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3D FINITE ELEMENT ANALYSIS OF THE EFFECT OF RAFT THICKNESS, PILE SPACING, AND PILE LENGTH ON THE BEHAVIOR OF PILED RAFT FOUNDATION

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ABSTRACT: Piled raft foundations can be effectively used when their hardness and bearing capacity are estimated sufficiently, and the total settlement, or the differential settlement, of the rafts, stays within a certain limit value. This research applies a 3D finite element method to analyze the response of the flat raft foundation when a minimum number of piles is installed under the raft foundation. The results show that when the pile length changes alternately (between the long pile and short pile), the settlement, the differential settlement, positive and negative moments, and the maximum shear force of the raft increase. The distance between the piles plays an important role in the performance of the piled raft foundation when the pile length is changed. It has a strong influence on the maximum settlement, differential settlement, bending moment of the raft, and distributes the load applied on the pile. In addition, the configuration of the piles is an important factor in the design of piled raft foundations. One reasonable pile configuration includes short piles being placed on the outside, and pile length being increased gradually from the outside to the center of the raft. The raft can also significantly influence the settlement between the center and the rim of the raft. When the thickness of the raft is increased to a certain value, the level of settlement is not significant. On the other hand, the raft's thickness has a small influence on the settlement of the piled raft foundation, it can affect the bending moment of the raft.

Keywords: Piled raft foundation, 3D finite element analysis, Pile length, Bearing capacity of the pile, Settlement.

1. INTRODUCTION

When a raft foundation does not meet the design requirements, piles can be introduced to improve the bearing capacity, settlement, uneven settlement, and the required raft thickness. A foundation is called a 'piled raft foundation' when both a raft and piles are used. The concept of piled raft foundations was proposed by Poulos (2001a, 2001b) [1], [2] and numerous other researchers [3-9].

Piled raft foundation is a combination of three elements Pile, raft, and soil. the response of the piled raft foundation depends on the interaction between the foundation and the soil. Katzenbach et al. [10] identified four types of interactions, including soil-pile interaction (S-P); soil- raft (S-R) interaction; pile- raft (P-R) interaction; and pile- pile (P-P) interaction. These are the important interactions that must be included in the analysis of the response of the piled raft foundation.

In the design of piled raft foundations, there are five problems that need to be considered. The first one is the limitation in load capacity where the structure may not withstand a certain level of horizontal, or vertical, loading and bending moment. The second problem is the highest total settlement. The third problem is the highest differential settlement. The fourth problem is the evaluation the of shear force and moment of the piled raft foundation design. The last problem is the evaluation of the moment and load capacity of the piled raft foundation.

Franke et al. [11] proposed a procedure to select the piled raft foundation. The piled raft foundation can be selected based on the safety factor of the raft. Poulos [12] showed favorable and unfavorable conditions for the underlying soil which contains the piled raft foundation. The favorable conditions include soil composed of relatively hard clay layer, and soil composed of relatively thick sand layer. The unfavorable condition includes the following cases: 1) the soil is composed of soft clay layers near the surface, 2) the soil is composed of loose sand layers near the surface, 3) the soil has weak compressibility in relatively shallow depth, 4) the soil may have undergone a settlement process due to external causes, and 5) the soil may have undergone an expansion process due to external causes.

To roughly determine the response of pile-raft raft and to determine the response of the load - settlement, a method has been developed by Poulos, Davis and Randolph (1994), which is called the Poulos - Davis - Randolph (PDR) method [13-16]. This method consists of two main steps. The first step determines the ultimate (final) load of the foundation and the second step determines the response of the load - settlement based on the relationship of three linear lines. Tan et al. [17] presented the use of piled raft foundation on soft clay. The results indicated that the applied load on the raft is small while the average settlement and the differential settlement are relatively high.

Many research methods have been proposed for analyzing the piled raft foundation. Burland [18] proposed a simplified method to design a piled raft foundation. In this method, the piles are designed to reduce the settlement of the foundation in the event where the piles come into contact with the clay. Horikoshi et al. [19] developed a method to estimate the total settlement of the piled raft foundation. Poulos [1, 2, 12] also summarized several numerical methods in the design of piled raft foundation.

Finite element method was used to predict the response of piled raft foundation by Reul et al. (2003, 2004), Reul (2004), Katzenbach et al. (2005), Liang et al. (2003), Lin et al. (2006), Singh et al. (2014), Hoa Cao Van, Tuan Nguyen Anh (2019, 2020), Ziaie-Moayed (2010) and Lee et al. (2010) [20-30]. In addition, the application of centrifuges to model the response of piled raft foundation was also conducted by Horikoshi et al. (1996, 1998), Vincenzo Fioravante (2008), etc. [19,31,32]

This research investigates the effect of the raft thickness, pile spacing, and pile length on the behavior of piled raft foundation. The aim is to propose the most appropriate pile arrangement model through 3D finite element analysis.

2. RESEARCH SIGNIFICANCE

Piled raft foundations have been widely used for high rise buildings because both bearing capacity and settlements of the foundation are significantly improved, compared to a conventional piled foundation. The piled raft is a geotechnical composite construction consisting of the three elements piles, raft and soil. A parametric study on pile number, pile length and raft thickness on piled raft foundation behavior are considered in this article. Research results help the designer to have an accurately theoretical basis in choosing the optimal parameters of the raft pile foundation.

3. MATERIALS AND METHOD

3.1. Parameters of Soil and Materials

The ground parameters, which are used in the standardized Mohr-Coulomb (M-C) model, are summarized in Table 1.

