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A Parametric Study of Piled Raft Foundation in Clay Subjected to Concentrated Loading

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Abstract: The use of piled raft foundation in building and infrastructure constructions is increasingly popular because of its effectiveness in reducing overall and differential settlements. Parameters influencing the performance of the piled raft foundation need to be comprehended in order to optimize the design of the piled raft system. Most of the current available literature focused on the piled raft foundation subjected to a uniform distributed load in sandy material. This parametric study aims to provide insights into the performance of the piled raft foundations subjected to concentrated loading in clay. A series of 2D finite element analyses were performed to investigate the influencing parameters affecting the load distribution and settlement behaviour of the piled raft. The results suggested that increases in both pile length and raft thickness, as well as a decrease in pile spacing would reduce the differential settlement of the piled raft. Comparatively, raft thickness was the most significant controlling parameter affecting the differential settlement. The study also revealed the importance of placing the pile nearer to the location of concentrated load as it would yield a more uniform load distribution, and hence a lower differential settlement.

Keywords: Finite element analysis, load distribution, piled raft, settlement

1. Introduction

The use of piled raft foundation has gained increasing popularity in recent years owing to its superior performance in settlement control and cost-effectiveness when compared to other alternatives. A study conducted by Moyes et al. [1] suggested that the utilization of a piled raft foundation can contribute up to about 30% of cost saving in comparison to conventional piled foundations without compromising their performances.

Piled raft foundations are assembled by combining a shallow foundation (raft) and a deep foundation (pile group). Typically, the raft alone is sufficient to support the structure without causing a bearing failure, despite it may not be able to control the settlement to an acceptable limit. Burland [2] suggested that incorporation of piles in raft foundation can effectively reduce the foundation settlement. In a piled raft foundation, the total imposed load transferred to both the pile group and the raft involves a complex mechanism depending on their relative stiffnesses [3]. The raft is assumed not to contribute to any load bearing in the conventional piled raft design approach which often leads to an excessive design for the number of piles required [4]. An optimum design with respect to accuracy and economic considerations shall take into account of the interaction between raft, piles and soil [5].

Fleming et al. [6] claimed that the raft alone in a piled raft system should possess an adequate bearing capacity. The emphasis of the design should be shifted from how many piles are required to support the weight of the structure to how many piles are required to minimize the differential settlement to an acceptable level. De Sanctis & Russo [7] claimed that the load sharing between raft and piles should be taken as the primary consideration as indicated by most

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of the recent studies. El-Mossallamy et al. [8] agreed with the above statement but stated that the settlement should be considered along with the load sharing between raft piles as the essential factors dictating the piled-raft foundation design.

Zhuang & Lee [9] investigated the load distribution among the piles in a piled-raft foundation by carrying out a three-dimensional finite element analysis. Brick elements were chosen to model the structure, raft, piles and soil. Their findings suggested that the load distribution among piles was strongly influenced by the pile length-width ratio, structural stiffness, pile stiffness and raft rigidity. Besides, a more uniform pile load distribution can be achieved by increasing the piles length while reducing the raft and pile rigidity. The effects of varying pile lengths and pile diameters on the performance of piled raft in medium sand were investigated by Srilakshmi & Darshan [10] using ANSYS. They found that the increase of pile diameter improved the ultimate load significantly. They suggested that the use of different pile diameter in a piled raft system could effectively reduce the differential settlement. The combination of larger inner pile diameter with smaller outer pile diameter resulted in a smaller differential settlement.

Shivanand & Baleshwar [11] simulated a large piled raft foundation using PLAXIS 3D to study the effect of pile spacing, pile length, pile diameter and raft-soil stiffness ration on the settlement, load-sharing, bending moments and shear force behaviour of the piled raft foundation. They suggested that increasing the pile spacing to 5-6 times of the pile diameter tended to reduce the average settlement, differential settlement and bending moment of the system.

Nguyen et al. [12] conducted a parametric study to investigate the optimal design of large piled raft foundations in sand using PLAXIS 3D. They suggested that applying a concentrated pile arrangement scheme according to the given load type yielded the best results. In the case of uniform distributed loading, piles should be located more densely at the central load area. As for the case of column loading, the piles should be placed more densely at the column positions according to the load ratio.

Abdel-Azim et al. [13] used finite element software, PLAXIS 3D to optimize the design of piled raft foundation system for a building in Germany. They concluded that the piled raft foundation concept is a more cost-effective solution in comparison with the conventional pile foundation for high-rise buildings founded on over-consolidated clay.

Meena & Nimbalkar [14] investigated the effects of water drawdown and dynamic loads on piled raft foundations. The analyses were carried out using PLAXIS 2D. They found that groundwater fluctuation may alter the peak ground acceleration, and hence affect the seismic response of the foundation system. The settlement of the piled raft foundation can be most effectively controlled by increasing the number of piles.

Nasrollahi & Hosseininia [15] developed an analytical approach to analyze vertically-loaded piled-raft foundations by considering the pile–soil–raft interaction. Their approach was capable of improving the settlement prediction and axial pile load of the complex piled raft system. They concluded that increasing dimensions of the raft up to about twice the pile length can significantly reduce the piled-raft settlement.

