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3D numerical analysis of piled raft foundation for Ho Chi Minh City subsoil conditions

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Abstract. Piled raft foundations are widely used and effective in supporting high-rise buildings around the world. In this study, a piled raft system was numerically simulated using PLAXIS 3D. The settlement comparison results between the actual building measurements and the three-dimensional (3D) numerical analysis, were in good agreement, indicating the usefulness of this approach for the evaluation of the feasibility of using a piled raft foundation in Ho Chi Minh City subsoil. The effects were investigated of the number of piles based on pile spacing, pile length, raft embedment on the settlement, load sharing, bending moments, and the shear force of the piled raft foundation in Ho Chi Minh City subsoil. The results indicated that with an increased number of piles, increased pile length, and embedding raft depth, the total and differential settlement decreased. The optimal design consisted of pile numbers of 60–70, corresponding to pile spacings is 5.5-6 times the pile diameter (D_p), in conjunction with a pile length-to-pile diameter ratio of 30. Furthermore, load sharing by the raft, by locating it in the second layer of stiff clay, could achieve 66% of the building load. The proposed model of piled raft foundations could reduce the total foundation cost by 49.61% compared to the conventional design. This research can assist practicing engineers in selecting pile and raft parameters in the design of piled raft foundations to produce an economical design for high-rise buildings in Ho Chi Minh City, Viet Nam, and around the world.

Keywords: 3D FEM; high-rise building; Ho Chi Minh subsoil; load sharing; parametric study; piled raft

1. Introduction

The number of high-rise building constructions in Viet Nam in general and in Ho Chi Minh City, in particular, has increased since the 1990s. Lately, high-rise building construction has been common in urban areas of Ho Chi Minh City, where the subsoil is soft-to-very soft clay on stiff clay and sand. The most common foundation design method uses the concept of piles that transfer the load to the deep soil that has sufficient bearing capacity. However, the current approach focuses on pile group capacity and settlement without considering the contribution of the raft.

A piled raft foundation has been introduced as new and effective concept for a large building. The piled raft is a geotechnical structure consisting of three elements: piles, raft, and soil. In the foundation, the total applied load of the combined piles and raft is transferred partly directly to the soil below the raft, thus reducing the load carried by the piles. Piled rafts have been used widely globally as an effective high-rise building foundation method (Bandyopadhyay *et al.* 2020, Katzenbach *et al.* 2000, Khanmohammadi and Fakharian 2018, Long 2010, Poulos 2001, Poulos *et al.* 2011, Tan 2006, Yamashita *et al.* 1994). However, the piled raft foundation has only been studied and not yet been accepted for regulated use in Viet Nam.

3D numerical modeling, which has the ability to model a real problem, is considered the most reliable method for the analysis of a piled raft foundation in clay soils (Amornfa *et al.* 2012, Poulos 2001). The maximum settlement, differential settlement, raft bending moments and shear force, axial loads, load sharing between raft and piles, and pile bending moments are considered as crucial parameters for the optimum design of a piled raft foundation. Many researchers have studied the behavior of piled raft foundations (Al-Omari *et al.* 2016, Bandyopadhyay *et al.* 2020, Cho *et al.* 2012, Fattah *et al.* 2013, Khanmohammadi and Fakharian 2018, Ko *et al.* 2018, Lee *et al.* 2010, Mali and Singh 2018, Nakanishi and Takewaki 2013, Roh *et al.* 2019, Sinha and Hanna 2016, Watcharasawe *et al.* 2021).

In Viet Nam, the parametric study of piled raft foundation was investigated using the Poulos-Davis-Randolph method (Quang *et al.* 2021). In that study, the recommendations for the pile spacing/pile diameter were 5–7 times and the pile length/pile diameter 30 times for effective design. In addition, the influences of the raft thickness and diaphragm wall on the behavior of the piled raft foundation have been studied (Lai *et al.* 2020, Nguyen *et al.* 2020), proving that the piled raft foundation was an effective method design for high-rise buildings in Viet Nam

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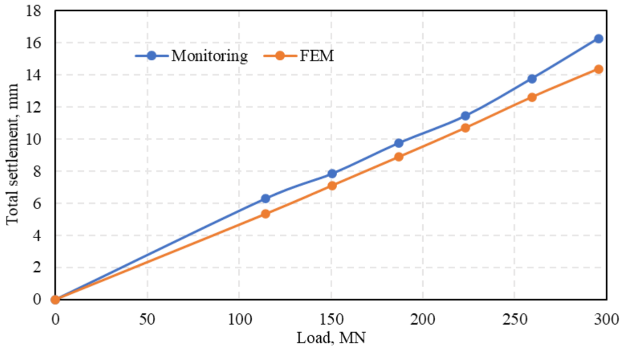

