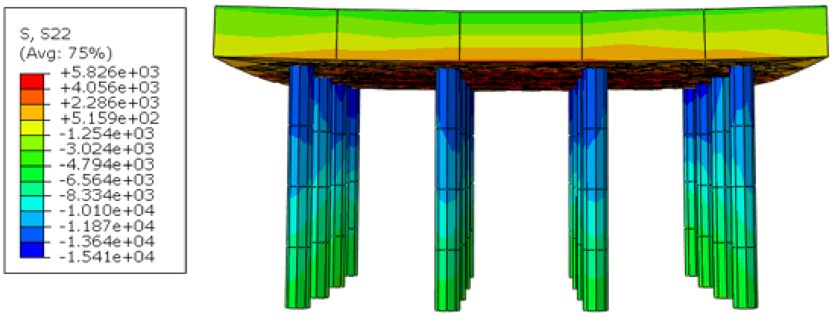
(a) (b)

Figure 10 Differential settlement in clay soil with raft size variation: (a) very stiff clay, (b) hard clay.

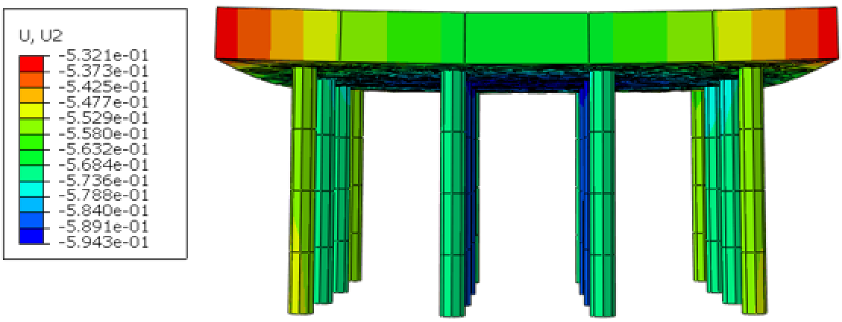
The differential settlements of the raft foundation for both soil consistencies are shown in Figure 10. The analysis result shows that both soil consistencies have the same trend, namely a larger size of the raft foundation, resulting in greater differential settlement. In this case, the introduction of piles into the pile-raft system was very effective in reducing the differential settlement [2].

3.1.3 Effect of Pile Length

The size of the raft used in this analysis was 24 x 24 m^2, with a thickness of 2 m. The pile configuration used in the analysis was 4 x 4 with a pile spacing of 5 times the pile diameter. In this study, the length of the piles was varied to evaluate its effect on the settlement of the foundation. The length of the piles used in this analysis were 10, 20, and 30 m. The total load applied to the raft for both types of soil was 1,000 kPa (see Figure 11).



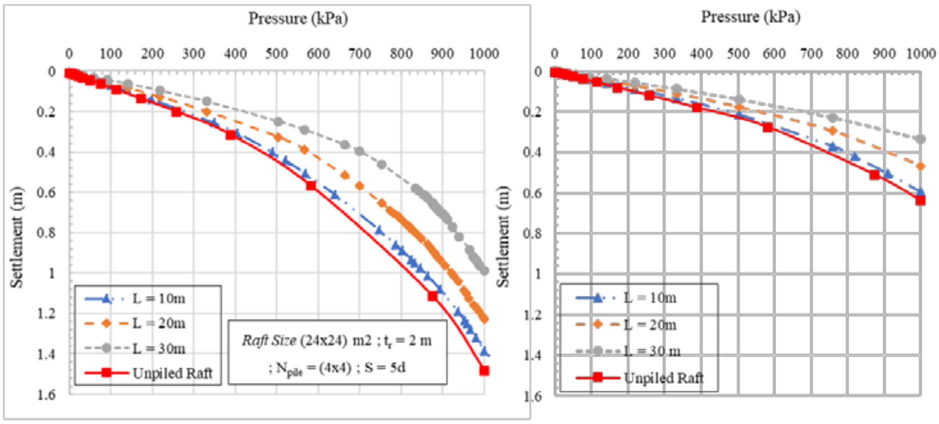
(a)



(b)

Figure 11 (a) Vertical stresses on the piles and raft; (b) displacement on the piles and raft.