Luo et al. [16] used 3D boundary element method to perform a parametric study to investigate the normalized settlement of piled raft foundation as the results of various soil conditions, pile dimensions, and soil-pile adhesions. They concluded that soil rigidity is a dominant factor affecting the normalized settlement of the piled raft foundation system. The normalized settlement of the piled raft was significantly influenced by the factor of safety (FoS) adopted when the FoS < 3, and hence they concluded that a FoS of 3 should be adopted in piled raft foundation design.

Mali & Singh [17] used PLAXIS 3D to investigate the performance of a large piled raft system under different loadings and pile-raft configurations. Two types of loading conditions were considered in their analyses, i.e. uniformly distributed load and equivalent point load. They concluded that the settlement of the piled raft was lower for piled-raft configurations with uniformly distributed load as compared to that of equivalent point load. They also found that an increase in the raft thickness would result in a decrease in differential settlement, but an increase in average settlement.

From the review of previous studies, it can be concluded that numerous numerical and experimental studies have been carried out to investigate the load transfer mechanism and settlement of the piled raft foundation. Amid these studies, several numerical models have been developed with each of them having its own advantages and disadvantages. Most of the previous studies focused on the load distribution and deformation of piled raft foundation in sandy soils and subjected to a uniform distributed load. The present study aims to provide more insights into the performance of piled raft foundations in clay under a concentrated load replicating a structural column load. Piled raft foundation is widely applied in clayey material as the settlement control in such material constitutes the most critical design consideration. A parametric analysis is carried out in this study using PLAXIS 2D to determine the influencing factors on the load distribution and settlement behaviour of the piled raft foundation. The two-dimensional finite element method was chosen over the three-dimensional analysis after considering the advantages offered by the 2D analysis with respect to the time constraint and computational effort.

2. Methodology

2.1 Numerical Model

The numerical analysis in the present study was performed by using a finite element analysis software, namely PLAXIS 2D. A hypothetical piled raft foundation of 20 m wide was modelled as a plain strain 2-dimensional model (Fig. 1). Plate elements are selected to model the raft structure. Two translational degrees of freedom (ux, uy) and one rotational degree of freedom (Φz) were assigned for each plate element of the plane strain model. The behaviours of the plate elements were governed by Mindlin's beam theory which considers deflection as a result of bending and shearing. Considering the modulus of elasticity of both raft and piles were greater than soil, a linear elastic material behaviour was assumed for the raft and piles. They were connected by a rigid connection. Piles were modelled using embedded pile row element as non-displacement piles with reinforced concrete assigned as the material. Settlements of the system were captured at the center and edge of the raft (plate), i.e. (x = 50 m, y = 100 m) and (x = 40 m, y = 100 m), respectively.

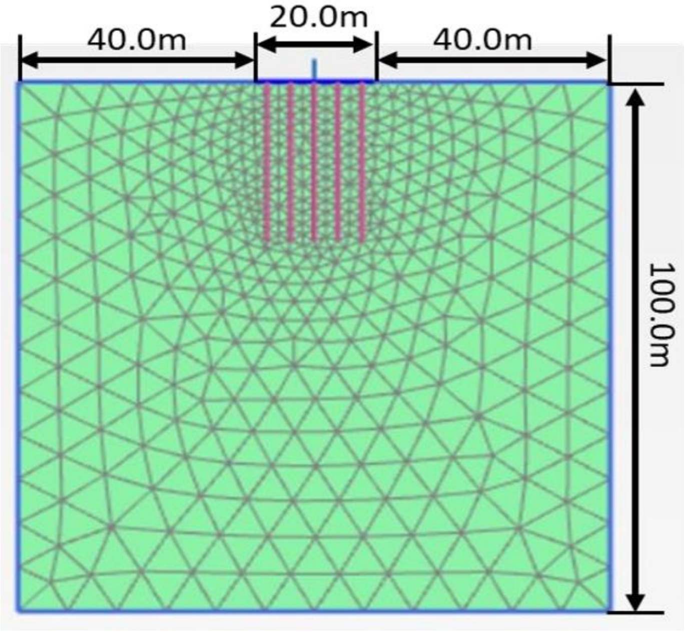

Fig. 1 - Finite element model of piled raft foundation

2.2 Input Parameters

Table 1 and Table 2 tabulate the input parameters for soil and structural elements of the modelled piled raft system, respectively. Considering the present study focused on piled raft behaviour in clay, typical properties of clay soil were selected as the input parameters for the soil material.

Table 1 - Input parameters for soil materials

Description	Symbol	Unit	Value
Types of soil	-	-	Clay
F.E.Model	HS	-	Hardening Soil
Type of model behavior	-	-	Drained
Unit Weight		kN/m^3	16
Secant Stiffness in Standard Drained Triaxial	E^{ref}_{50}	kPa	7500
Tangent Stiffness for Primary Oedometer Loading	E^{ref}_{oed}	kPa	20480
Unloading/Reloading Stiffness	E^{ref}_{ur}	kPa	22500
Cohesion	c	kPa	60.0
Friction angle	ϕ	degree	10.0
Poisson's Ratio	v	-	0.35
Interface Reduction factor	R_{inter}	-	0.7
Angle of dilatancy	φ	-	0
Exponential Power	m	-	1.0

Table 2 - Input parameters for structural elements

Description	Symbol	Unit	Value
Material	-	-	Concrete
F.E. Model	-	-	Linear Elastic
Unit Weight	γ	kN/m/m	24
Modulus of Elasticity	E	GPa	20
Raft thickness	d	m	1.0
Poisson's Ratio	v	-	0.2

2.3 Study Variables

Four variables were identified in the present study, namely pile length, raft thickness, pile spacing, and pile diameter. These variables were selected as they formed an important set of parameters when designing a piled raft system. Table 3 summarizes the values considered for these variables.