Fig. 1 Comparison of total settlement between measurement and FEM

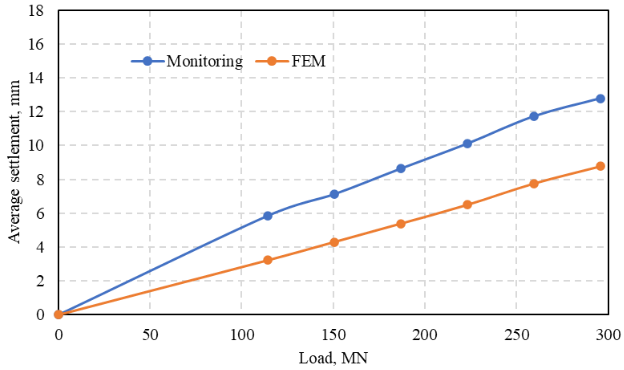

Fig. 2 Comparison of average settlement between measurement and FEM

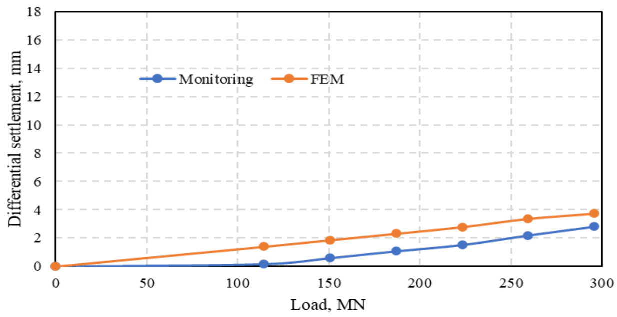

Fig. 3 Comparison of differential settlement between measurement and FEM

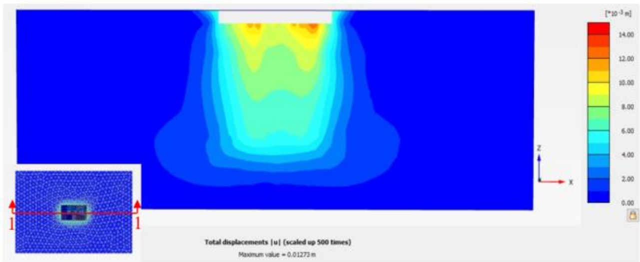

Fig. 4 Section 1-1 total displacement model shadings in PLAXIS 3D of actual design

currently and in the future. However, there have been few parametric studies on piled raft foundations and this gap needs to be filled in Viet Nam by suitable investigation.

In this paper, the settlement was calculated using the 3D finite elements method (FEM) using the PLAXIS 3D program and compared with the measurement results for a building in Ho Chi Minh City, Viet Nam. In addition, the effects were studied of different parameters of the piled raft on the settlement, load-sharing, shear force, and bending moments. The results from the comparison suggested an economical design concept for piled raft foundations.

2. Design and construction of SGR Tower foundation

The SGR project was built on Ho Chi Minh subsoil in 2019. The building has a height of 73.7 m with 18 stories and a basement floor. The geology at the site is very soft-to-soft clay with a thickness 22–25 m. The piled foundation concept was applied in the foundation design of this building. There were 90 bored piles, which had a diameter of 1.2 m and a length of 64.4 m. The pile tip was put in the fine-to-coarse sand that was medium-to-very dense.

In the construction, the bored piles passed the static test with a test load of 230% (26.45 MN) of the piles' allowable bearing capacity (11.54 MN). The building used the bottom-up method for construction. Currently, the basement and the structure of the building have been completed, so only the dead load of 295.655 MN is being applied on the foundation.

3. Measured and computed settlements of piled raft foundation

This section presents the settlement results of the measurement and the 3D numerical simulation using PLAXIS 3D of a building in Ho Chi Minh City, Viet Nam.

The settlement monitoring results were presented in Quang *et al.* (2021) based on 21 measurement marks to measure settlement during construction. The measurement frequency was 30 days/time during which 3 floors were built. The settlement results were very small as the total and differential settlements were equal to 16.2 mm and less than 3 mm, respectively.

For the comparison between the settlement results of measurement and from using PLAXIS 3D, the similarity of the total, average, and differential settlements with increased total load are shown in Figs. 1-3, respectively.

The results obtained using PLAXIS 3D were in comparably good agreement with those from the measurements. The total, average, and differential settlements were 14.35 mm, 8.78 mm, and 3.75 mm, respectively, based on the PLAXIS 3D simulation. The total and average settlements based on the actual measurements were a little higher than those from using PLAXIS 3D, whereas it was opposite for the differential settlement. These differences between numerical and experimental results were found in this study, which came from modeling the complex soil model and the complex structure's foundation.

In general, the settlement results were very small, thus, the foundation specifications in this project were

Table 1 Soil parameters of BH1 and BH2

Type			Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
			1	2a	2b	3	L3	3	L3	3
Materials model		Model	Hardening soil	Hardening soil	Hardening soil	Hardening soil	Hardening soil	Hardening soil	Hardening soil	Hardening soil
Thickness	BH1	m	0-22	22-25.5	25.5-32	32-41	-	41-56	56-59	59-110
	BH2	m	0-25	-	25-31	31-41	41-45	45-54	54-61	61-110
Unit weight	γ_{sat}	kN/m^3	14.34	14.34	18.5	19.6	19	19.6	19	19.6
	γ_{unsat}	kN/m^3	14.34	14.34	18.5	19.6	19	19.6	19	19.6
Cohesion (c)		kN/m^2	8.9	8.9	28.9	14	32.6	14	32.6	32.6
Friction angle (φ)		°	19.9	19.9	23.6	37.7	24.5	37.7	24.5	24.5
Young's modulus (E_{50})		kN/m^2	3200	4800	33000	70000	70000	70000	70000	70000
Young's modulus (E_{oed})		kN/m^2	1600	2500	33000	70000	70000	70000	70000	70000
Young's modulus (E_{ur})		kN/m^2	16000	24000	99000	210000	210000	210000	210000	210000
Poisson's ratio(ν)		-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
p_{ref}			100	100	100	100	100	100	100	100
Power			1	0.9	1	0.5	0.5	0.5	0.5	0.5

