Soil-Structure Interaction of a Piled Raft Foundation in Clay – a 3D Numerical Study

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Abstract. Piled raft foundation designs consider the contribution of the pile cap in transferring load to the ground and distributing load over the piles. The concept of a piled raft foundation requires a comprehensive evaluation of a number of factors that affect the performance of the foundation system. In this research the interaction among piles, pile cap and soil of a piled raft system on medium and stiff clays was studied. The effects of various distances between piles (s/d) in affecting load transfer mechanisms and deformation were considered. The study was performed by utilizing the 3D finite element method with a professional software package called Plaxis3D Foundation. A case study of the piled raft foundation performances of a foundation design for a high-rise building based on the soil stratification in Jakarta was also performed and is presented in this paper.

Keywords: *3D finite element; 3D numerical analysis; load transfer mechanism; piled raft foundation; raft foundation; settlement reduction pile; soil structure interaction.*

1 Introduction

It is widely accepted that a shallow foundation system can be used to support relatively small structures. Larger structures such as high-rise buildings, on the other hand, generally require a deep foundation system due to the large pressures they generate. The question is: what if the building is constructed on stiff or even hard clays so that the bearing capacity of the soil can handle the design load but still has the potential problem of settlement? Can we rely on the combination of raft and bored piles–only in limited numbers–to reduce settlement at the same time?

Recently, the piled raft foundation is one of the most efficient solutions to support larger loads that potentially cause large settlement. Many researches of piled raft foundations have been conducted, such as Eslami, *et al.* [1],

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Balakumar [2] and Abate [3]. The stiffness of the pile cap influences the load transfer mechanism of the foundation system. The role of the pile cap becomes significant if the pile cap is in direct contact with the foundation soil. However, the concept of the piled raft foundation requires a comprehensive evaluation of a number of factors that affect the performance of the foundation system. In this research, the load transfer mechanism and settlement of a piled raft foundation were investigated by analyzing the effects of various ratios of spacings and distances of piles (s/d). Since the study of the foundation system was focused on clay, this study considered both undrained and drained conditions. This load transfer mechanism study was conducted by investigating the portions of the load carried by the raft and the piles.

This paper also discusses a case study of the piled raft foundation performances of a high-rise building in Jakarta, Indonesia. The study was more focused on investigating the transfer load portions to raft and piles and settlement performance.

2 Analysis of Load Transfer Mechanism and Settlement of Piled Raft Foundation

2.1 Verification of Model of Analysis

Before conducting the study, the planned model was verified. The verification of the finite element program was based on the soil modeling by Apoji [4] and the piled raft foundation system modeling by Roesyanto [5]. The soil modeling by Apoji [4] proved that the hardening soil model can represent a soil's behavior appropriately. The result is shown in Figure 1.

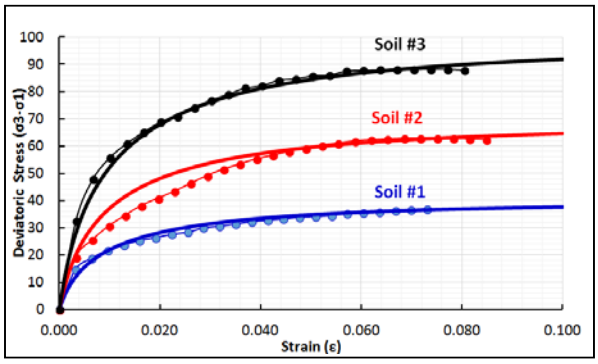

Figure 1 Deviatoric stress vs. strain curve of triaxial CU laboratory testing vs. soil modeling result by hardening soil model (Apoji [4]).

The analysis of a piled raft foundation using the finite element method by Roesyanto [5] proved that the finite element method can predict the load-displacement behavior appropriately. The results of the numerical analysis and the laboratory test by Roesyanto [5] are shown in Figure 2.

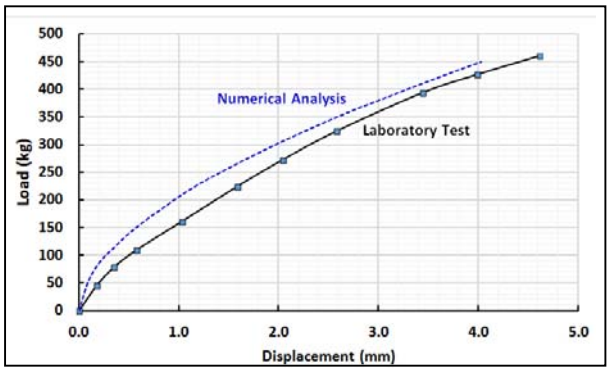

Figure 2 Load-displacement curves of laboratory testing and finite element simulation results (Roesyanto [5]).

2.2 Load-Displacement of a Pile Raft Foundation

After verifying the finite element model, the next stage was analyzing the load-displacement of the piled raft foundation system. This analysis consisted of two (2) cases: (1) analysis of load-displacement on a single pile, and (2) analysis of load-displacement on a group of piles with various spacings of piles (s/d). The soil consistencies of the investigated clays consisted of medium clay and stiff clay. By taking the upper bound of the N-SPT values of medium and stiff clays, the inputted soil parameters were as presented in Table 1.

Table 1 Soil parameters.