Table 3 - Variables considered in analysis

Pile length (m)	Raft thickness (m)	Pile spacing (m)	Pile diameter (m)
10	0.5	2.5D	0.5
20	1.0	3.0D	1.0
30	1.5	3.5D	1.5
		4.0D	
		4.5D	
		5.0D	

3. Results and Discussions

The simulation results are discussed herein with respect to the maximum settlement, differential settlement, and percentage of load transferred to piles. Poulos [18] stated that the most critical aspects to be considered for the design of piled-raft foundations are the ultimate load capacity, maximum settlement and differential settlement under vertical loads. The differential settlement is defined as the difference between the maximum settlement at the center and the minimum settlement which typically occurs at the corner of a raft foundation.

To facilitate the subsequent discussions, each case of the simulations was given a specific notation. For example, D1.0_L10_S4.0_T1.0 indicated that the diameter (D) of pile was set at 1.0 m, with the pile length (L) of 10 m spaced (S) at 4D on a raft thickness (T) of 1.0 m.

3.1 Effect of Pile Length

Piled rafts with three different pile lengths (i.e. 10 m, 20 m and 30 m) were modelled to investigate the effect of pile length on the performance of the foundations. The raft thickness was fixed at 1.0 m, while the pile diameter and spacing were set at 1.0 m and 4 times of pile diameter, respectively. Fig. 2 to Fig. 4 show the maximum settlement, differential settlement and percentage of load transferred to piles, respectively under applied loading of 1,000 – 5,000 kN/m. The results showed that the maximum settlement of the foundation reduced from 558.1mm to 489.5mm when the pile length was increased from 10 m to 30 m under the point load of 5,000 kN/m. A similar trend was reported by Maharaj and Anshuman [19] who investigated the settlement performance of piled raft using NLAXIFEM-Nonlinear axisymmetric finite element software, but with a larger change in settlement values because larger pile length to diameter ratios were considered in their study. The reduction in maximum settlement at the center of the raft was caused by the increase in the mobilized shaft resistance from piles. The longer the pile length, the greater the amount of the shaft friction mobilized, and hence the lower the resultant maximum settlement at the center of foundation. The results of differential settlement also showed a similar linear trend as the maximum settlement. The percentage of load transferred to piles increased with increasing length of piles. As the portion of load transferred to the raft was reduced, the raft deformed less and hence a lower differential settlement was obtained.