Figure 12 shows the settlement versus load graphic for various pile lengths. Based on the results of the analysis, the settlement on both types of soil had the same trend. A longer pile has a higher bearing capacity. A comparison of the settlement in both types of soil with a final loading of 1,000 kPa is shown in Figure 13.



(a) (b)

Figure 12 Load settlement on clay soil with pile length variation: (a) very stiff clay, (b) hard clay.

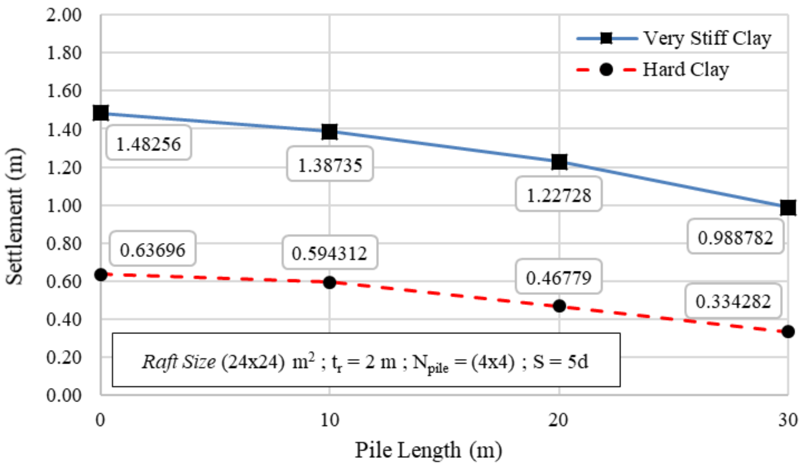
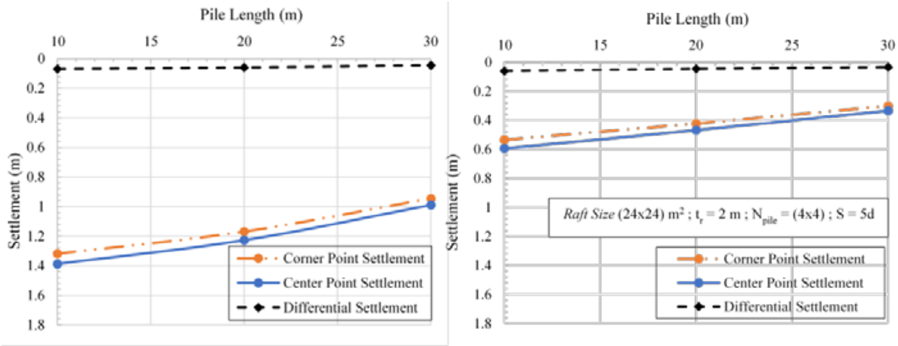


Figure 13 Final settlement with pile length variation**.**

Generally speaking it can be seen that the harder the soil, the smaller the settlement became as the pile length increased. The settlement of the foundation in hard clay was 57% to 67% lower than the settlement in very stiff clay. The differential settlements of the piled-raft foundation for several pile lengths are shown in Figure 14. Based on the results of the analysis, additional pile length reduced the differential settlement of the piled-raft foundation system. However, the reduction was not significant, at only around 20%.