Parameters	Symbol	Medium Stiff Clay	Stiff Clay	Unit
Material model	-	Hardening soil	Hardening soil	-
Type of behaviour	-	Undrained	Undrained	-
Dry unit weight	γ_{dry}	16	17	kN/m^3
Wet unit weight	γ_{wet}	17	18	kN/m^3
Young modulus	$E^{ref}_{/50'}$	5333	10000	kN/m^2
Oedometer modulus	E_{oed}	5333	10000	kN/m^2
Power	m	0.8	0.7	-
Unloading modulus	E_{ur}	16000	30000	kN/m^2
Poisson ratio	v_{ur}	0.2	0.2	-
Cohesion	c_{ref}	1	1	kN/m^2

Table 1 ***Continued.*** Soil parameters.

Parameters	Symbol	Medium Stiff Clay	Stiff Clay	Unit
Friction angle	φ	25	28	degree
Dilatancy	Ψ	0	0	degree
R_{inter}	Rinter	0.7	0.7	-
K_{0nc}	K_{0nc}	0.58	0.53	-
Permeability	k	0.0008	0.0008	m/day

This research used bored piles with a diameter of 1 meter and various lengths of 15 and 20 meters. The raft dimension was 26 x 26 m^2 with a thickness of 1 meter. The inputted parameters of the piles and raft are shown in Tables 2 and 3, respectively.

Table 2 Inputted parameters of piles.

Parameters	Symbol	Medium Clay	Stiff Clay	Unit
Diameter of pile	d	1.0		m
Modulus of elasticity	E	23,500,000		kN/m^2
Unit weight of pile	ϒ	24		kN/m^3
Section area of pile	A	0.785		m^2
Perimeter of pile	K	3.142		m
Bearing capacity				
Ttop, max	skin friction	69.12	129.59	kN/m
Tbottom, max	skin friction	69.12	129.59	kN/m
Fmax	end bearing	282.74	530.144	kN

Table 3 Inputted parameters of raft.

Parameters	Symbol	Value	Unit
Raft thickness	d	1.0	m
Modulus of elasticity	E	23,500,000	kN/m^2
Unit weight of raft	ϒ	24	kN/m^3
Poisson ratio	ν	0.2	-

Before conducting the analysis of the piled raft foundation system, an analysis of the load transfer mechanism and settlement of a single pile was conducted. A single pile was loaded gradually to reach failure to see the load transfer mechanism. Modeling was conducted on a single pile with various lengths (15 and 20 meters) on medium and stiff clays. The model of the analysis is shown in Figure 3 and the results are presented in Figure 4.

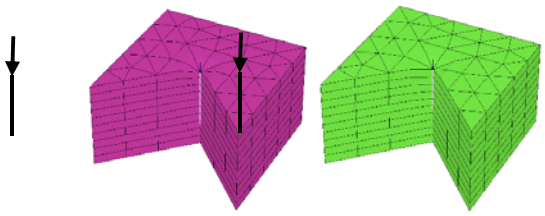

Figure 3 Simulation of load test on a single pile.

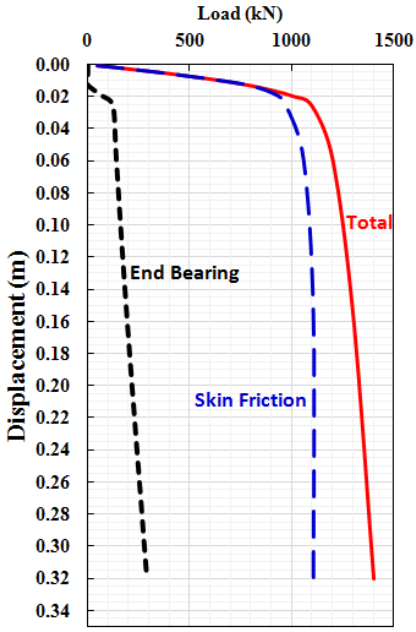

Figure 4 Load-settlement curve of load test simulation of a single pile with 15 meter pile length on medium clay soil.

The simulation results presented in Figure 4 show that for a test load of a single pile with a length of 15 meters in medium clay, the skin friction resistances were mobilized from the beginning of loading up to an approximate load of 1000 kN. The calculated displacement was approximately 0.02 meter. At a load level of 1000 kN, the skin friction resistance was 933.62 kN and the rest was taken by the end bearing resistance with a working stress of 66.38 kN. When the load was increased subsequently, it was transferred to end bearing. The end bearing resistance was fully mobilized at an approximate load of 1300 kN with

a calculated displacement of 0.1 meter or approximately 10% of the diameter (pile diameter = 1 meter).

In addition to the load-settlement curve, the simulation results also illustrated the load transfer along the pile at each level of loading, as shown in Figure 5.

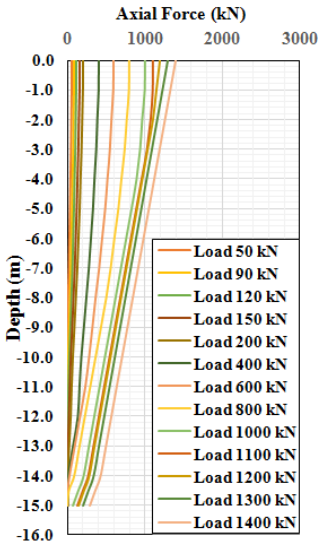

Figure 5 Load transfer mechanism along a single pile with 15 meter pile length on medium clay soil.