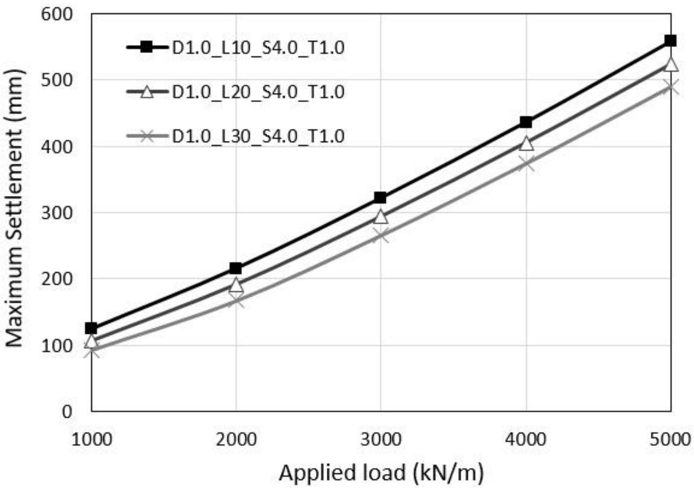

Fig. 2 - Maximum settlements of piled raft for piles with different lengths

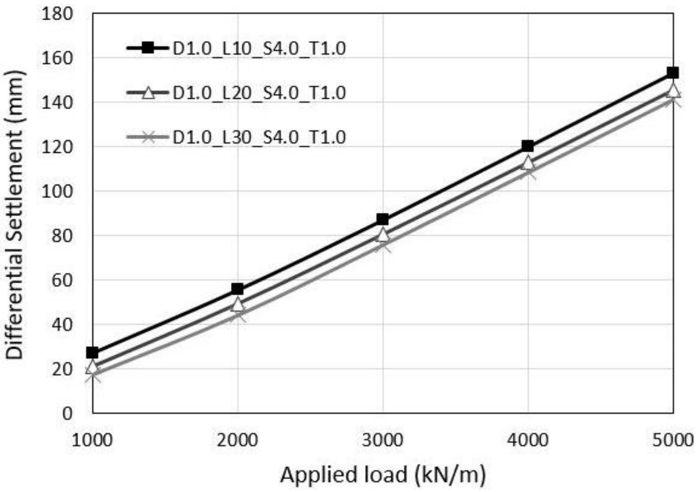

Fig. 3 - Differential settlements of piled raft for piles with different lengths

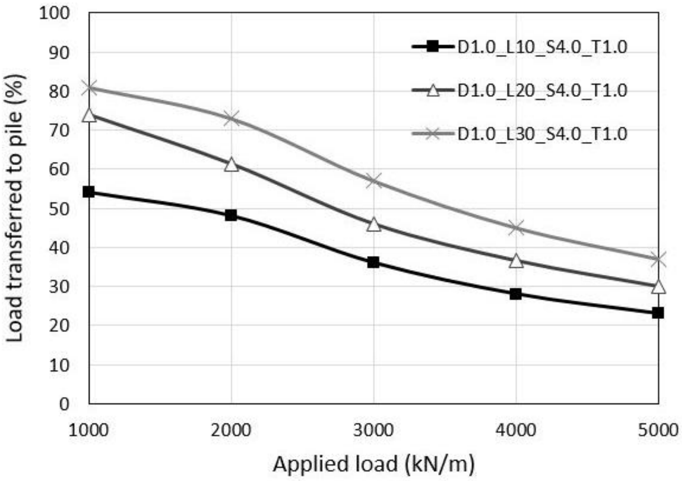

Fig. 4 - Loads transferred to piles for different pile lengths

3.2 Effect of Raft Thickness

Fig. 5 to Fig. 7 show the maximum settlement, differential settlement, and percentage of load transferred to pile for the piled raft system with different raft thicknesses. The results showed that the reduction in maximum settlement was more profound when the raft thickness was increased from 0.5 m to 1.0 m in comparison with 1.0 m to 1.5 m. For instances, under the applied load of 5,000 kN, the maximum settlement was reduced by 139.5 mm when the raft thickness was increased from 0.5m to 1.0m in comparison with only 46.4 mm reduction recorded when the raft thickness was further increased from 1.0m to 1.5m. The results of differential settlement (Fig. 6) showed that the differential settlement of the piled raft system was constantly reduced by about 50% as the raft thickness was increased by 0.5 m (for both increments of 0.5 – 1.0 m and 1.0 – 1.5 m). Increasing the thickness of the raft would increase the relative stiffness of the raft. As the relative stiffness of the raft was increased, the applied load tended to be distributed more uniformly, and hence the resultant maximum and differential settlements were lower. This is in agreement with the behaviour of rigid and flexible rafts as defined by Horikoshi & Randolph [20].