Table 1. Parameters in standardized Mohr-Coulomb model

Parameter	Type of materials								Unit
	Layer 1 Sandy Clay	Layer 2 Sandy Clay	Layer 3 Clayey sand	Layer 4 Sand	Layer 5 Clay	Layer 6 Sandy Clay	Layer 7 Clayey sand	Concrete	
Model	M-C	M-C	M-C	M-C	M-C	M-C	M-C	M-C	-
Unit weight γ_{unsat}	19.3	19.6	19.2	18.9	19.7	19	19.5	25	kN/m^3
Saturated unit weight γ_{sat}	19.3	19.6	19.2	18.9	19.7	19	19.5	-	kN/m^3
Modulus E	83650	109200	92000	72500	77140	67200	136800	3E+07	kN/m^2
Poisson's ratio ν	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.15	-
Cohesion c	21.9	26	6.9	4.5	50.4	14.3	9.5	-	kN/m^2
Friction angle φ	19	22	27	29	18	18	23	-	degree
Dilatancy angle ψ	0	0	0	0	0	0	0	-	degree
Vertical permeability k_v	10^{-6}	10^{-6}	$4x10^{-4}$	10^{-2}	10^{-8}	$2.4x10^{-6}$	$4x10^{-4}$	-	m/day
Horizontal permeability k_h	10^{-6}	10^{-6}	$4x10^{-4}$	10^{-2}	10^{-8}	$2.4x10^{-6}$	$4x10^{-4}$	-	m/day
Intensity reduction coefficient R_{inter}	0.7	0.7	0.8	0.8	0.7	0.7	0.8	-	-

3.2. Effect of the Raft Thickness and Pile Spacing in Piled Raft Foundation

3.2.1. Case studies

Three cases (with 9 subcases) for the size of a raft of 20x20 m are investigated to consider the effect of the pile length and pile spacing on the settlement, the moment, the shear force, and the stress distribution of the piled raft foundation. From this a suitable layout in the design of the piled raft foundation can be chosen. The most appropriate model is selected for the calculation of piled raft foundation. Details of the types of piles used in the three case studies are summarized in Table 2.

Table 2. Details of types of piles used in three cases of research

Case	Pile length (m)	Pile bearing capacity (kN)
P1	35	2835
P2	40	3516
P3	45	4286
P4	50	5147

Case 1: The pile length in the piled raft foundation is the same. The pile diameter (d) is 1 m while the raft thickness is 1.5 m. The problems of this case are summarized in Table 3.

Table 3. Problems of case 1

Subcase	Pile length L_{p1} (m)	Pile number, n	Pile spacing	Applied load (kN/m^2)
11	50	16	6d	205
12	50	25	3d	205
13	40	25	3d	205

Case 2: The pipe length varies between long pipes and short pipes. The pile diameter (d) is 1 m while the raft thickness is 1.5m. The problems of this case are summarized in Table 4.

Table 4. Problems of case 2

Sub-case	Pile length (m)		Pile number, n	Pile spacing	Applied load (kN/m^2)
	L_{p1}	L_{p2}			
21	50	40	13	4.5d	205
22	50	40	25	3d	205
23	40	35	25	3d	205

Case 3: The pile length changes in the following way. Short piles are placed outside and their length gradually increases toward the center of the raft. The piles diameter (d) is 1.0 m and the raft thickness is 1.5 m. For this case, the problems are summarized in Table 5. The case studies on the effect of pipe length are showed in Fig. 1.

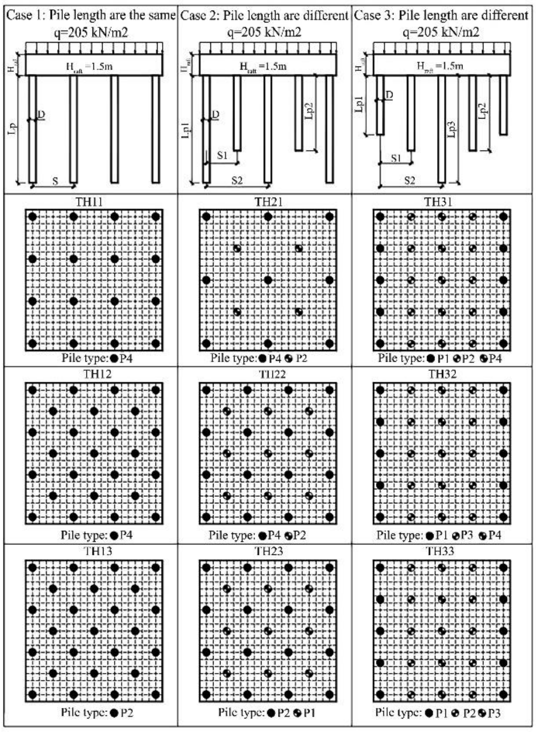

Fig. 1. Case studies on the effect of the pile length

Table 5. Problems of case 3

Sub-case	Pile length (m)			Pile number, n	Pile spacing	Applied load (kN/m^2)
	L_{p1}	L_{p2}	L_{p3}			
31	35	45	50	25	4.5d	205
32	35	40	50	25	4.5d	205
33	35	45	45	25	4.5d	205

3.2.2. Calculation model

The models are simulated with the finite element method [33] in Figs. 2- 4.