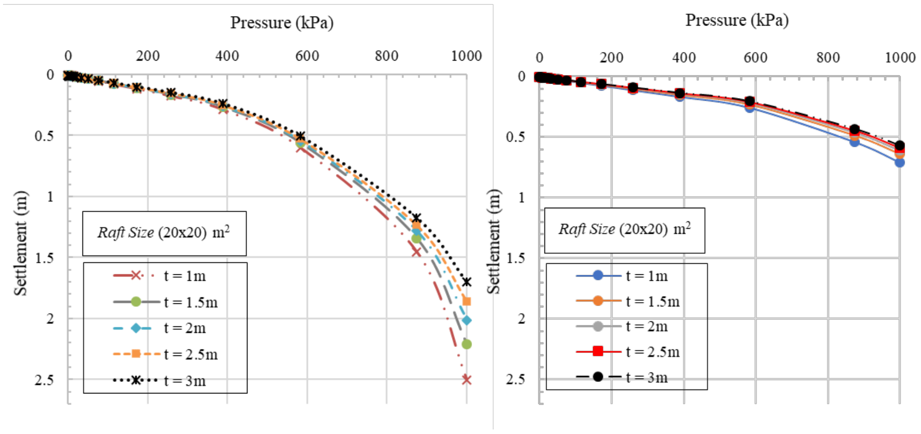


(a) (b)

Figure 14 Differential settlement in clay soil with pile length variation: (a) very stiff clay, (b) hard clay.

3.1.4 Effect of Raft Thickness

In this case study, the size of raft used for the analysis was 20 x 20 m^2 with thickness varied at 1, 1.5, 2, 2.5 and 3 m. The final result expected from this case study is the percentage of the difference in settlement with varied raft thickness. The total load applied to the raft for both types of soil was 1,000 kPa. The result of the analysis shows that as raft foundation thickness increases, the settlement of the foundation decreases (Figure 15).



(a) (b)

Figure 15 Load settlement on clay soil with raft thickness variation: (a) very stiff clay, (b) hard clay.

A comparison of the settlement between very stiff clay and hard clay with a final load of 1,000 kPa is shown in Figure 16. Generally speaking it appears that harder soil consistency resulted in smaller settlement along with the increase of raft foundation thickness. However, an increase of the raft thickness had no significant effect on the settlement of the foundation in hard clay. The differential settlements of the piled-raft foundation system with various thicknesses of the raft are shown in Figure 17. The figure shows that the increase in raft thickness resulted in reduced settlement. The differential settlement was quite large for the foundation with a raft thickness of 1 m. The settlement of the foundation in very stiff clay soil was 27 cm, while in hard clay soil it was 18 cm.

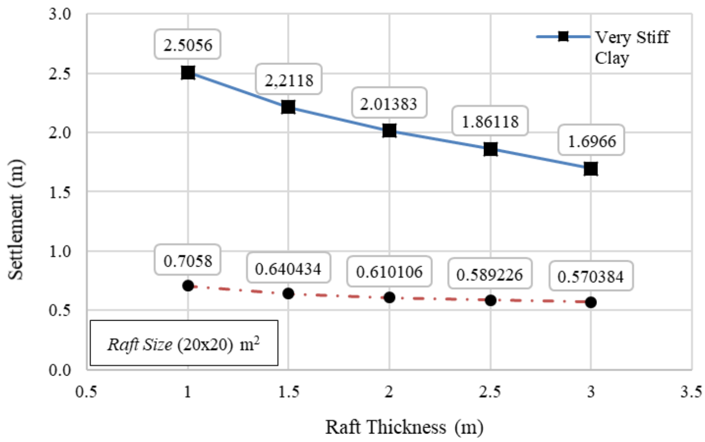


Figure 16 Final settlement with variation of raft thickness.