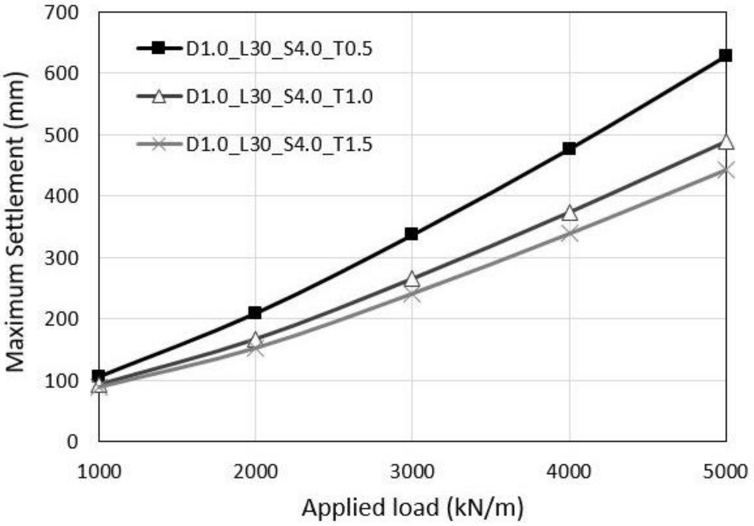

Fig. 5 - Maximum settlements of piled raft with different raft thicknesses

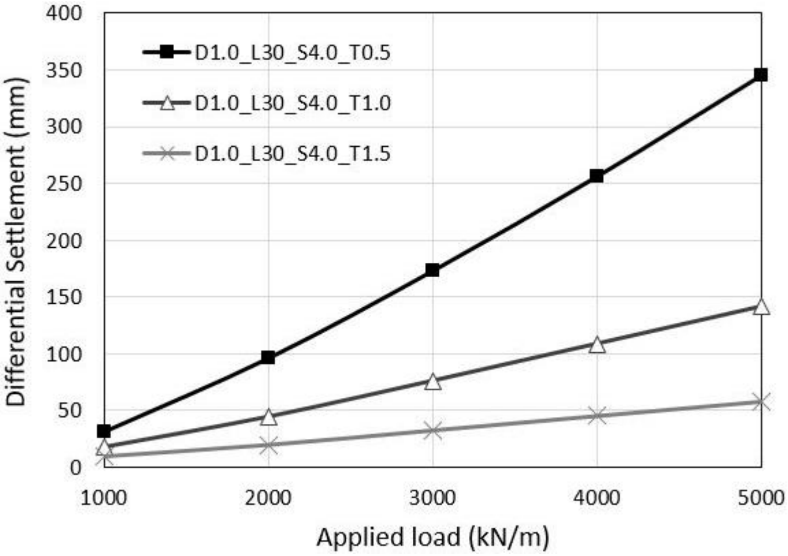

Fig. 6 - Differential settlements of piled raft with different raft thicknesses

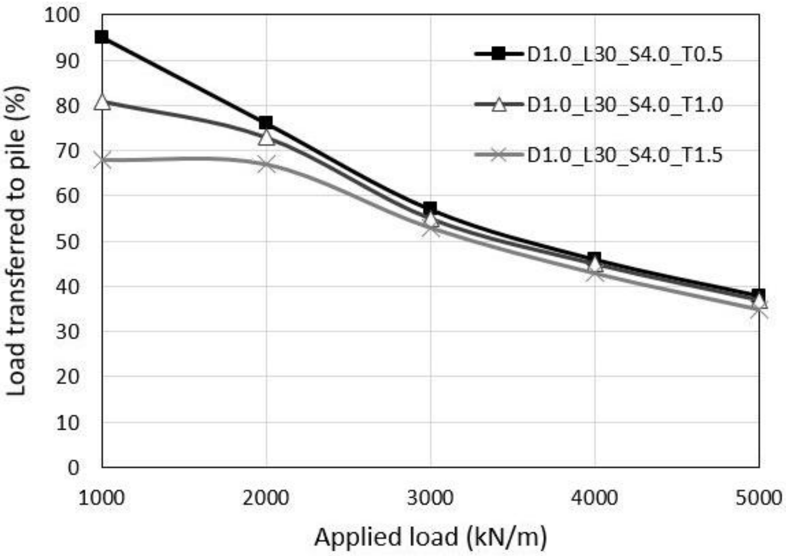

Fig. 7 - Load transferred to piles for piled raft with different raft thicknesses

With respect to the load distribution, increasing the raft thickness has reduced the load transferred to piles. This was because the imposed load tended to be distributed to the stiffer structure. The load transferred to piles decreased significantly with the increase in the applied load. At a low imposed load (i.e. 1,000 kN/m), the load resistance of pile was mobilized earlier than that of the raft, and hence a higher percentage of load was transferred to pile. As a higher load was imposed, the settlement increased and caused the raft to undertake a higher portion of load than the piles. In order to provide more insights into the load transfer mechanism of the piled raft system, the load mobilized by each pile was recorded (Fig. 8). Apparently, the load distribution among the piles was more uniformly distributed with a thicker raft. This was believed to be the main contributing factor to the low differential settlement yielded from a system with a thick raft.

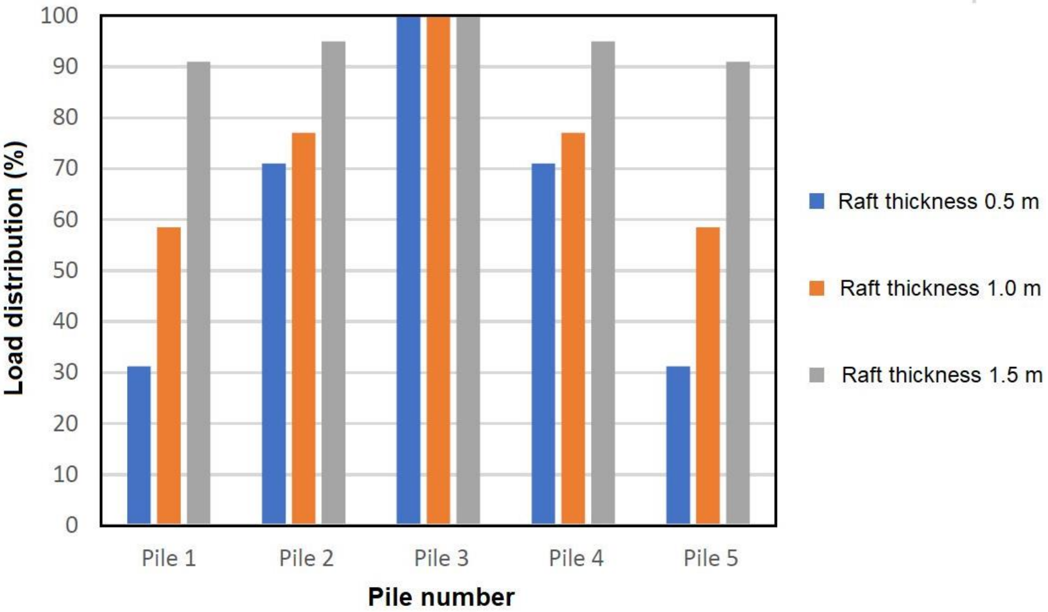

Fig. 8 - Distributions of load mobilisation in piles for piled rafts with different raft thicknesses

3.3 Effect of Pile Spacing

Fig. 9 to Fig. 11 show the changing trends of maximum settlement, differential settlement, and percentage of load transferred to pile in piled raft foundations with different pile spacing. The results of differential settlement and load transferred to pile showed clear and consistent trends in which the increase in pile spacing increased the differential settlement and reduced the load transferred to piles. However, an inconsistent trend was observed for the maximum settlement of the piled raft system. For the applied loads above 3,000 kN/m, the maximum settlement increased with the increase in pile spacing. A reverse trend was observed for the loading case of 1,000 kN/m. In the case of 2,000 kN/m applied load, the maximum settlement decreased as the pile spacing increased from 2.5D to 3.0D. These results opposed previous findings by Lee & Chung [21] who suggested that under the configurations of large pile spacing, i.e. 4D – 5D, the shaft friction of pile would be increased significantly due to a favourable soil-pile interaction, and hence the maximum settlement would be reduced. However, the applied load considered in Lee & Chung [21]'s study was a uniform distributed load in contrast to the application of concentrated point load in this study. Luo et al. [16] who considered uniform distributed load in their study also concluded that the normalized settlement of piled raft decreased consistently with an increase in pile spacing. Under the application of a point load, the importance of placing the piles nearer to the location of loading with a narrower pile spacing outweighed the benefits gained by increasing the pile spacing. This was in line with the findings reported by Mali & Singh [17] who considered both uniform distributed load and equivalent point load in their parametric study.