The results of the load test for various pile lengths and various clay consistencies were consistent: friction was developed initially until it reached its ultimate capacity, followed by end bearing. The results are consistent with other researches, such as the one conducted by Poulos [6]. The skin friction resistance was mobilized with approximate displacements of 0.5% to 2% of the pile diameter, while mobilization of end bearing occurred at approximate displacements of 5% to 10% of the pile diameter.

After conducting simulations of single piles, the study was continued by studying the load displacement of a piled raft foundation system. This analysis consisted of two conditions: (1) analysis of the raft system, and (2) analysis of a piled raft system with various configurations of piles: 5 x 5 (s/d = 6), 6 x 6 (s/d = 5), 7 x 7 (s/d = 4) and 9 x 9 (s/d = 3). The dimension of the raft was set to be constant at 26 x 26 m^2.

Sketches of the pile raft system with various s/d ratios are shown in Figure 6.

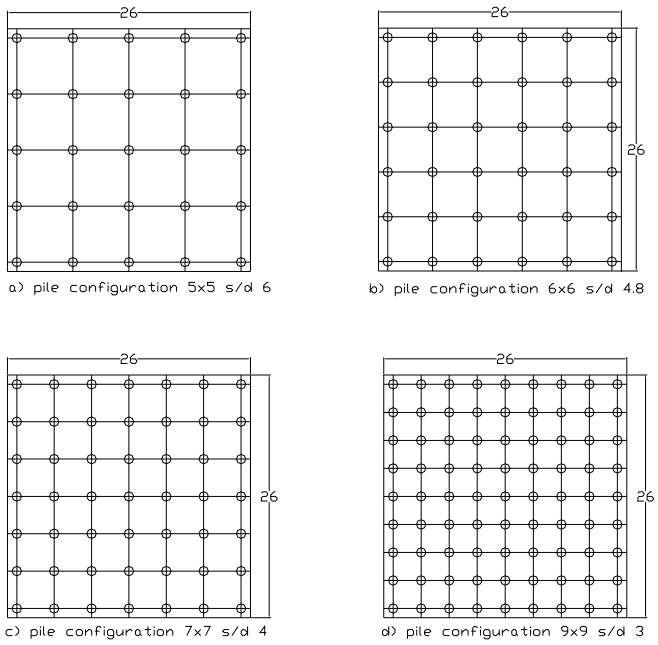

Figure 6 Various configurations of piled raft foundation system.

The raft foundation and piled raft foundation was modeled by Plaxis3D Foundation at full scale, as shown in Figure 7.

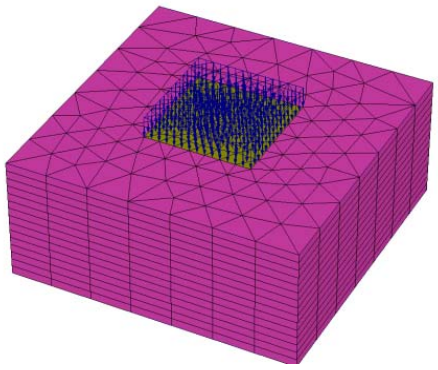

Figure 7 Finite element model for analysis of piled raft foundation system.

The analysis consisted of 3 stages: 1) initial condition, 2) installation of foundation system, and 3) loading on the foundation system.

The foundation system was loaded to reach its ultimate state to obtain full load-settlement behavior in both medium and stiff clays. The load-settlement curves under various conditions are shown in Figures 8 to 11.

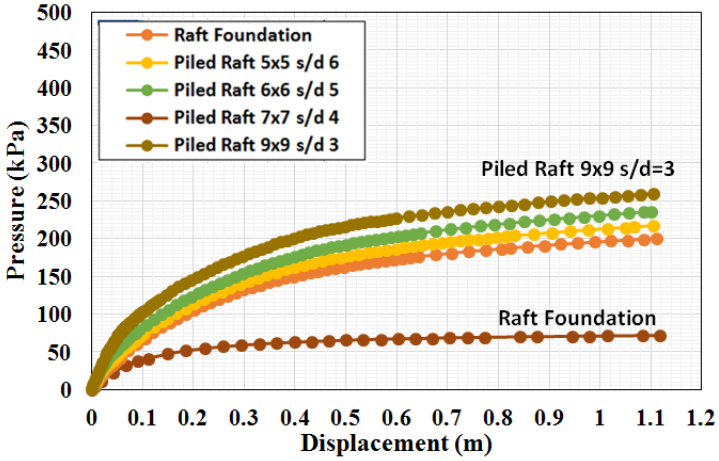

Figure 8 Load-settlement curves of a foundation system in medium clay with a pile length of 15 meters.

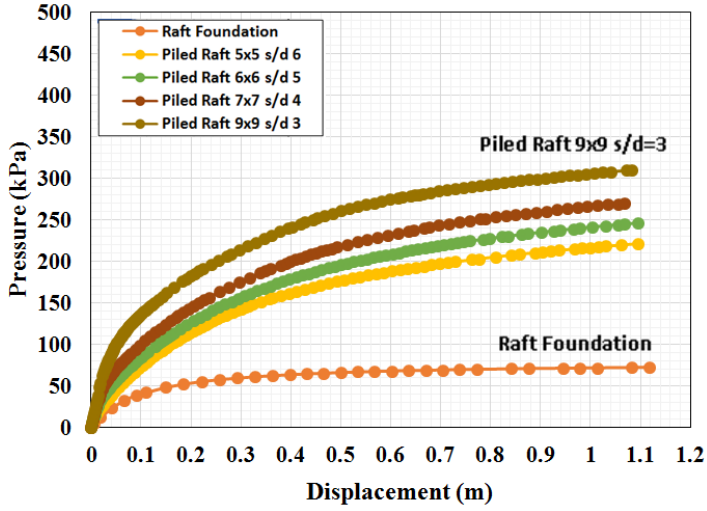

Figure 9 Load-settlement curves of a foundation system in medium clay with a pile length of 20 meters.