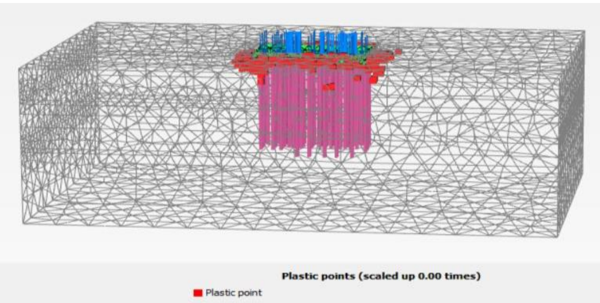

Fig. 5 Plastic point in PLAXIS 3D of actual design

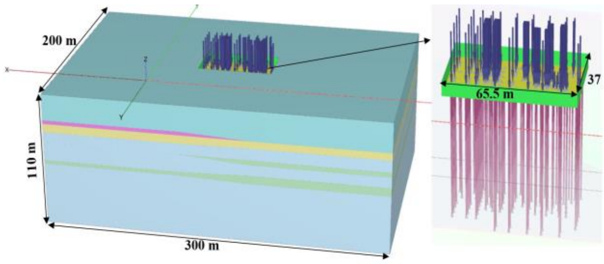

Fig. 6 Soil and structural model using PLAXIS 3D

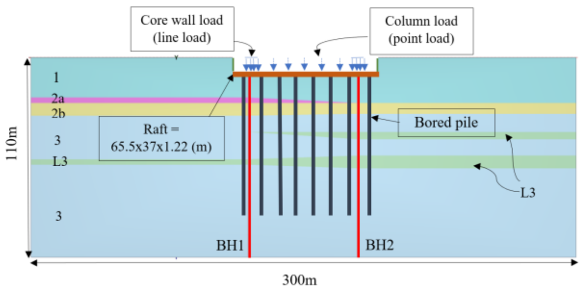

Fig. 7 Cross-section of piled raft foundation in PLAXIS 3D

conservative, which was not optimal for the design. The results of the numerical simulation using PLAXIS 3D are shown in Figs. 4 and 5. Therefore, the study of varying parameters on the behavior of piled raft using PLAXIS 3D was necessary to select the most effective design model.

4. Numerical study of piled raft

4.1 Finite element modeling using PLAXIS 3D

4.1.1 Soil and foundation structural modelling

To avoid the effect of boundary conditions, the soil boundary simulation used widths and lengths 5 times those of the raft. According to Gandhi and Maharaj (1995), the depth was 2 times the raft width plus two-third the length of the pile; this, the width and the length of the boundary were set at 200 m and 300 m, respectively. The depth was 110 m (Fig. 6).

In this study, the Ho Chi Minh subsoil was modeled using the Hardening soil model, which is an advanced model for simulating the behavior of different types of soil, both soft and stiff. The parameters required for input to the software are the unit weight, friction angle, cohesion, Young's modulus (plastic straining due to primary deviatoric loading (E_{50}^{ref}), plastic straining due to primary compression (E_{oed}^{ref}), elastic unloading-reloading (E_{ur}^{ref})), and Poisson's ratio. More specifically, the PLAXIS 3D software can model multiple boreholes concurrently, even if they are not in the same soil profile. The structure's foundation and information on the complex soils obtained from two boreholes, were simulated using PLAXIS 3D, as shown in Fig. 7. The groundwater level was assumed to be at ground level. The soil parameters used as input to PLAXIS 3D are shown in Table 1. The value of E_{ur}^{ref} from the surface to 20 m depth was 5 times the plastic straining due to E_{50}^{ref} (Ngo-Duc 2019). There were 5 types soil in the geology: organic clay, dark gray, very-soft-to-soft (1), silty clay, medium-stiff (2a), silty clay, stiff-to-very-stiff (2b),

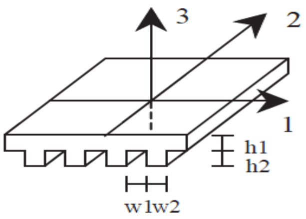

Fig. 8 Concrete floor with T-shape

Table 2 Structural foundation parameters

Structure	Raft	Piles
Material model	Linear elastic	Linear elastic
Thickness d (m)	1.22	-
Diameter D_p (m)	-	1.2
Unit Weight (kN/m^3)	25	25
Modulus E(kN/m^2)	3.2e7	3.2e7
Poisson's ratio	0.15	0.15
T_{max} Top* (kN/m)	-	70
T_{max} Bot* (kN/m)	-	600
F_{max}* (kN)	-	8260

* T_{max} is maximum traction allowed at the skin of the embedded bea m (can vary along the pile); F_{max} Maximum force allowed at the foot of the embedded beam

fine to coarse sand, medium-to-very dense (3), and sandy clay and silty clay, stiff-to-very stiff (L3).

The bored piles were simulated as embedded beam elements. In PLAXIS 3D, an embedded beam is a beam element with an embedded interface element to describe the interaction with the soil at the pile skin and the pile foot. The interaction of the pile with the soil at the foot of the pile is described by a linear elastic perfectly plastic interface element. The plate element was used to model the raft. In this study, the raft was T-shaped so the equivalent raft thickness (d) was 1.22 m, as determined using Eq. (1) in the PLAXIS Manual (BV, 2020). In addition, the piles and raft were considered as rigid connections and linear elastically was applied for the materials in both the bore piles and raft.

$$d = \frac{h_1 w_1 + (h_1 + h_2) w_2}{w_1 + w_2} \quad (1)$$

where parameters are shown in Fig. 8.

The properties of materials are shown in Table 2 derived from the concrete mix design.

4.1.2 Load applied

The location and magnitude of the applied load are shown in Fig. 9 and Table 3, as determined using the mass of the building structures. There were two types of load in this study (point load and line load) used to simulate the load at the columns and core walls, respectively.

4.2 Parametric study

Variations in the pile number (N) obtained by varying pile spacing (S_p), the pile length (L), and the embedded raft

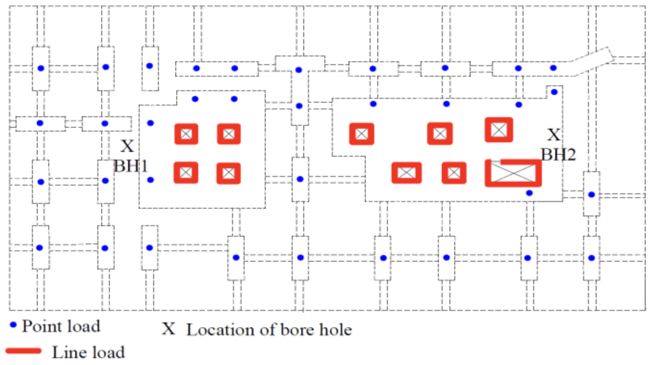

Fig. 9 Load and borehole locations

Table 3 Load magnitude

Period / Type	3 Floors (30 days)	6 Floors (60 days)	9 Floors (90 days)	12 Floors (120 days)	15 Floors (150 days)	18 Floors (180 days)
Line load (kN/m)	358	472	585	699	813	927
Point Load (kN)	2283	3009	3735	4461	5187	5913
Total load (MN)	114.2	150.5	186.8	223.1	259.4	295.7

(Z_{emb}) were investigated to determine the behavior of the piled raft foundation for the Ho Chi Minh subsoil. The results of the parametric study cases are summarized in Table 4 based on the settlement, bending moment, shear force, and load sharing ratio.