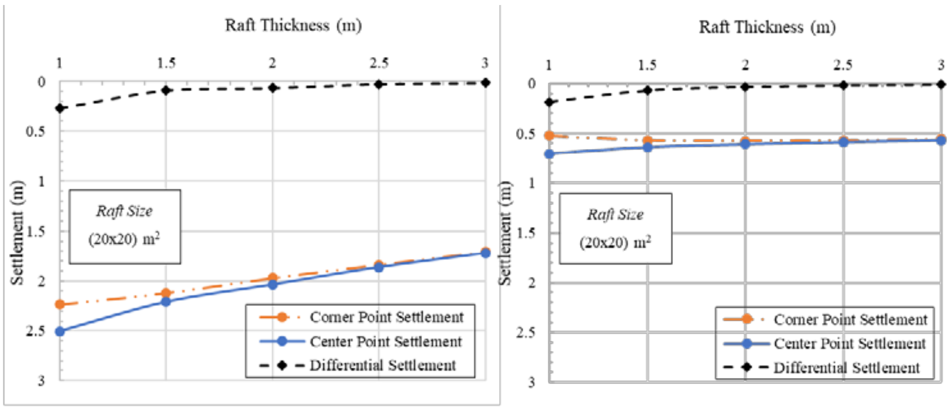


Figure 17 Differential settlement in clay soil with variation of raft thickness: (a) very stiff clay, (b) hard clay.

3.1.5 Load Transfer Mechanism on Raft Piles

A study of the load transfer mechanism was conducted for both soil consistencies using 4 x 4 (spacing of piles = 6D) and 5 x 5 (spacing of piles = 5D) configurations. The size of the raft used in this analysis was 24 x 24 m^2 with a thickness of 2 m. Figure 18 shows the model used for the analysis.

The raft was supported by a 10-m long pile. The total load applied to the raft foundation was 1000 kPa, considering the ultimate capacity of a single pile. The simulation steps of load transfer on the foundation are shown in Figures 19 to 21.

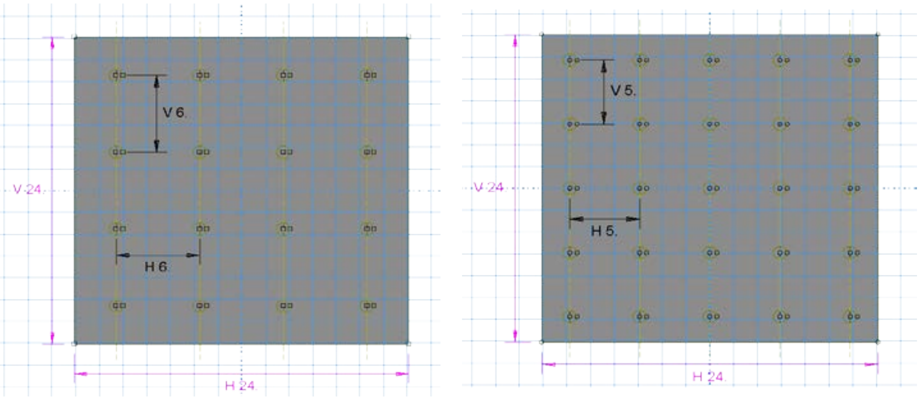


Figure 18 Model used for load transfer mechanism analysis.

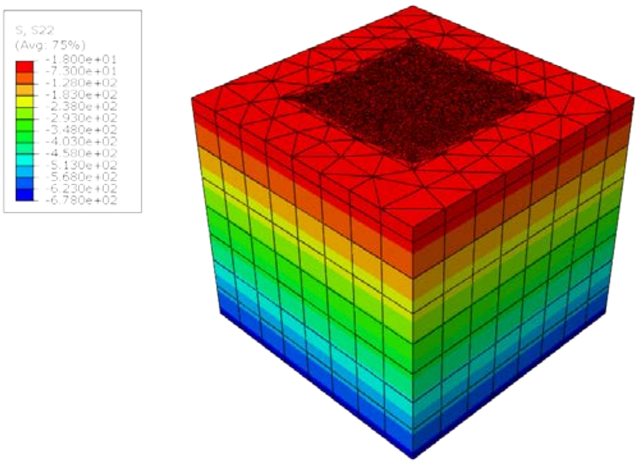


Figure 19 Step 1 (Geostatic): Existing soil condition.