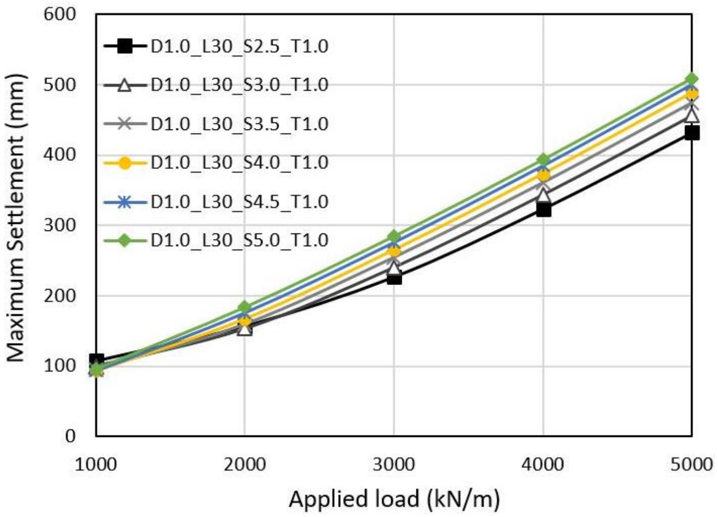

Fig. 9 - Maximum settlements of piled raft with different pile spacing

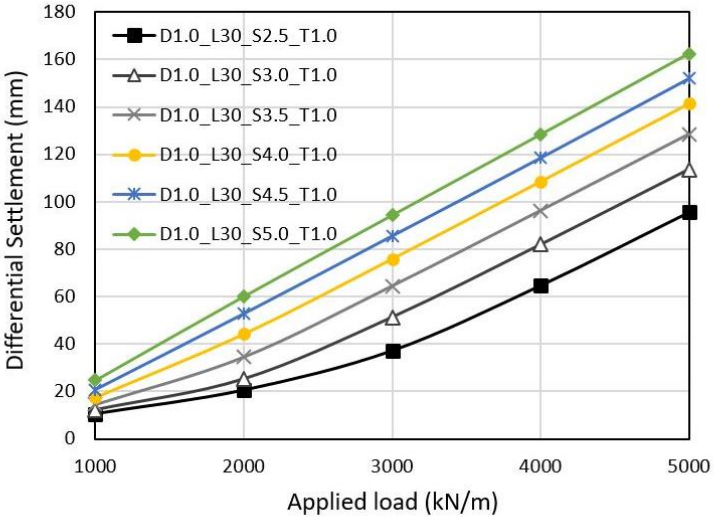

Fig. 10 - Differential settlements of piled raft with different pile spacing

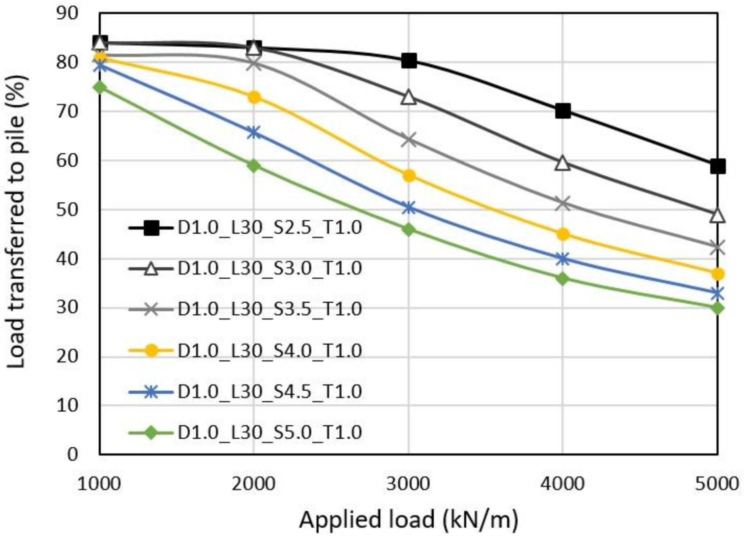

Fig. 11 - Load transferred to piles for piled raft with different pile spacing

3.4 Effect of Pile Diameter

To study the effect of pile diameter on the performance of piled raft, the diameter of pile was set as a variable ranging from 0.5m to 1.5m. The pile spacing, however, could not be fixed at 4D because of the nature of loading. From the above, the results on the effect of pile spacing highlighted the importance of placing the piles near to the point of loading with the effect of narrower spacing between pile and loading point outweighed the benefits gained by increasing the pile spacing. If the pile spacing was fixed at 4D, as the pile diameter increased, the distance between the pile location and the loading point would become wider, and hence it may cause an adverse effect on the piled raft performance. To avoid this inconsistency, the pile spacing was fixed at 4.0 m when study the effect of pile diameter on the performance of piled raft.