Eq. (2) from Reul and Randolph (2004) was used to calculate the differential settlement (s_{diff})

$$s_{diff} = s_{center} - s_{corner} \quad (2)$$

The total settlement ratio (R_{tot}) and the differential settlement ratio (R_{diff}) were defined using Eqs. (3) and (4) from Mali and Singh (2018).

$$R_{tot} = \frac{s_{tot-piledraft}}{s_{tot-un-piledraft}} \quad (3)$$

$$R_{diff} = \frac{s_{diff-piledraft}}{s_{diff-un-piledraft}} \quad (4)$$

The load sharing ratio by the piles (α_{pr}) from the parametric studies was calculated using Eq. (5)

$$\alpha_{pr} = \frac{\sum P_{pile}}{P_{tot}} \quad (5)$$

where ΣP_{pile} and P_{tot} are the total load carried by piles and the total applied load, respectively. (Reul and Randolph, 2003).

According to Poulos (2017), a piled raft performed well with the soil conditions of Frankfurt am Main clay, despite the settlement being greater than 100 mm. The final settlement for tall structures could be well over the conventional design values of 50–65 mm. The settlement based on the conventional design in this study was about 16 mm. Therefore, a settlement design criterion of 66–81 mm was applied in preliminary optimum model design in this study that equaled 0.5–0.6 when converted to R_{tot}.

The load sharing ratio (α_{pr}) was varied from 0.4 to 0.7 for the optimal design of the piled raft foundation based on Katzenbach *et al.* (1998).

4.3 Effect of pile numbers (N)

The effect of the number of pile obtained by varying the pile spacing was studied in combination with a pile length of 64.4 m and the raft embedded at 7.2 m from the surface. The different numbers of piles were 209, 105, 60, 18 and 0, corresponding to pile spacings of $3D_p$, $4.3D_p$, $6D_p$, $9D_p$, and an un-piled raft, respectively.

Figs. 10 and 11 show the effect of the number of piles on R_{tot} and R_{diff}, respectively. It can be seen that R_{tot} decreased as the numbers of piles increased; however, the decrease was much greater for 0 to 60 piles and only little where the number of piles was greater than 60. R_{diff} decreased as the number of piles increased, though the increase was minor when the number of piles was 60.

For R_{tot} values of 0.5–0.6, the pile numbers were 10–13 piles for the practice design based on Poulos (2017). Nevertheless, there was a loss due to the interaction between piles (Clancy and Randolph 1993), which is important in a piled raft foundation. Hence, the optimal piled raft foundation design in Ho Chi Minh City should be from 60–70 piles corresponding to $5.5D_p$–$6D_p$ pile spacing/pile diameter.