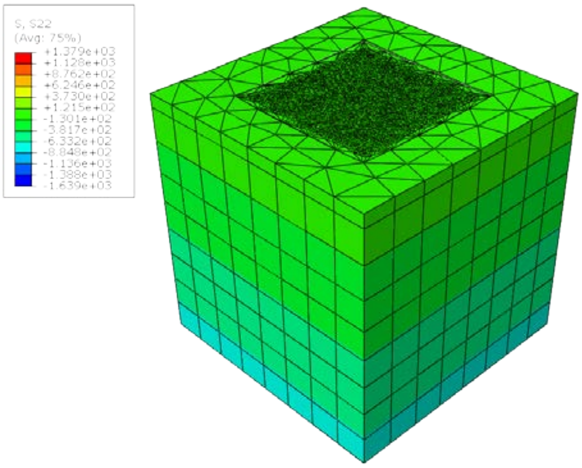


Figure 20 Step 2: Installation of piles and raft.

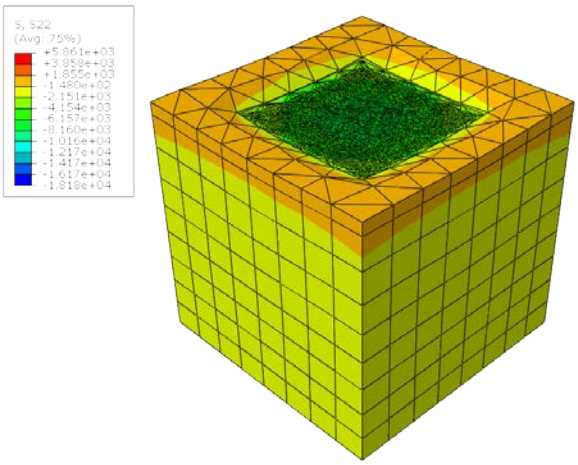


Figure 21 Step 3: Application of load.

Evaluation of the load transfer mechanism was performed using the average value of the vertical stress on each element for each part in each increment step (see Figures 22 and 23).

Analysis of the load distribution on piles was conducted in drained and undrained conditions for each configuration. The effective soil parameters were chosen based on Table 5 [18]. The Young modulus of the soil was calculated using a correlation of 2/3 Eu [19]. Table 6 shows the effective parameters of the soil used in the analysis. The concrete used for the piles and raft used in this analysis had a compressive strength of 25 MPa (i.e. K-300 concrete).

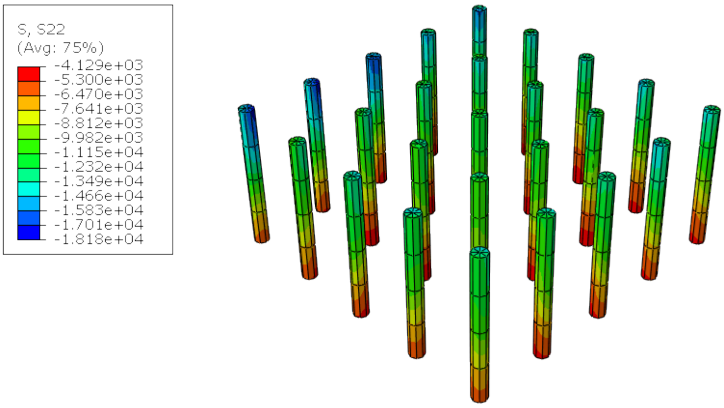


Figure 22 Stress received by piles in the last step.