Fig. 12 to Fig. 14 show the changing trends of maximum settlement, differential settlement, and percentage of load transferred to pile in piled raft foundations with different pile diameters. The results showed that the pile diameter has a negligible effect on the maximum settlement, particularly at a high imposed load. This could be explained by the settlement required to fully mobilize the shaft resistance of pile. There was a possibility that the settlement induced was insufficient to mobilize full resistance of large diameter pile, and hence increasing the pile diameter would have a minimal effect on the maximum settlement. A similar finding was reported by Luo et al. [16] in which the normalized settlement only decreased slightly (< 0.4%) with the increase in pile diameter from 0.4 m to 0.8 m, and the influence was negligible when the factor of safety (FoS) was lower than 3.

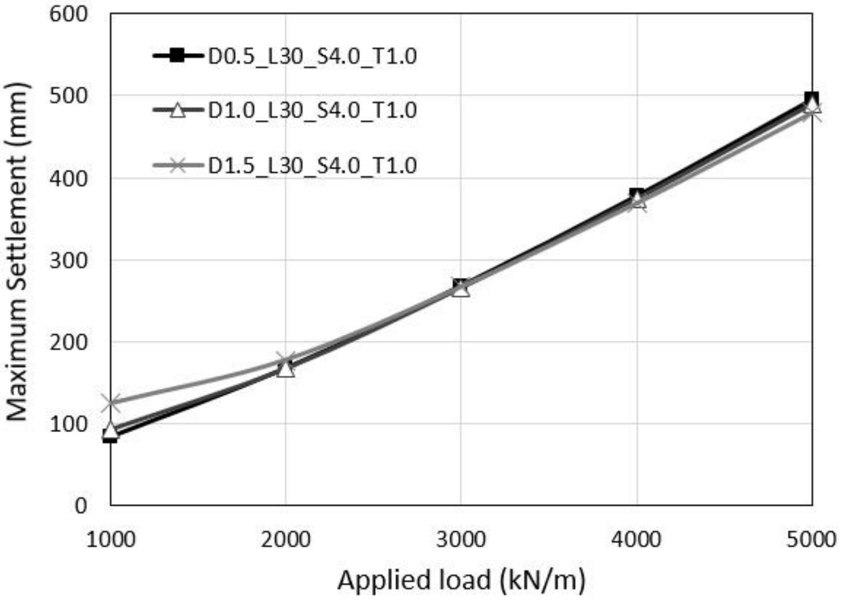

Fig. 12 - Maximum settlements of piled raft with different pile diameters

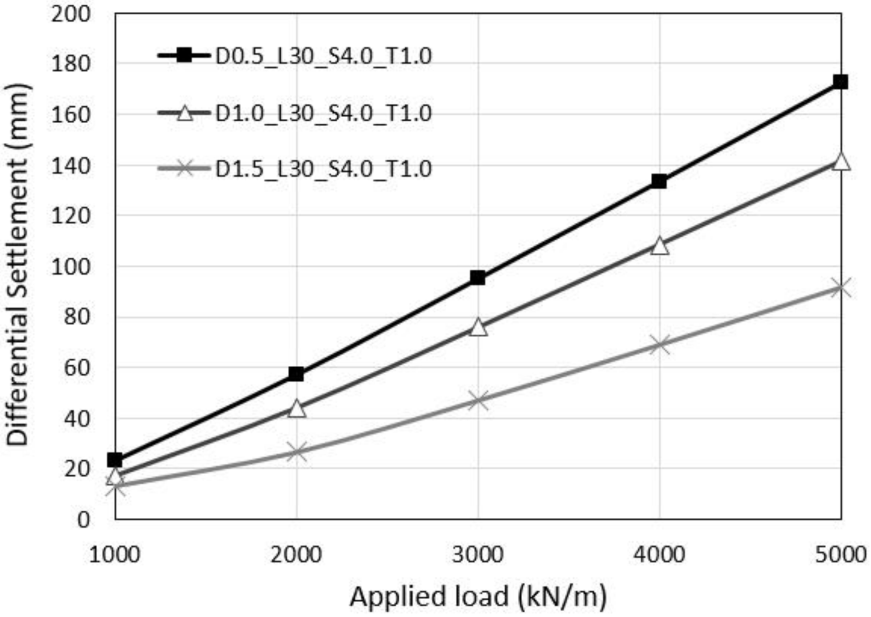

Fig. 13 - Differential settlements of piled raft with different pile diameters

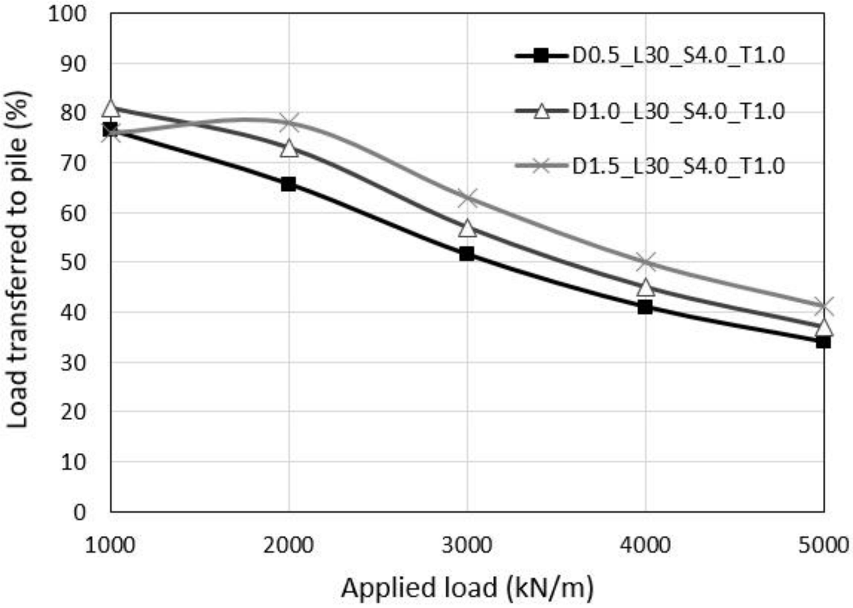

Fig. 14 - Load transferred to piles for piled raft with different pile diameters

However, the effect of pile diameter on differential settlement was significant. The differential settlement reduced with the increase in pile diameter, particularly when the pile diameter was increased from 1.0 m to 1.5 m. The percentage of load transferred to piles generally increased with the increase in pile diameter, except for the case with a low applied load (1,000 kN/m). These results implied that the differential settlement increased when less load was transferred to piles. A greater portion of load was transferred to the raft when the pile diameter was small. As the load resisted by the raft increased, a larger differential deformation can be expected from the raft.

3.5 Relative Significance of Studied Parameters

The relative significance of each of the studied parameters on the performance of the piled raft foundation in clay was examined by assessing their influences on the differential settlement. The differential settlement was selected as the key indicator because even a small differential settlement is capable of causing cracks, spalling in foundations, and hence severely undermine the serviceability of the building. A set of mean values were defined, i.e. raft thickness at 1.0