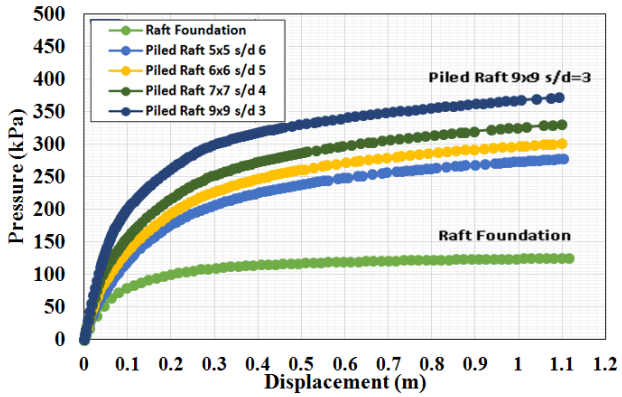

Figure 10 Load-settlement curves of foundation system in stiff clay with a pile length of 15 meters.

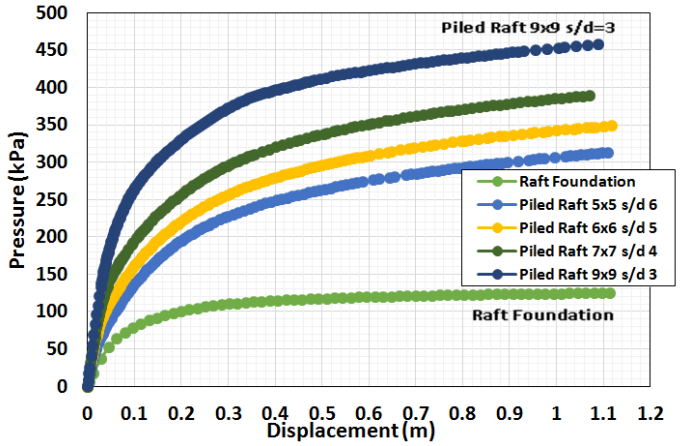

Figure 11 Load-settlement curves of foundation system in stiff clay with a pile length of 20 meters.

When the piled raft system and the raft system were loaded at the same load level, the calculated settlement of the raft system was larger than that of the piled raft system. The load-settlement curves of the piled raft foundation system showed that bored piles as settlement reducers can significantly reduce settlement, depending on the spacing and length of the bored piles. The reason is that the piles in a piled raft system distribute the load to deeper soil layers, generally approximately 2/3 of the length of the piles [6]. The compressibility of the deeper soil is generally smaller than that of the upper soil layers. The

'area' of load distribution of a piled raft foundation system is also larger than the area of distribution of a raft foundation, which affects settlement.

2.3 Pile Raft Loaded to Failure

Furthermore, an analysis was conducted on the load transfer at various levels of axial load. In this study, a piled raft system was loaded gradually until failure. Calculations of the load distribution to the piles were conducted at each level of the load.

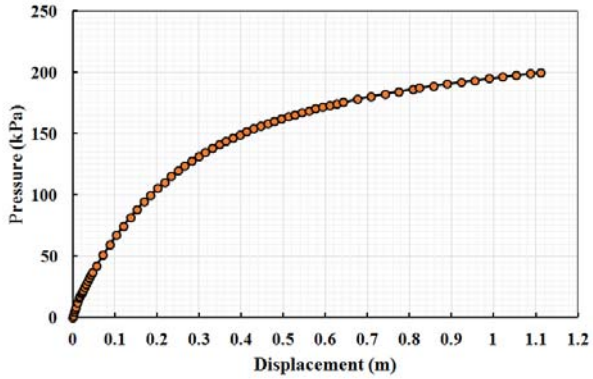

Figure 12 Pressure vs. displacement curve with configuration of piles 5 x 5 s/d 6 in medium clay.

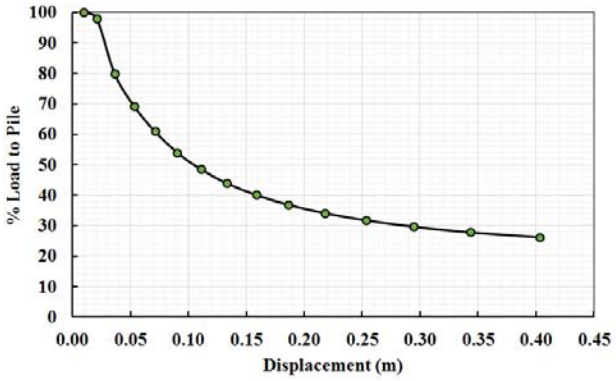

Figure 13 Load distribution on piles vs. displacement curve with configuration of piles 5 x 5 s/d 6 in medium clay.