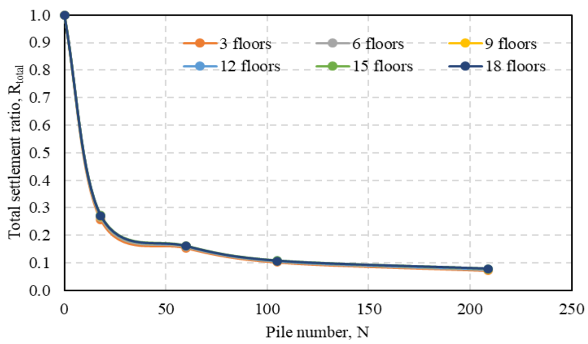

Fig. 10 Effect of pile number on total settlement ratio

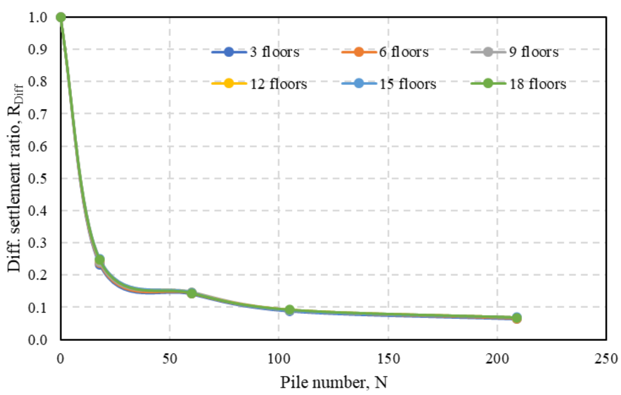

Fig. 11 Effect of pile number on differential settlement ratio

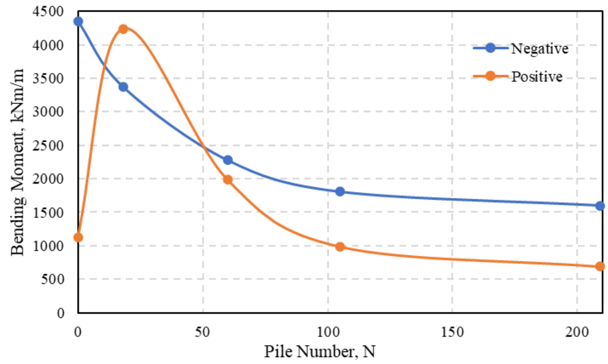

Fig. 12 Effect of pile number on bending moment of the raft

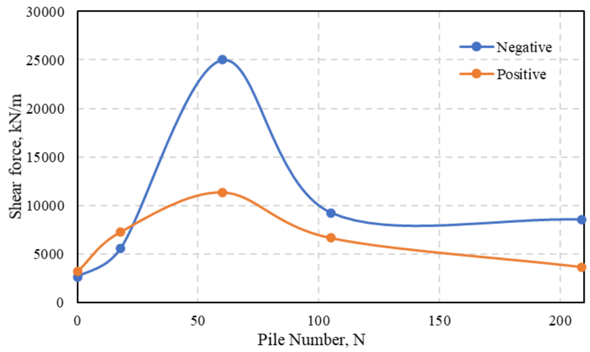

Fig. 13 Effect of pile number on the shear force of raft

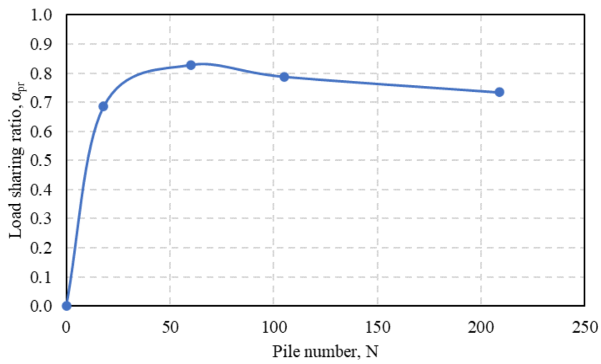

Fig. 14 Effect of pile number on load sharing ratio

The effect of the pile number on the bending moment is shown in Fig. 12. The bending moment decreased as the pile number increased, with the shear force of the raft increasing up to a pile number of 60 and thereafter decreasing, as shown in Fig. 13.

For 18 floors loading case, the value of α_{pr} increased from 0 to 0.83 with the number of piles from 0 to 60, and then it decreased from 0.83 to 0.73 as the number of piles increased from 60 to 209, as shown in Fig. 14. The α_{pr} value of 1 indicates that the entire load is being carried by the piles.

4.4 Effect of pile length

The values for R_{tot}, R_{diff}, the bending moment, shear

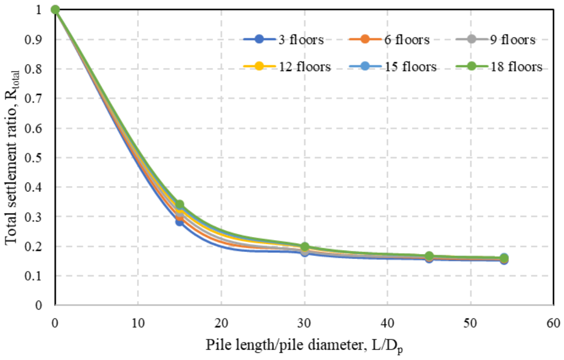

Fig. 15 Effect of pile length on total settlement ratio

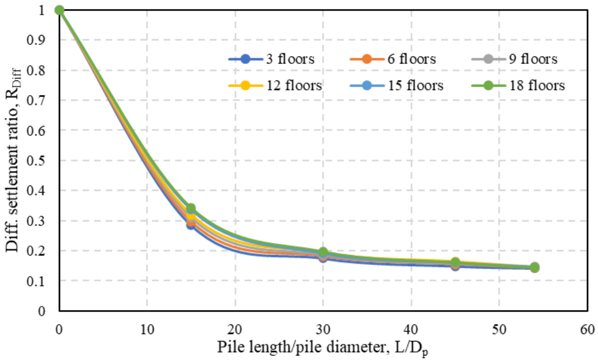

Fig. 16 Effect of pile length on differential settlement ratio

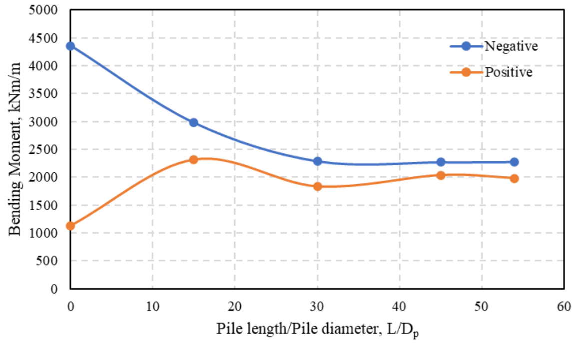

Fig. 17 Effect of pile length on bending moment of raft

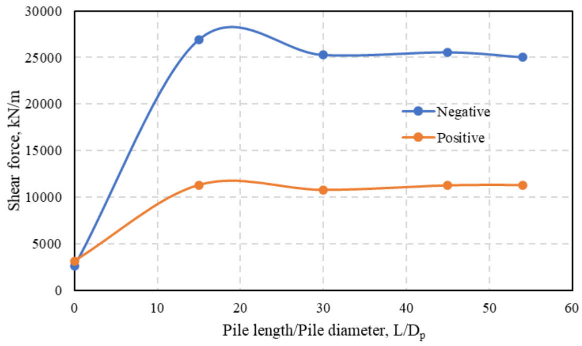

Fig. 18 Effect of pile length on shear force of raft

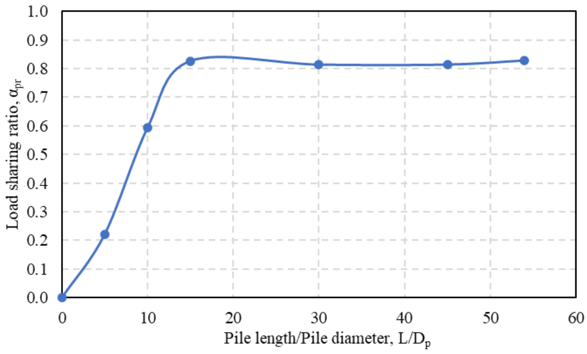

Fig. 19 Effect of pile length on load sharing ratio

force, and α_{pr} were determined under the effect of differing pile length-to-pile diameters (L/D_p) of 54, 45, 30, and 15 with the pile spacing being $6D_p$.