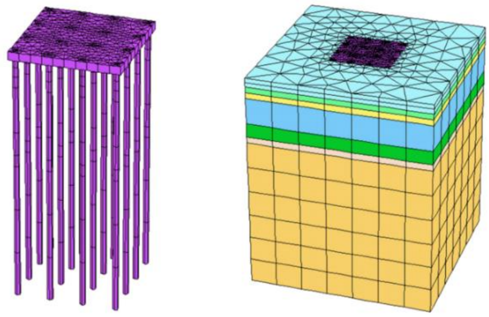

Fig. 2. Case 1 model

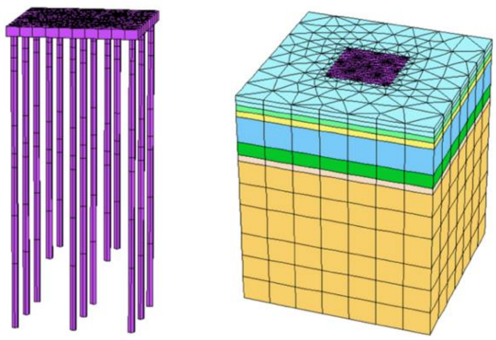

Fig. 3. Case 2 model

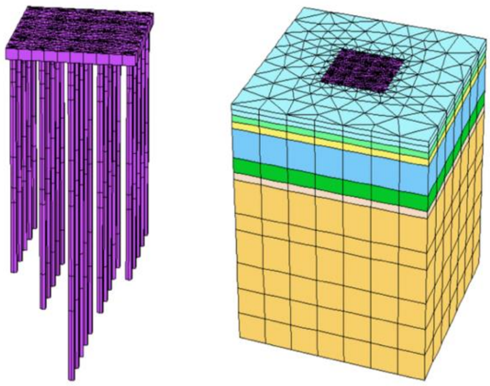

Fig. 4. Case 3 model

3.3. Effect of the Raft Thickness and Pile Spacing in Piled Raft Foundation

3.3.1. Case studies

Four cases are selected for the analysis where the first two cases focus on raft foundation while the other two cases examine the piled raft foundation to have a better understanding on the effect of pile on the response of piled raft foundation (including settlement, differential settlement, and bending moment)

Case 1: The raft foundation has a dimension of (8m x 8m), the raft thickness varies among 0.4m, 0.8m, 1.5m, and 3m. The applied load on the raft is 205 kN/m^2. The calculation diagram of this case is shown in Fig. 5.

Case 2: The raft foundation has a dimension of (15m x 15m) and the raft thickness varies among 0.4m, 0.8m, 1.5m, and 3m. The applied load on the raft is 205 kN/m^2. The calculation diagram of this case is shown in Fig. 6.

Case 3: The raft foundation has a dimension of (8m x 8m) andthe raft thickness varies among 0.4m, 0.8m, 1.5m, and 3m. The pile spacing is 3d, the pile diameter is 1m, and the pile length is 22m. The applied load on the raft is 205 kN/m^2. The calculation diagram of this case is shown in Fig. 7.

Case 4: The raft foundation has a dimension of (8m x 8m), the raft thickness is 1.5m, the pile spacings are 3d, 4d, 5d, and 6d. The pile has a diameter of 1m and length of 22m. The applied load on the raft is 205 kN/m^2. The calculation diagram of this case is shown in Fig. 8.

3.3.2. Calculation models

The models are simulated with the finite elements [32] in Figs. 5-8.

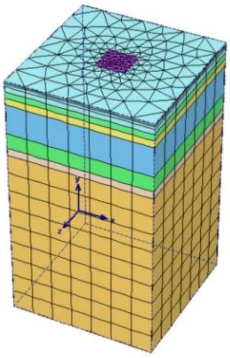

Fig. 5. Calculated model of case 1

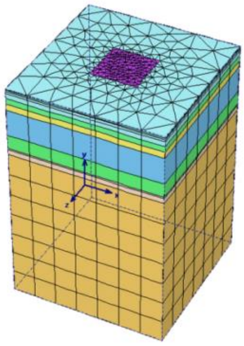

Fig. 6. Calculated model of case 2

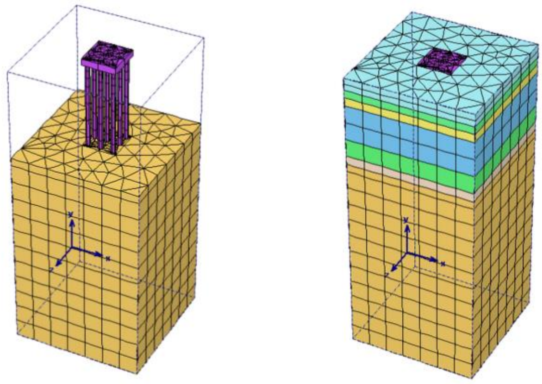

Fig. 7. Calculated model of case 3

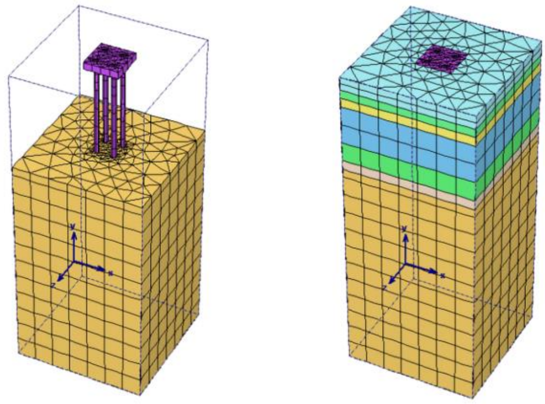

Fig. 8. Calculated model of case 4 (S= 3d, 4d, 5d, 6d)

4. RESULTS AND DISCUSSION

4.1. Effect of the raft thickness and pile spacing in piled raft foundation

4.1.1. Results

The simulation results are summarized in Table 6.