This study was conducted at various ratios of spacing and diameter (s/d = 3 to s/d = 6) constructed in medium and stiff clays. The results of the load transfer

analysis on a piled raft foundation system with a configuration of 5 x 5 (s/d = 6) in medium and stiff clays are shown in Figures 12 and 13.

The presented analysis results of load transfer to piled raft foundation (s/d 6) show that the piles carried 100% of the working load in the early stages of loading. When the loading was increased, the percentage of distributed load to the piles decreased and the percentage of distributed load to the raft increased. The same phenomenon also occurred in the piled raft foundation system with various spacings, i.e. s/d = 3, s/d = 4 and s/d = 5.

The results of the load transfer to the piled raft foundation are represented by the curves of distributed load and calculated displacement shown in Figure 14.

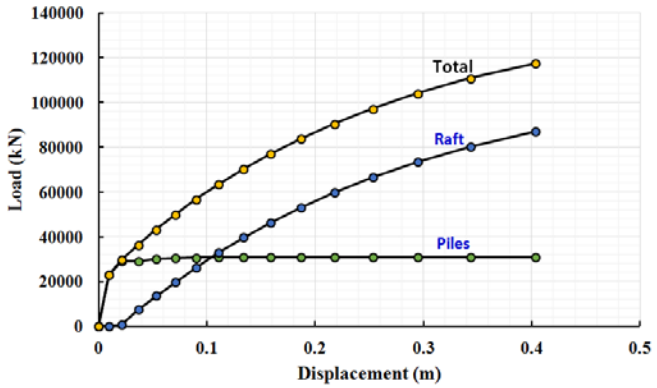

Figure 14 Mechanism of distributed load to piles for various spacings between piles (s/d).

The curves in Figure 14 are divided into three (3) zones. Zone 1 is when the piles are approximately at their allowable capacity (100 % working load). Zone 2 is when the piles are almost at their ultimate condition, already in the non-linear zone. Zone 3 is when the piles have reached their ultimate capacity. When the piles carried approximately 100% of their working load (allowable capacity), they carried almost all the load. If the load was increased, the piles reached a non-linear condition and the raft would carry part of the load. The same result occurred for various distances between the piles (s/d = 3, s/d = 4 and s/d = 5).

Next was the analysis of distributed load to the piles in both undrained and drained conditions. The piled raft system was loaded at the same level in both conditions. The piled raft system was loaded to 70 kPa in medium clay and to 120 kPa in stiff clay.

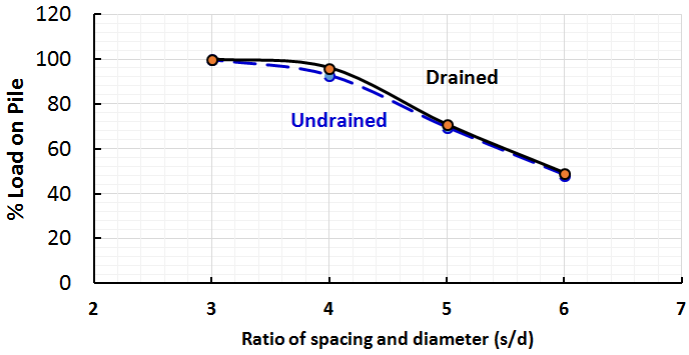

Figure 15 Distributed load to piles with a pile length of 15 m in medium clay.

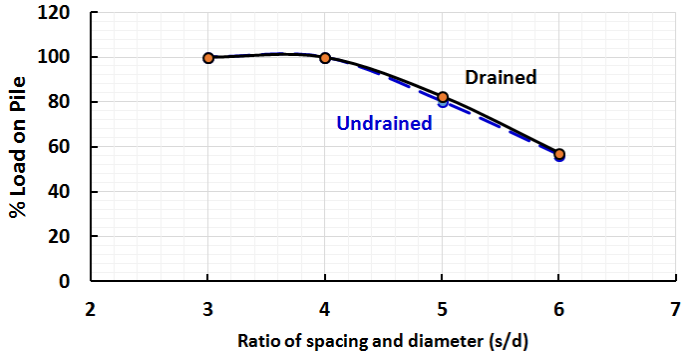

Figure 16 Distributed load to piles with a piles length of 20 meter in medium clay.

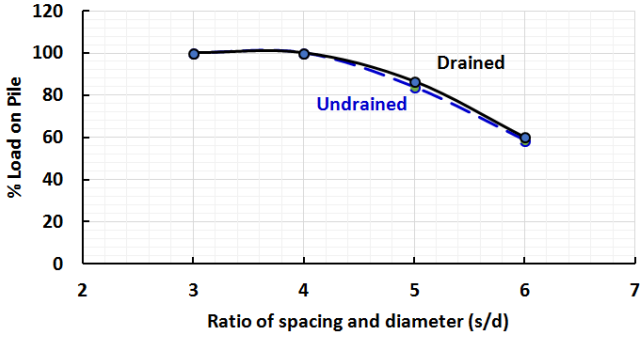

Figure 17 Distributed load to piles with a pile length of 15 meter in stiff clay.

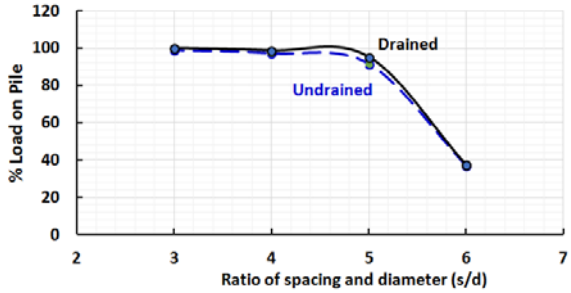

Figure 18 Distributed load to piles with a pile length of 20 meter in stiff clay.