The values of R_{tot} and R_{diff} decreased with increasing L/D_p, as shown in Figs. 15–16. Based on the proposal of Poulos (2017), an R_{tot} value from 0.5 to 0.6 corresponds to L/D_p values of $9.5D_p$–$12D_p$. However, this was not suitable for the geology in Ho Chi Minh City, which was characterized by the presence of very-soft-to-soft clay from the surface to a depth of 22–25 m ($21D_p$) and thus, its bearing capacity was not sufficient to carry the load from high-rise buildings. On the other hand, the chart was clearly divided into two parts, with the first having L/D_p values from 0 to 30, while in the second, L/D_p varied from 30 to 54. The settlement reduction was mainly concentrated in the first part with R_{tot} equal to 1 to 0.2 and R_{diff} equal to 1 to 0.3. In the second part, the settlement reduction was a little; thus, for optimum design, it can be suggested to select L/D_p equal to 30.

Figs. 17 and 18 show the effects of the pile length on the bending moment and the shear force of the raft. The mobilization of the bending moment and the shear force were mostly in the first part with L/D_p values from 0 to 30. In the second part, the bending moment and the shear force were more stable. Thus, the shear force and the bending moment did not affect costs in the case suggested to have optimal model design.

As shown in Fig. 19, the α_{pr} increased as the pile length increased; clearly, the α_{pr} increased as the L/D_p from 0 to 15 and did not change when the L/D_p increased from 15 to 54. When the L/D_p was higher than 15, the piles were plotted on the stiff to very stiff clay. Thus, the effect of pile length on α_{pr} was negligible.

4.5 Effect of embedded raft (Z_{emb})

The elevation of the raft Z_{emb} was varied from 7.2 to 25 m under the surface. Figs. 20 and 21 show the influence of the raft embedment on the settlement, with R_{tot} and R_{diff} reducing as the raft was placed deeper. There was no substantial difference in R_{tot} and R_{diff} between the periods of construction from 3 floors to 18 floors.

The bending moment and the shear force decreased when the raft was placed deeper, as shown in Figs. 22 and 23. The differential between the minimum and maximum value of bending moment was small when the raft was embedded at 11.2 to 19.2 m from the surface. The smallest shear force differential was at 25 m, where the raft was placed in the second layer of stiff clay.

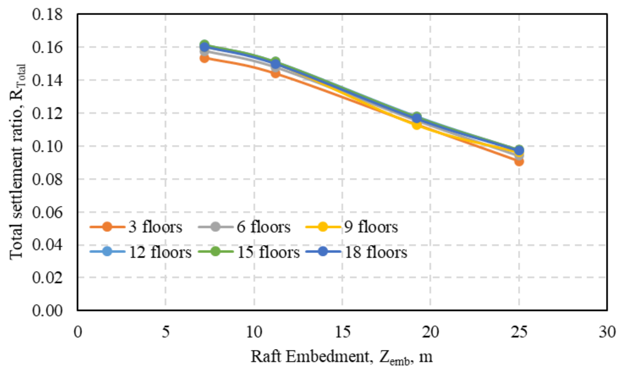

Fig. 20 Effect of embedded raft depth on total settlement ratio

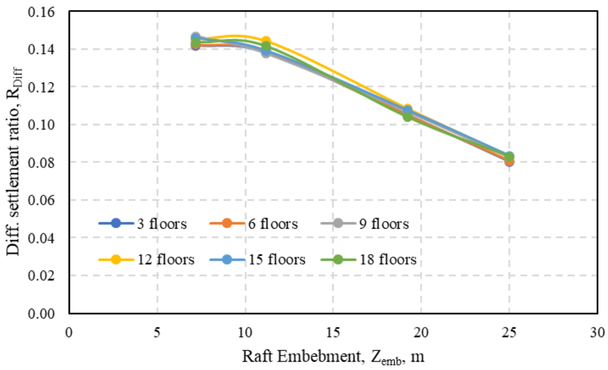

Fig. 21 Effect of embedded raft depth on differential settlement ratio

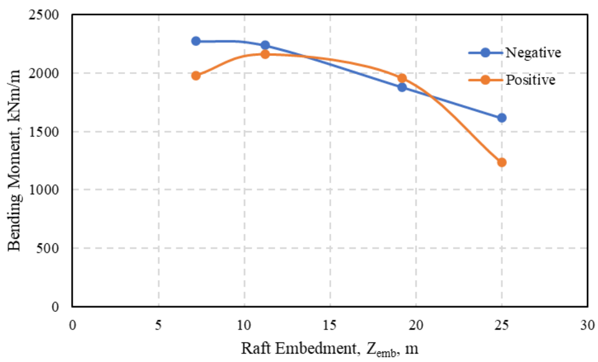

Fig. 22 Effect of embedded raft depth on bending moment of raft

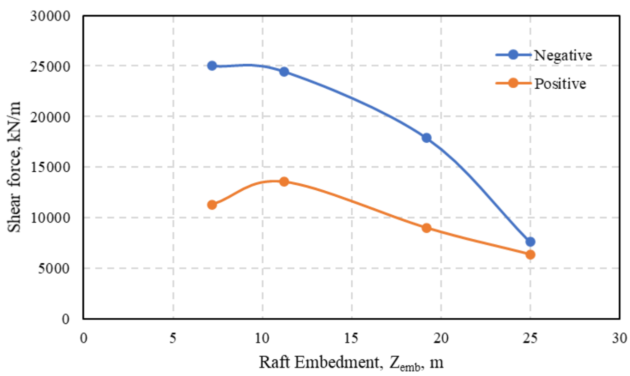

Fig. 23 Effect of embedded raft depth on shear force of raft

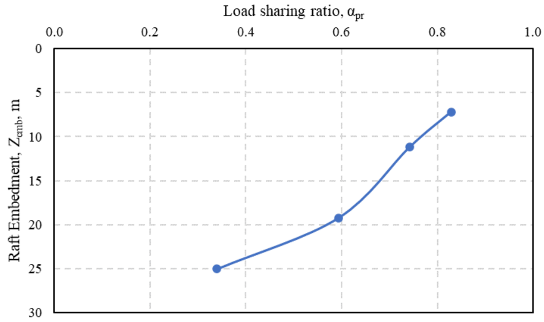

Fig. 24 Effect of raft embedded on load sharing ratio

Fig. 24 shows a substantial decrease in α_{pr} when the raft was placed in the stiff clay of the second layer where the load sharing ratio was 0.34, indicating that the load shared by the raft could reach 66% of the building load. Thus, it could be beneficial to include an underground supermarket or a multi-story parking car project.