Figs. 9-15 show the results for the analysis with finite element method.

Table 6. Maximum results of analysis cases

Case	Total length of piles (m)	Settlement (mm)	Differential settlement (mm)	Negative moment (kN.m/m)	Positive moment (kN.m/m)	Shear force (kN)	% Load applied to the piles
TH11	800	18.5	12.45	-1130	327	1660	65.4
TH12	1250	15	9	-739.4	236.9	1210	73.2
TH13	1000	16.62	8.4	-791.3	243.2	1230	71.7
TH21	610	19.85	13.64	-1240	475.2	1910	60.4
TH22	1160	15.65	9.55	-786.6	247.6	1270	72.7
TH23	955	17.24	8.93	-841.57	245.95	1300	70.4
TH31	1000	16.87	9.49	-741.3	188.42	1290	71.6
TH32	1050	16.53	9.12	-734.83	185.16	1260	71.9
TH33	975	17.24	8.59	-772.89	191.87	1280	71.2

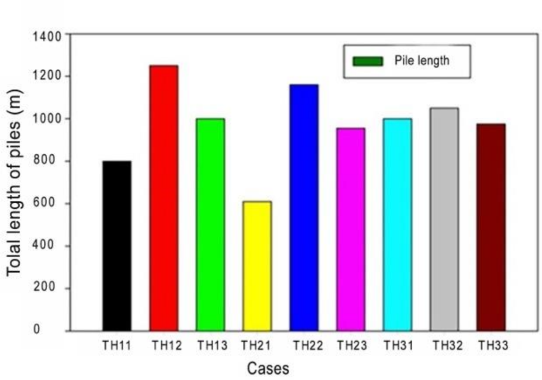

Fig. 9. Comparison of the pile length in 9 subcases

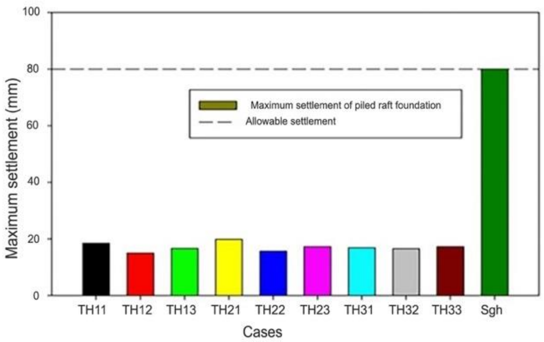

Fig. 10. Settlement of piled raft foundation in 9 subcases

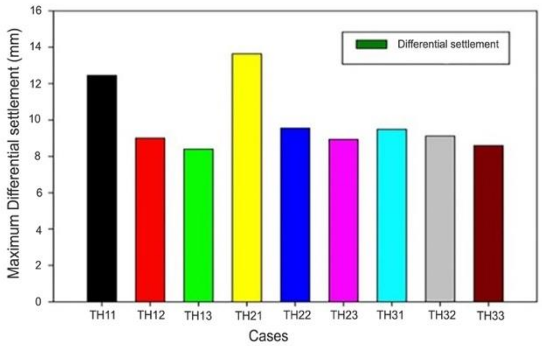

Fig. 11. Maximum settlement of piled raft foundation in 9 subcases

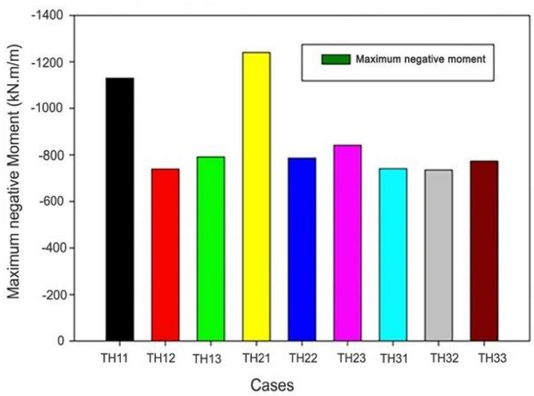

Fig. 12. Negative moment of piled raft foundation in 9 subcases

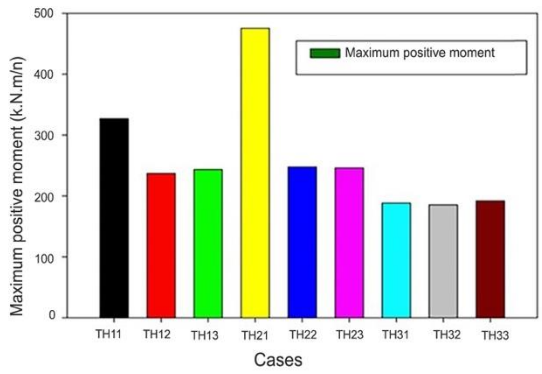

Fig. 13. Positive moment of piled raft foundation in 9 subcases

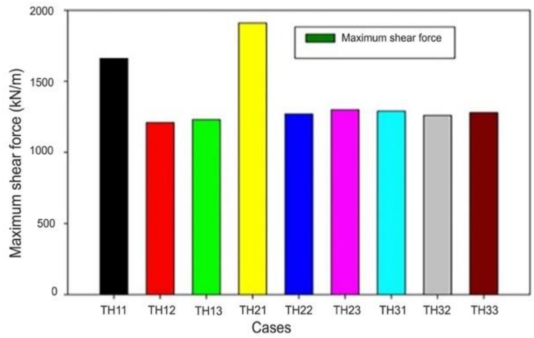

Fig. 14. Shear force of piled raft foundation in 9 subcases

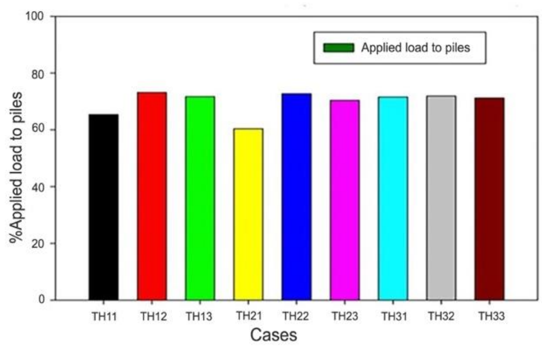

Fig. 15. Percentage of load that piles bear of piled raft foundation in 9 subcases.

Furthermore, this study also considers the ability of load applied to piles in 9 subcases. The graphs for maximum applied load to the piles are shown in Figs. 16 -19.

HG Poulos (2001) proposed that, in order to optimize the design of piled raft foundation, it is necessary to examine aspects such as maximum settlement, differential settlement, bearing limitation of piled raft foundation, shear force and moment in raft foundation design, and the bearing capacity and moment in pile design.

Figs. 9- 19, show all the research results, including the total length of piles, settlement, moment, shear force, percentage of the applied load to the piles, and the applied load to the types of piles

(P1->P4). In the case with TH11 and TH21 piles, P4 and P2 piles do not meet the bearing capacity therefore they are not considered.

When increasing the pile number (the pile spacing decreases TH11(6D), TH12(3D)), the settlement is reduced from 18.5 mm to 15 mm, the negative moment decreases from 1130kN·m/m to 739kN·m/m, the positive moment drops from 327kN·m/m to 237kN·m/m, the shear force decreases from 1660kN to 1210kN but the percentage of applied load to the piles increases from 65.4% to 73.2%.