The analysis results for distributed load to piles in both undrained and drained conditions for each consistency of soil are presented in Figures 15 to 18 and summarized in Table 4.

Table 4 Distributed load to piles in undrained and drained condition for pile lengths of 15 and 20 meters.

s/d	Configuration	Soil Type	Pres-sure	Total Load	Axial Force to Piles		% Load to Piles	
					Undrained	Drained	Undrained	Drained
			(kPa)	(kN)	(kN)	(kN)	(%)	(%)
6	5x5 s/d 6 15m	Medium Clay	70	63,544	30,760	31,235	48.4	49.2
5	6x6 s/d 5 15m		70	63,544	44,304	44,979	69.7	70.8
4	7x7 s/d 4 15m		70	63,544	59,134	61,123	93.1	96.2
3	9x9 s/d 3 15m		70	63,544	63,544	63,544	100	100
6	5x5 s/d 6 20m	Medium Clay	70	63,544	35,862	36,420	56.4	57.3
5	6x6 s/d 5 20m		70	63,544	51,025	52,445	80.3	82.5
4	7x7 s/d 4 20m		70	63,544	63,544	63,544	100	100
3	9x9 s/d 3 20m		70	63,544	63,544	69,215	100	100
6	5x5 s/d 6 15m	Stiff Clay	120	97,344	57,155	58,570	58.7	60.2
5	6x6 s/d 5 15m		120	97,344	81,622	84,256	83.8	86.6
4	7x7 s/d 4 15m		120	97,344	97,344	97,344	100	100
3	9x9 s/d 3 15m		120	97,344	97,344	97,344	100	100
6	5x5 s/d 6 20m	Stiff Clay	120	97,344	35,862	36,420	36.8	37.4
5	6x6 s/d 5 20m		120	97,344	89,161	92,631	91.6	95.2
4	7x7 s/d 4 20m		120	97,344	94,792	96,023	97.4	98.6
3	9x9 s/d 3 20m		120	97,344	96,382	97,344	99	100

The table shows that the load transferred to the piles in drained condition was slightly larger than in undrained condition.

The next analysis was the settlement analysis since the settlement is crucial for the design of piled raft systems. The principal considerations were the maximum and the differential settlement. The outputs of the calculated settlements of the piled raft are shown in Figure 19.

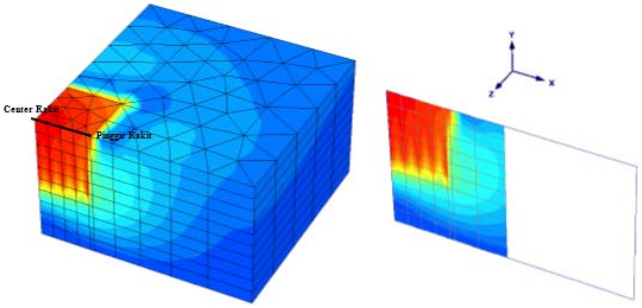

Figure 19 Contours of settlement of a piled raft system.

The calculated differential and maximum settlements of a piled raft system in undrained and drained conditions at various distances between piles are presented in Figures 20 to 27.

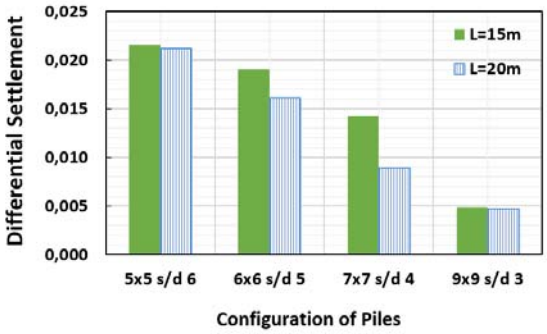

Figure 20 Differential settlement of piled raft in medium clay (q = 70 kPa) for undrained condition with pile lengths of 15 and 20 meters.

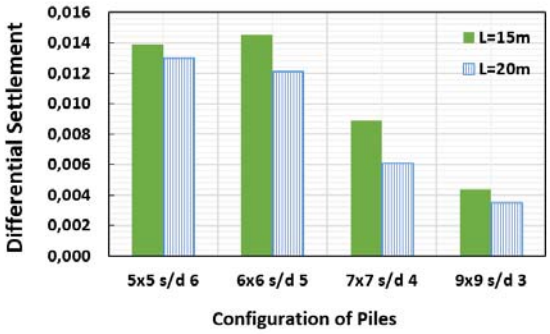

Figure 21 Differential settlement of piled raft in medium clay for drained condition with pile lengths of 15 and 20 meters.

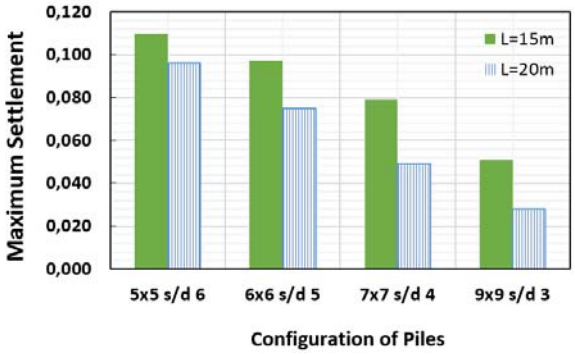

Figure 22 Maximum settlement of piled raft in medium clay (q = 70 kPa) for undrained condition with pile lengths of 15 and 20 meters.