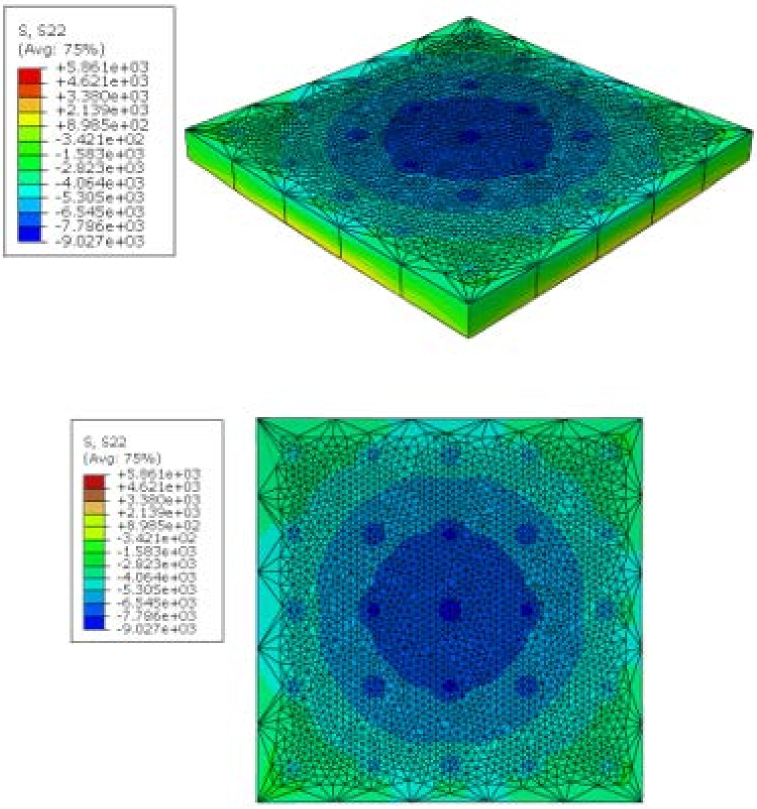


Figure 23 Stress received by the raft in the last step.

Table 5 Effective strength parameters of cohesive soils.

Type	Soil Description/state	Effective Cohesion (kPa)	Friction Angle (deg)
Cohesive	Soft - organic	5 – 10	10 - 20
	Soft - non-organic	10 – 20	15 - 25
	Stiff	20 – 50	20 - 30
	Hard	50 – 100	25 - 30

Table 6 Effective soil parameters.

Parameter	Unit	Very Stiff Clay	Hard Clay
Model material	-	Mohr-Coulomb	Mohr-Coulomb
Elastic modulus, E'	kN/m^2	16000	24000
Poisson's ratio, υ	-	0.3	0.3
Unit weight, γ	t/m^3	1.75	1.8
c'	kN/m^2	60	90
ϕ'	deg	27	30

Based on the results of the analysis, the bearing capacity of the piles was greater in drained condition than in undrained condition. In drained condition, the shear strength of soil was greater so that the soil-pile friction also increased. The load distribution on the piles is also influenced by the number of piles. More piles in the piled-raft foundation system results in a greater load received by the piles. The influence of soil consistency on load distribution should also be considered, since piles carry a greater load in hard clay than piles in very stiff clay. At the initial loading stage, the piles received all applied load until the ultimate capacity of the piles was exceeded. Once the ultimate capacity of the piles is reached, the load is transferred to the raft foundation. Recapitulation of the load distribution on the piled-raft foundation system under drained and undrained conditions is presented in Table 7. As shown in the table, the majority of the applied load was carried by the raft, which is consistent with [5].

Table 7 Load distribution on piled-raft foundation system.

P = 1000 kPa	**Raft Size (24x24) m^2 ; t_r = 2 m ; L_p = 10 m Piles Configuration (4 x 4)**			**Raft Size (24x24) m^2 ; t_r = 2 m ; L_p = 10 m Piles Configuration (5 x 5)**		
Soil Type	**Raft**	**Piles**	**Settlement (m)**	**Raft**	**Piles**	**Settlement (m)**
VSC $_{\text{(Undrained)}}$	85.9%	14.1%	1.3865	83.0%	17.0%	1.3251
VSC $_{\text{(Drained)}}$	79.8%	20.2%	0.8805	69.8%	30.2%	0.8401
HC $_{\text{(Undrained)}}$	83.9%	16.1%	0.5942	74.9%	25.1%	0.5942
HC $_{\text{(Drained)}}$	77.1%	22.9%	0.5559	67.8%	32.3%	0.5257

* VSC = Very Stiff Clay; HC = Hard Clay

3.1.6 Elastic-Plastic Zone in Pile Foundation

The compressive strength of the concrete used in this analysis remained the same; K-300 concrete was used. The load applied to the piled-raft foundation system is broken down according to soil type. The total load applied to the piled-raft foundation system in very stiff clay was 1,000 kPa, while the total load in hard clay was 1,500 kPa. The total load applied to the system was varied to determine the elastic-plastic zone of the piles along with the differences in soil consistency. The analysis was conducted under undrained conditions.