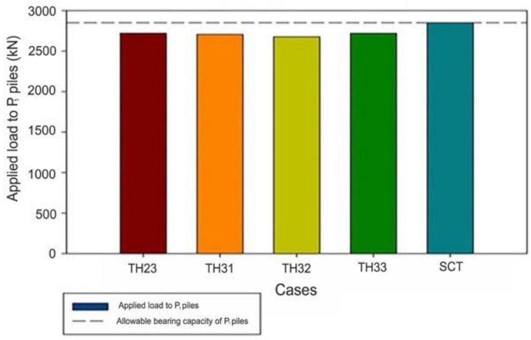

Fig. 16. Maximum applied load to P1 pile

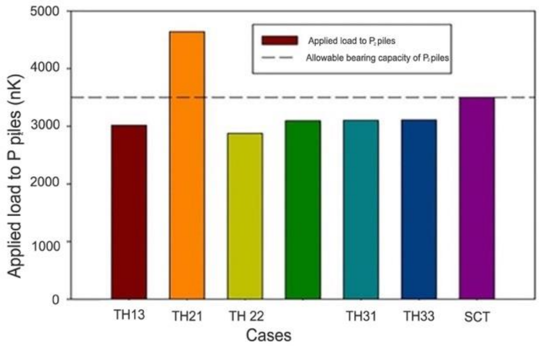

Fig. 17. Maximum applied load to P2 pile

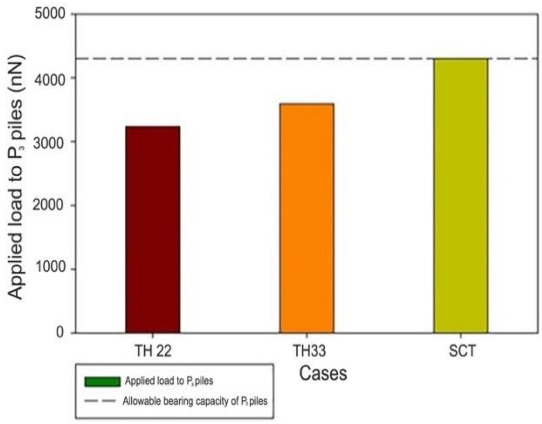

Fig. 18. Maximum applied load to P3 pile

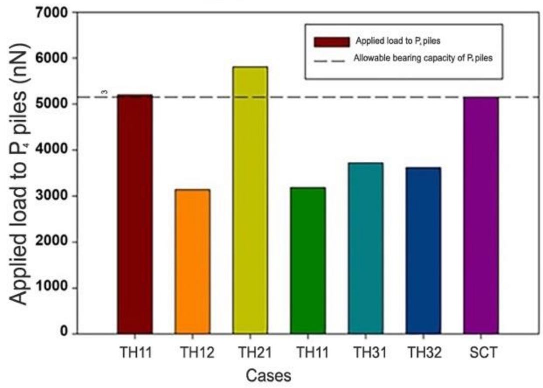

Fig. 19. Maximum applied load to P4 pile

4.1.2. Discussion

Table 7. Selection of optimal type of pile arrangement from obtained results

No.	Total length of piles (m)	Maximum negative moment of the pile (kN·m/m)	Maximum positive moment of the pile	The maximum shear force of the pile (kN/m)
1	~~TH21(610)~~	~~TH32(-735)~~	~~TH32(185)~~	~~TH12(1210)~~
2	~~TH11(800)~~	**TH12(-739)**	~~TH31(189)~~	**TH13(1230)**
3	**TH23(955)**	~~TH31(-741)~~	**TH33(192)**	~~TH32(1260)~~
4	**TH33(975)**	**TH33(-773)**	~~TH12(237)~~	~~TH22(1270)~~
5	**TH13(1000)**	~~TH22(-787)~~	**TH13(243)**	**TH33(1280)**
6	~~TH31(1000)~~	**TH13(-791)**	**TH23(246)**	~~TH31(1290)~~
7	~~TH32(1050)~~	**TH23(-842)**	~~TH22(248)~~	**TH23(1300)**
8	~~TH22(1160)~~	~~TH11(-1130)~~	~~TH11(327)~~	~~TH11(1660)~~
9	~~TH13(1250)~~	~~TH21(-1240)~~	~~TH21(-475)~~	~~TH21(1910)~~

According to the results presented above, Table 7 is prepared to show the rank for each model with the parameters from Fig. 9 to Fig. 15. From the results, we can recommend the appropriate layout for the piled raft foundation. In Fig. 16-19, all piles in each model are less than the bearing capacity of the pile, except for TH11 and TH21 models.