m, pile diameter at 1.0 m, pile spacing at 4D, and pile length at 20 m. The differential settlements induced by deviations of the studied parameters from these predefined mean values were evaluated (Fig. 15).

The results indicated that increases in both pile length and raft thickness, as well as a decrease in pile spacing tended to reduce the differential settlement. Comparatively, raft thickness was the most significant controlling parameter affecting the differential settlement of the piled raft, as indicated by the steepest gradient of the curve.

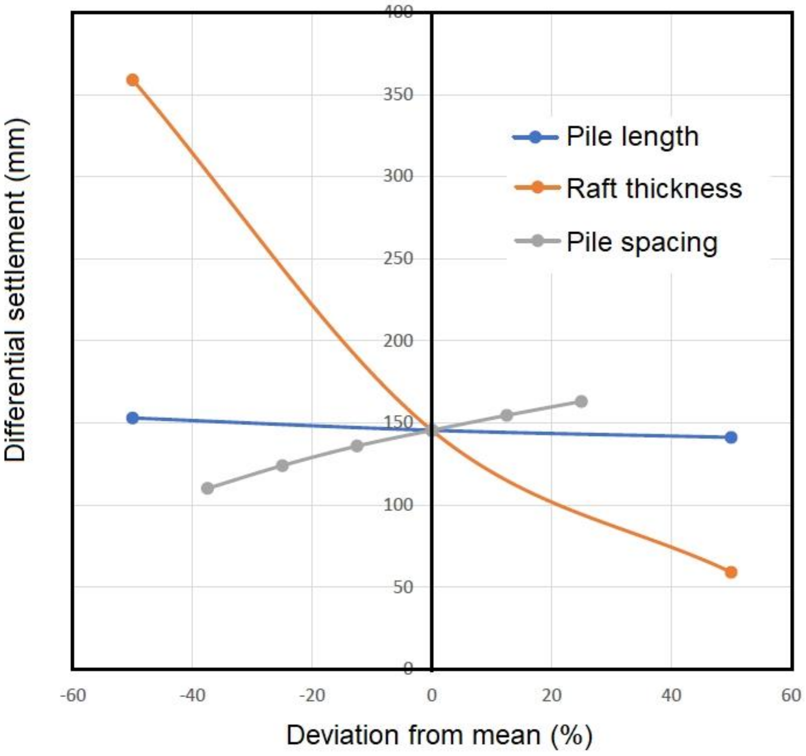

Fig. 15 - Relative significance of studied parameters affecting differential settlement of piled raft

4. Conclusion

A series of finite element analyses were performed to investigate the performances (gauged by maximum settlement, differential settlement, and load distribution) of piled raft foundations in clay subjected to a concentrated load. Following findings can be drawn from the present parametric study:

- Increasing the pile length reduced the maximum and differential settlements of the foundation. When a long pile was used, the mobilized shaft resistance was high, and hence the overall settlement could be reduced.
- As the raft thickness increased, both the maximum and differential settlements reduced. The increase in the raft thickness increased its structural stiffness, and resulted in larger portions of the imposed load distributed to the raft. A stiff raft foundation would also induce a more uniform distribution of load on the raft, and minimizes both the maximum and differential settlements.
- Closely spaced pile (2.5D) was recommended for the piled raft foundation as it yielded the least maximum and differential settlements. Under the concentrated loading, the importance of placing piles nearer to the location of load outweighed the benefits gained by increasing the pile spacing.
- Pile diameter has a negligible effect on the maximum settlement, particularly at a high imposed load. However, the effect of pile diameter on differential settlement was significant. The differential settlement reduced with the increase in pile diameter.
- Among the studied parameters in the present study, raft thickness played the most profound role in affecting the differential settlement of piled raft foundations.

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