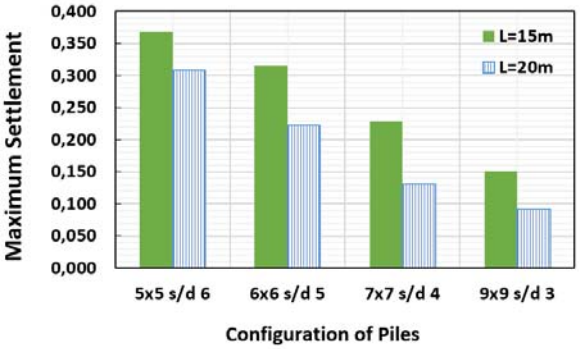

Figure 23 Maximum settlement of piled raft in medium clay for drained condition with pile lengths of 15 and 20 meters.

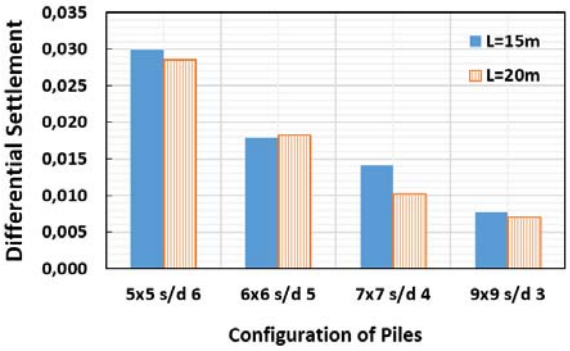

Figure 24 Differential settlements of a piled raft in stiff clay (q = 120 kPa) for undrained condition with pile lengths of 15 and 20 meters.

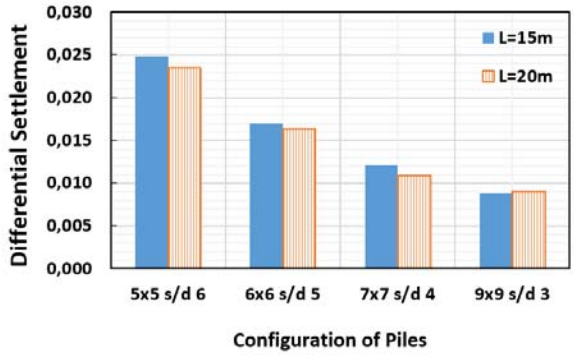

Figure 25 Differential settlement of piled raft in stiff clay for drained condition with pile lengths of 15 and 20 meters.

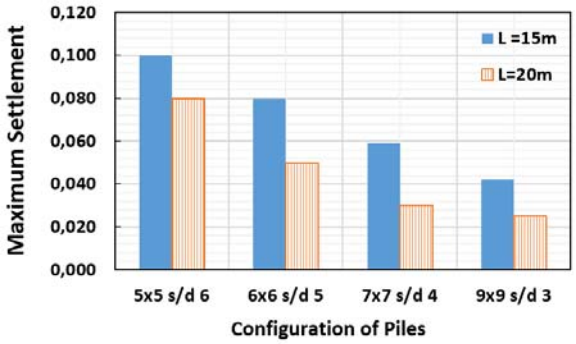

Figure 26 Maximum settlement of piled raft in stiff clay (q = 120 kPa) for undrained condition with pile lengths of 15 and 20 meters.

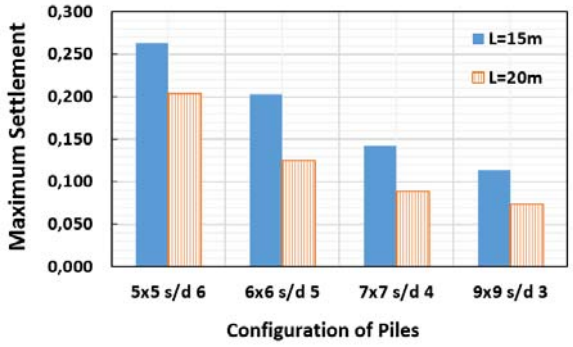

Figure 27 Maximum settlement of piled raft in stiff clay for drained condition with pile lengths of 15 and 20 meters.

The above figures show that the maximum and the differential settlement of the piled raft system were significantly reduced, depending on the length and the spacing of the piles.

3 Case Study of Piled Raft Foundation System

This part discusses the pile-raft-soil interactions of a high-rise building in Jakarta that utilizes a piled raft system to support the upper structures. The thickness of the raft was 3 meters and it consisted of 240 piles. A schematic design of the high-rise building is shown in Figure 28.

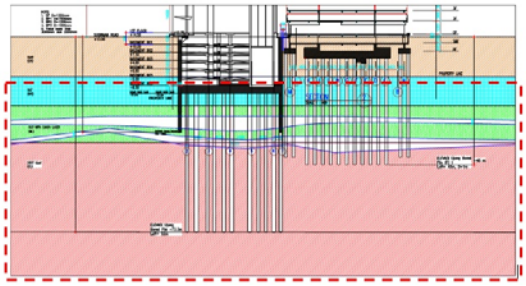

Figure 28 Schematic cross section of the studied piled raft system.