4.6 Cost comparison

The cost comparison between the piled foundation and the proposed models of the piled raft foundation was investigated and is summarized in Table 5. The cost of the concrete was assumed to be USD 100/m^3. According to BS EN 1992-1-1:2004 (Union, 2004), the quantity of steel rebar in the raft was 0.15% of the raft cross-section and cost approximately USD 6,600/m^3. The bored pile price was USD 200/m for a diameter of 1.2 m. Based on the change in the bending moment, the area of the steel rebar in the raft changed proportionally.

The results showed that the costs of the piled raft reduced by 26.56%, 49.61%, and 22.47% for the pile number, pile length, and increased embedment, respectively, and that these were substantial reductions on the economy of the proposed model design. Furthermore, these results demonstrated that the piled raft foundation was effective for high-rise building construction.

4.7 Pile stiffness ratio

The plate on springs method was applied to the design of the piled raft foundation. There are many computer software packages that can be used, including SAP2000, SAFE, ETAB, or STAAD PRO. In this method the spring stiffness in the pile is considered in the simulation.

Kiattivisanchai (2001) reported stiffness values (k_p) for a bored pile in Bangkok subsoils based on the settlement curves for 237 static pile load tests, with k_p varying from 0.5EA/L to 4EA/L; 2EA/L was the average value, as shown in Fig. 25.

The differential settlements between the center pile, corner pile, and edge pile were determined based on dead-load conditions. The stiffness ratio $k_p/(EA/L)$ of the actual design, the change in pile length, and the number of piles are shown in Figs. 26-30, where k_p represents pile stiffness, E is Young's modulus of the pile, A is section area of the pile, and L is the pile length.

Table 2 Cost comparison between piled foundation and piled raft foundation

Design concept	Number of pile	Length of pile	Elevation of raft	Cost of raft concrete	Cost of pile	Cost of steel rebar in raft	Total cost of pile+ raft	Foundation cost reduction
	N	m	m	USD	USD	USD	USD	%
Piled foundation	90	64.6	-7.2	295,667	1,162,800	29,271	1,487,738	0
Piled raft foundation (reduced number of piles)	60	64.6	-7.2	295,667	775,200	21,768	1,092,635	26.56
Piled raft foundation (reduced length of piles)	60	36	-7.2	295,667	432,000	21,951	749,618	49.61
Piled raft foundation (increased raft embedment depth)	60	46.8	-25	295,667	561,600	15,346	872,613	41.30

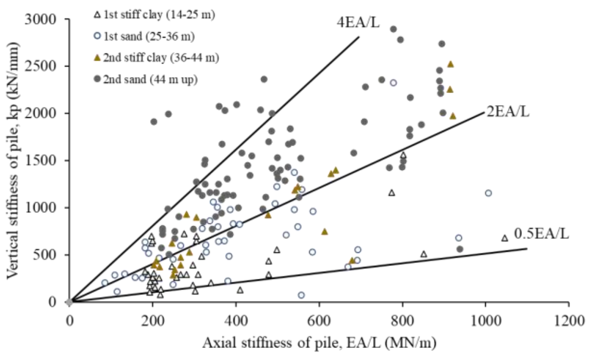

Fig. 25 Relationship between axial stiffness and vertical stiffness of bored piles (Kiattivisanchai 2001)

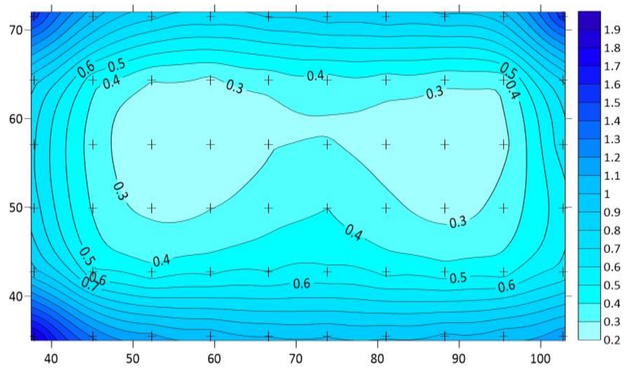

Fig. 28. Stiffness ratio of each pile in the piled-raft system (L= 54 m, N= 60)

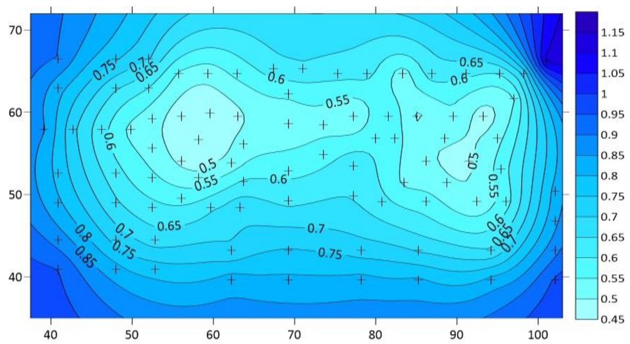

Fig. 26 Stiffness ratio of each pile in the piled-raft system (actual design case, L= 64.6 m, N= 90)