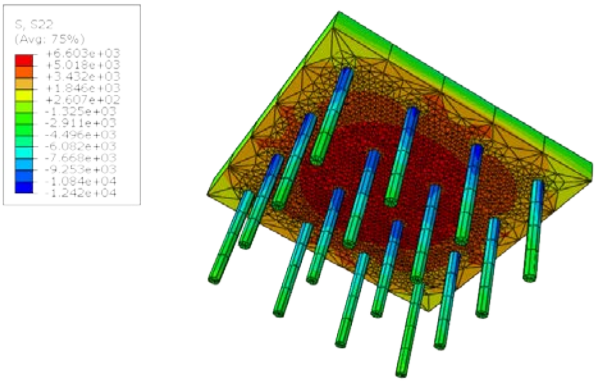


Figure 24 Illustration of the stress received by the raft and piles at the final loading stage.

Figures 25 and 26 show the load distribution in the piles. The load distribution in the piles was categorized into three zones. Zone 1 is the elastic pile zone, Zone 2 is the non-linear (almost plastic) pile zone, Zone 3 is the zone when the pile reached its ultimate capacity or plastic condition. The load distribution results from the analysis were similar to those from the previous research reported in [14].

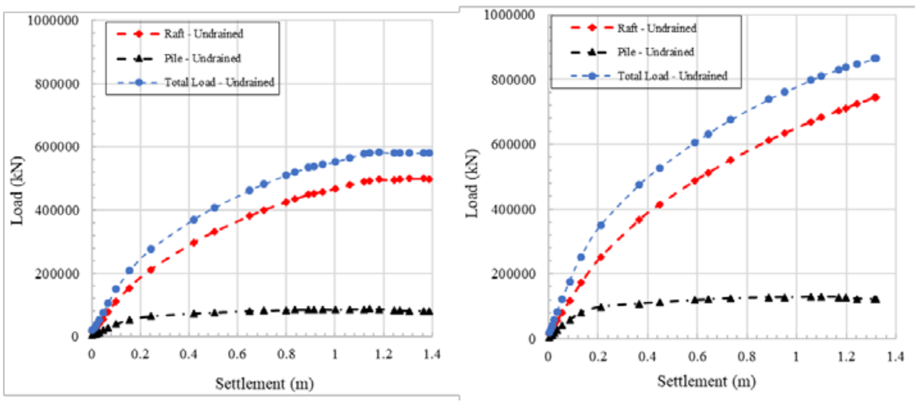


Figure 25 Total load distribution for piles and rafts in: (a) very stiff clay, (b) hard clay.

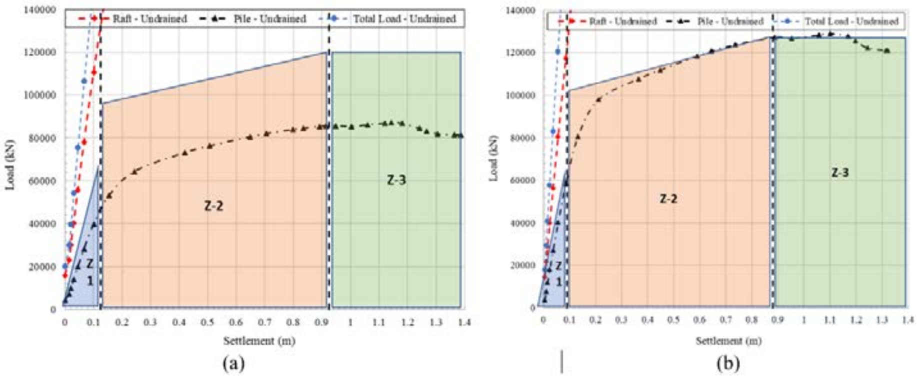


Figure 26 Elastic-plastic zone in the piles: (a) very stiff clay, (b) hard clay.