From the three cases, the three models with the smallest total pile length of TH13, TH23, and TH33 are selected. It can be seen that the TH13 model has the largest total pile length and therefore it is not selected. Although the TH23 model has the smallest total length of piles, it has the largest moment and shear force. Therefore, the TH33 model is more economical compared to the other models. Therefore, the TH33 model has the most reasonable layout for the piled raft foundation.

4.2. Effects of the raft thickness and pile spacing in piled raft foundation

4.2.1. Results

The calculated results of simulated cases are summarized in Fig. 20 and Fig. 31 where, Br is the width of the raft foundation and x/Br is the ratio of the distance to the width of the raft foundation.

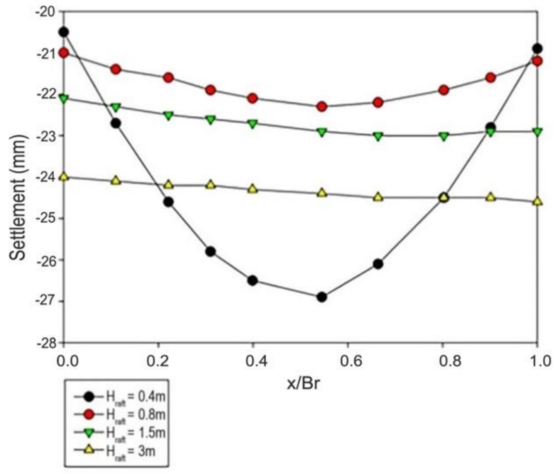

Fig. 20. Effect of the raft thickness on the settlement of raft foundation in case 1

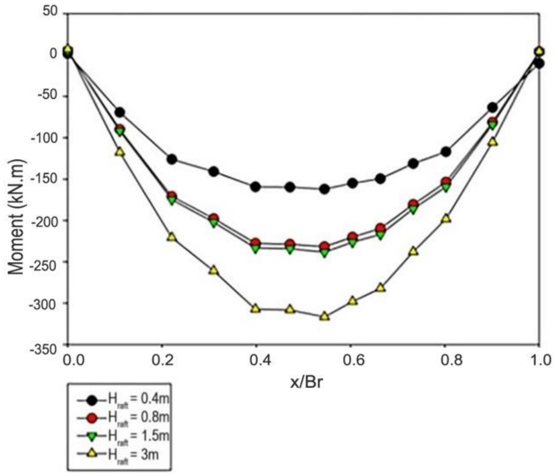

Fig. 21. Effect of the raft thickness on the moment of raft foundation in case 1

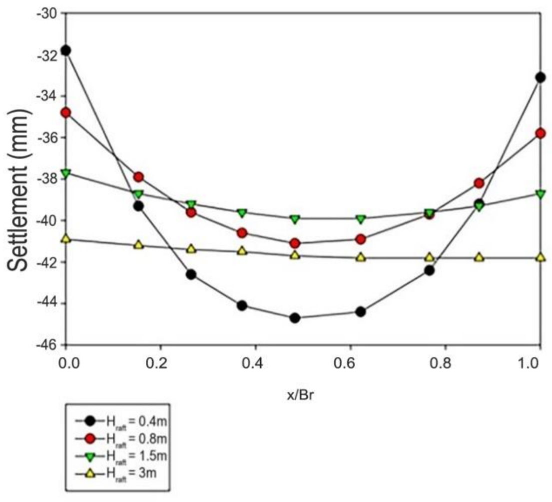

Fig. 22. Effect of the raft thickness on the settlement of raft foundation in case 2