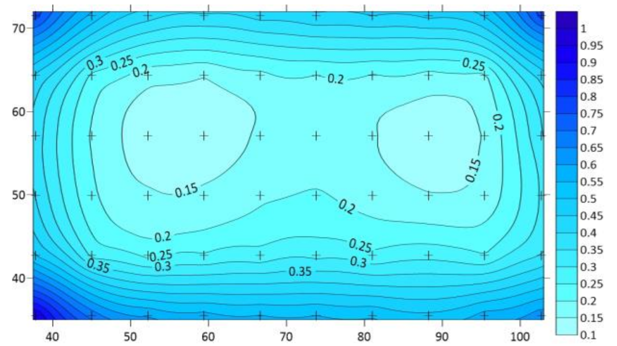

Fig. 29 Stiffness ratio of each pile in the piled-raft system (L= 36 m, N= 60)

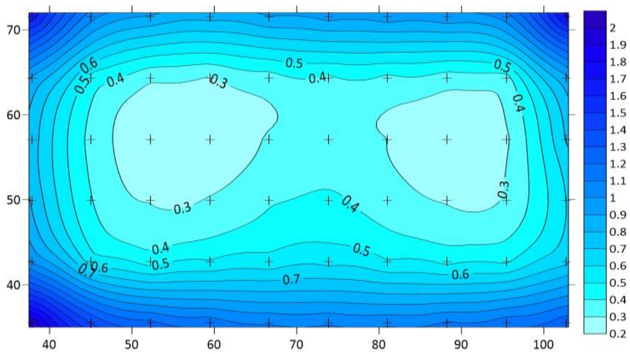

Fig. 27 Stiffness ratio of each pile in the piled-raft system (L= 64.6 m, N= 60)

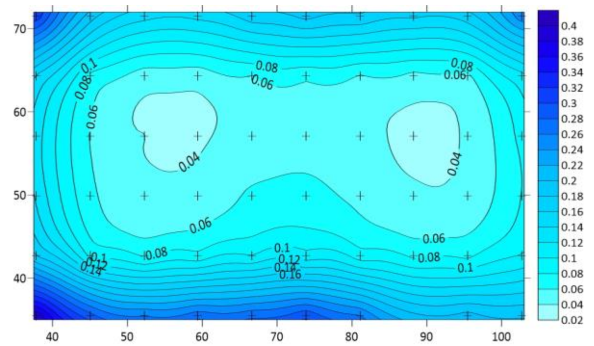

Fig. 30 Stiffness ratio of each pile in the piled-raft system (L= 18 m, N= 60)

The results showed that the pile stiffness in the center was the lowest, increased toward the edge of the raft, and was highest in the corner. The proposed pile stiffness in the piled raft foundation is shown in Table 6. There was a clear

Table 3 Stiffness of piles in piled-raft system

Case	Number of piles	k_p (kN/mm)		
		Corner	Edge	Center
Actual Design, pile length =64.6	90	$0.8\frac{EA}{L}$	$0.7\frac{EA}{L}$	$0.55\frac{EA}{L}$
Pile length =64.6	60	$1.03\frac{EA}{L}$	$0.67\frac{EA}{L}$	$0.31\frac{EA}{L}$
Pile length =54	60	$0.96\frac{EA}{L}$	$0.63\frac{EA}{L}$	$0.3\frac{EA}{L}$
Pile length =36	60	$0.51\frac{EA}{L}$	$0.34\frac{EA}{L}$	$0.16\frac{EA}{L}$
Pile length =18	60	$0.18\frac{EA}{L}$	$0.13\frac{EA}{L}$	$0.05\frac{EA}{L}$

effect of pile slenderness on the stiffness of the pile, with increased stiffness as the pile length increased. The effect of pile spacing on the stiffness ratio is shown in Figs. 26 and 27. The stiffness ratio increased as the pile spacing increased for the corner piles, the ratio decreased for the piles in the center, and there was almost no changed in the edge piles.

5. Conclusions

This paper presents a comparison between real-world monitoring data and 3D numerical simulation. The parametric study of the behavior of a piled raft was modeled using PLAXIS 3D on Ho Chi Minh subsoil. The effects were investigated of the number of piles (N) based changing the pile spacing (S_p), the pile length (L), the raft embedment (Z_{emb}) on the settlement, load sharing, the bending moment, and the shear force of the raft. Based on the results, an optimal model was proposed for a piled raft foundation design for Ho Chi Minh soil conditions. The main conclusions were:

1) The total, average, and differential settlement were 14.35 mm, 8.78 mm, and 3.75 mm, respectively, based on the PLAXIS 3D simulation. These values were in good agreement with the measured settlement results, proving that the 3D numerical analysis using PLAXIS 3D was suitable for the evaluation of the feasibility of using piled raft foundations in Ho Chi Minh City subsoil.

2) For any period of construction, as the pile number increased, the total and differential settlement ratios, and bending moment decreased. In addition, the load sharing ratio changed little as the pile number changed. For the study case, 60–70 piles corresponded to $5.5D_p$–$6D_p$, respectively, converted to pile spacing, which was considered the optimal design.

3) The total and differential settlement ratios decreased with an increase in the pile length-to-diameter ratio. The load sharing ratio changed little with any variation in the pile length-to-diameter ratio. Thus, for the optimum design, L/D_p should equal 30.

4) With an increase in the embedded raft depth, the total, and differential settlement ratios, and the bending moment, the shear force of the raft decreased. Furthermore, the load sharing ratio decreased as the elevation of the raft increased and equaled 0.33 when the raft was located in the second layer of stiff clay, where the load shared by raft could reach 67% of the building load.

5) There was a substantial reduction in the foundation cost in the proposed model based on a piled raft foundation. The reductions in pile number and pile length and the increase in the raft embedment depth were 26.56%, 49.61% and 41.30%, respectively, for the total foundation cost of the building compared with the conventional design.

6) The stiffness of the center piles was the lowest and it increased toward edge piles. Pile stiffness was greatest in the corners among the pile types.

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