In this research, the elastic-plastic pile zone was defined based on pile diameter. Elastic-plastic zone determination was based on the verification result using different pile diameters. Figure 27 shows the definition of the elastic-plastic pile zone based on pile diameter. The result shown is only for the piles with a diameter of 1 m in 4 x 4 piles configuration (pile spacing of 6D). The results obtained for the other model were almost the same.

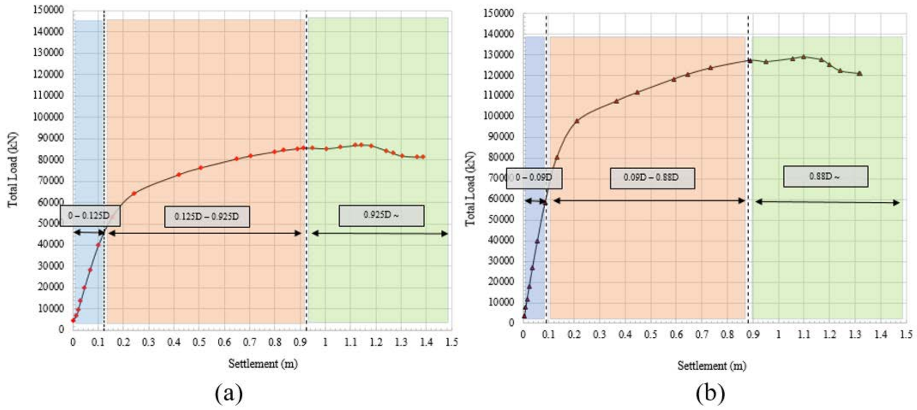


Figure 27 Elastic-plastic zone definition based on pile diameter on: (a) very stiff clay, (b) hard clay.

Table 8 Elastic-plastic zone definition based on the diameter of the pile.

	Very Stiff Clay	
Zone 1 (elastic) S = 0 - 0.125D	Zone 2 (non-linear) S = 0.125D - 0.925D	Zone 3 (plastic) S = 0.925D ~
	Hard Clay	
Zone 1 (elastic) S = 0 - 0.09D	Zone 2 (non-linear) S = 0.09D - 0.88D	Zone 3 = (plastic) S = 0.88D ~

4 Conclusions

The effects of pile spacing, raft size, length of pile, and raft thickness on the total and differential settlements of a piled-raft system were evaluated using finite element model. The load transfer mechanism between the piles and the raft was also discussed. Model verification showed good agreement with previous experimental laboratory work.

Based on this study's outcomes, the settlement of pile-raft system is affected by soil consistency. A harder soil consistency results in lower total and differential settlements of the piled-raft system. In this specific case study, the soil conditions and piled-raft configurations studied, both total and differential settlements were slightly affected by pile spacing. The evaluation of various raft sizes showed that the larger the raft foundation, the greater the differential settlement is. Meanwhile, as the raft foundation thickness increases, the settlement of the foundation decreases. Thus, increasing the raft thickness is an effective way of reducing the settlement of pile-raft system. Additional pile length is considered less effective in reducing the differential settlement of a piled-raft system since the settlement reduction is only around 20%. More piles in the piled-raft system results in greater load received by the piles.

The influence of soil consistency in load distribution was also assessed, since the piles in hard clay carry greater load than piles in very stiff clay. In the initial loading stage, the piles received all applied load until the ultimate capacity of the piles was exceeded. Beyond pile's ultimate capacity, the load was transferred to the raft foundation. This study also shows that the elastic-plastic zone of the piles could be defined based on the pile diameter.

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