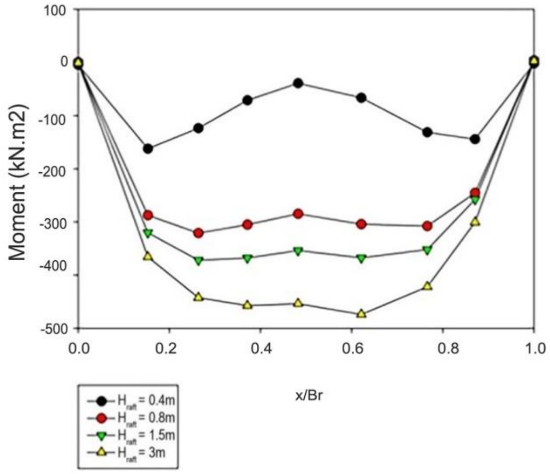

Fig. 23. Effect of the raft thickness on the moment of raft foundation in case 2

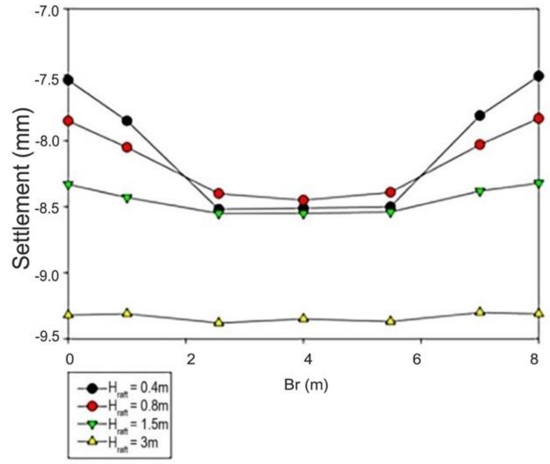

Fig. 24. Effect of the raft thickness on the settlement of piled raft foundation in case 3

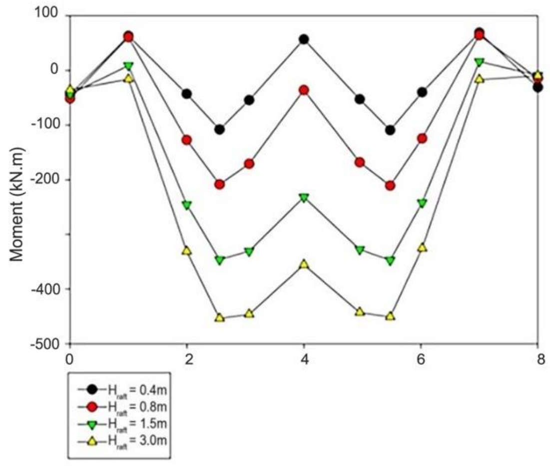

Fig. 25. Effect of the raft thickness on the moment of piled raft foundation in case 3

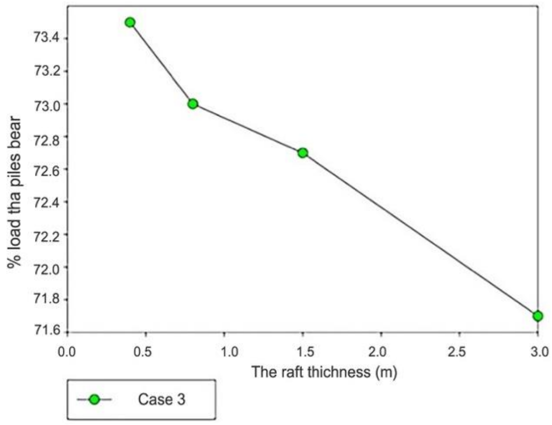

Fig. 26. Effect of the raft thickness on the load distribution between piles and soil surrounding piles in piled raft foundation in case 3

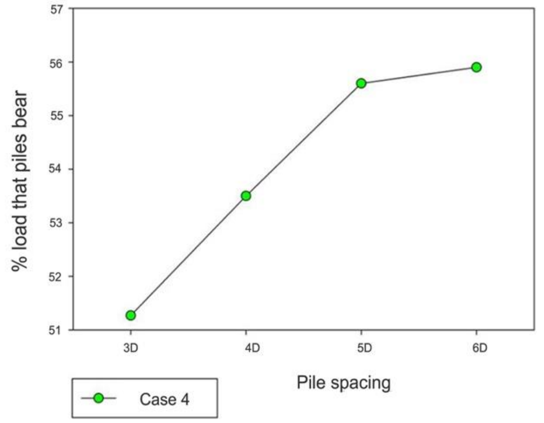

Fig. 29. Effect of pile spacing on the load distribution between piles and raft in piled raft foundation in case 4

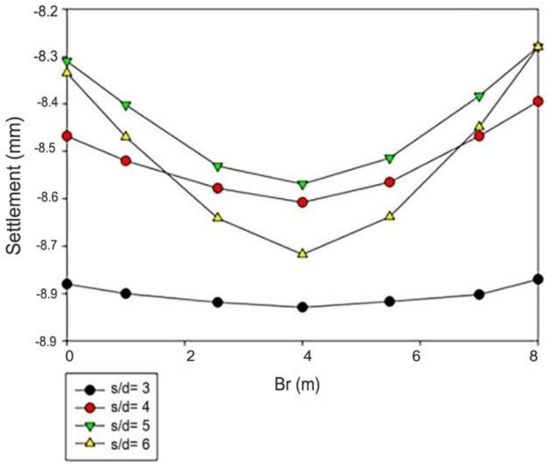

Fig. 27. Effect of pile spacing on the settlement of piled raft foundation in case 4