The subsurface soil conditions at the studied location in Jakarta consist of 3 soil layers, as shown in Figure 29 and summarized in Tables 5 and 6.

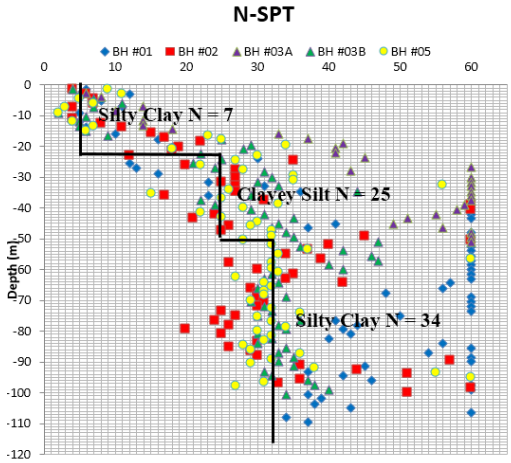

Figure 29 Distributions of N-SPT.

Table 5 Soil properties.

Layer	Depths (m)	Soil Type	N-SPT	Consistency	Soil Model	Material Type	Properties of Soils		Permeability	
							γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	k_x (m/day)	k_y (m/day)
1	0 – 21	Silty clay	7	Medium	HS	Undrained	16	17	9 x 10^{-4}	9 x 10^{-4}
2	21 - 48	Clayey silt	25	Very Stiff	HS	Undrained	17	18	9 x 10^{-4}	9 x 10^{-4}
3	48 - 100	Silty clay	34	Hard	HS	Undrained	17.5	18.5	9 x 10^{-4}	9 x 10^{-4}

Table 6 Soil stiffness and soil strength parameters.

Layer	Depths (m)	Soil Type	N-SPT	Consis-tency	Soil Model	Material Type	Soil Stiffness			Strength		
							$E_{oed}ref$ (kPa)	$E_{ur}ref$ (kPa)	m	c_{ref} (kPa)	ϕ (deg)	ψ (deg)
1	0 – 21	Silty clay	7	Medium	HS	Undrained	5,100	15,300	0.9	10	7	0
2	21 - 48	Clayey silt	25	Very stiff	HS	Undrained	6,658	19,974	0.9	20	8.3	0
3	48-100	Silty clay	34	Hard	HS	Undrained	8,534	25,602	0.9	25	18.2	0

Modeling of the piled raft system was conducted to get the load transfer to the piles and the raft. The stages of construction of the piled raft system consisted of: 1) initial phase; 2) excavation; 3) installation of piled raft; and 4) 664 kPa loading. The analysis model of the piled raft system is shown in Figure 30.

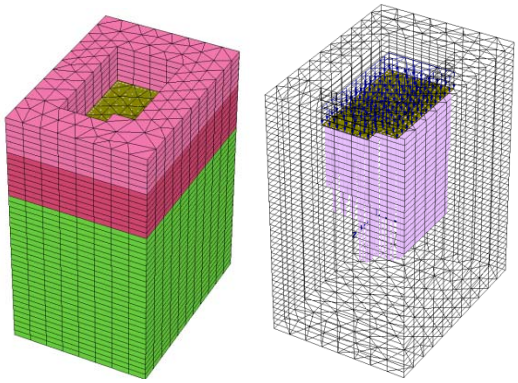

Figure 30 3D model of piled raft system.

The aim of the analysis was to obtain the percentage of load carried by the piles in both undrained and drained conditions (Table 7).

Table 7 Distribution of loads carried by piles and raft.

Type of Analysis	Total Load (kN)	Pile (kN)	Raft (kN)	Ratio (%)	
				Pile	Raft
Undrained	1,645,696	887,213	758,483	54	46
Drained	847,444	726,439	121,005	86	14

The calculated results show that the distributed load carried by the piles in drained condition was larger than in undrained condition. Hence, for practical design purposes, designers may model the drained condition only of the piled raft system.

4 Summary and Conclusions

In this research the soil structure interaction of a piled raft system in medium and stiff clays was investigated. This study utilized the professional finite element software Plaxis3D Foundation to investigate the load transfer mechanism and settlement of a piled raft system.

The model was first verified. Verification of the finite element program consisted of soil modeling and modeling of a piled raft foundation system. The results showed that the selected soil constitutive model and the predicted load settlement behavior were appropriate and comparable to measurements. Simulation results of load tests for various lengths of piles and various consistencies of clays showed that the skin friction resistance was mobilized at approximate displacements of 0.5% to 2.0% of the pile diameter and approximate displacements of 5% to 10% of the pile diameter to mobilize the end bearing resistance.

The analysis results of load transfer to piled raft foundation (s/d = 3 to 6) showed that the piles carried 100% of the working load during the early stages of loading. When the loading was increased, the percentage of distributed load to the piles decreased, after which the percentage of the distributed load to the raft increased at a certain level of load. At the same level of load, the distributed load to the piles in drained condition (86% in the case study) is larger than the distributed load to the piles in undrained condition (54% in the case study). The consolidation process causes the stiffness of the soil to increase, therefore the distribution of the load to the piles also increases.

The number of piles and the length of the piles can reduce settlement effectively. The reduction of the settlement depends on the number, length, soil layer and consistency of the bearing layers. This proves the effectiveness of bored piles as settlement reduction tool. Utilization of foundation systems requires great care and proper analysis.

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