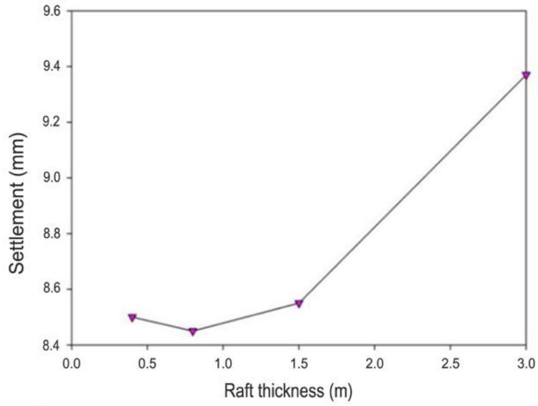

Fig. 30. Effect of raft thickness on the settlement of piled raft foundation

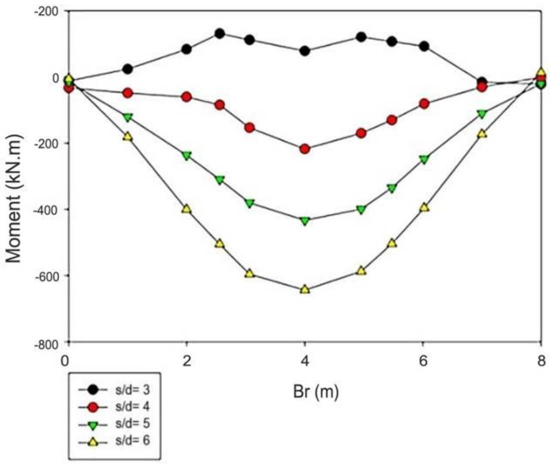

Fig. 28. Effect of pile spacing on the moment of piled raft foundation in case 4

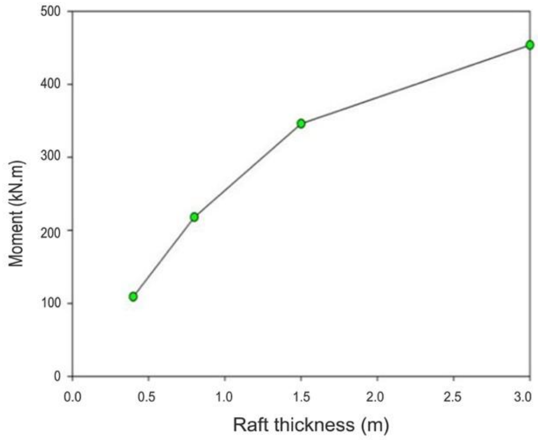

Fig. 31. Effect of raft thickness on the moment of piled raft foundation

4.2.2. Discussion

From the four case studies for the raft foundation and the piled raft foundation. It can be seen that the maximum settlements are 26.9 mm and 44.7 mm for a raft of 8x8x4 m and 15x15x4 m, respectively;

increasing the raft thickness by 3 m reduces the maximum settlement of the raft to 24.6 mm and 41.8 mm for the 8x8x4 m and 15x15x4 m rafts, respectively. On the contrary, the maximum bending moment of the raft increases when the raft thickness increases. For instance, for the raft of 0.4 thick, the maximum bending moments are 159.6 kN.m and 162.6 kN.m for the 8x8x4 m and 15x15x4 m rafts, respectively; When the raft's height increases to 3 m, the maximum bending moments of 8x8x4 m raft and 15x15x4 m raft are 310.8 kN.m and 476.8 kN.m, respectively.

The maximum settlement of the raft is 26.9 mm, but when installing more piles to the raft, the maximum settlement of the piled raft foundation with the raft of 0.4m thick decreases to 8.2 mm.

When the raft thickness in the piled raft foundation varies among 0.4 m, 0.8 m, 1.5 m, and 3 m;the corresponding maximum settlements are 8.52 mm, 8.45 mm, 8.55 mm, and 9.38 mm;the corresponding maximum bending moments are 109 kN.m, 218 kN.m, 346.6 kN.m, and 453.7 kN.m.

When the raft thicknesses are 0.4 m, 0.8 m, 1.5 m, and 3 m, the load distribution between piles and soil surrounding the raft is that the piles bear the loads of 73.5%, 73%, 72.7%, and 71.7%.

With the thickness of 1.5m, whenthe pile spacings are 3d, 4d, 5d, and 6d the maximum settlements are 8.8 mm, 8.6 mm, 8.55 mm, 8.7 mm, respectively; the bending moments at the center of the raft are 80.8 kN.m, 217.8 kN.m, 433.2 kN.m, and 644.2 kN.m, respectively.

With the thickness of 1.5m, when the pile spacings are 3d, 4d, 5d, 6d the load distribution between piles and the raft is that the piles bear loads of 51.27%, 53.5%, 55.6%, and 55.9%.

5. CONCLUSIONS

When the length of piles changes alternately (between long pile and short pile), the settlement, uneven settlement, positive moment, negative moment, maximum shear force in the raft increase. In contrast, the percentage of applied load to the pile decreases.

The pile spacing plays an important role in the performance of the piled raft foundation. It has a strong influence on the maximum settlement, uneven settlement, bending moment in the raft, and the applied load distributed within the pile.

The reasonable pile layout for the piled raft foundation involves short piles on the outside; the pile's length increases gradually as we move toward the center of the raft.

The response of the raft foundation has a prominent effect when a limited pile number is installed under the raft, to minimize the settlement of the raft foundation.

The raft thickness can significantly affect the differential settlement between the center and the edge of the raft. When the raft thickness is increased to a certain value, the settlement is not significant (almost zero). However, it is also important to note that, by increasing the raft thickness to prevent the penetration force of both applied forces from the pile and the column. As a result, an increase in the raft thickness can prevent force caused by piles and columns from penetrating the structure.

The raft thickness has a negligible influence on the settlement of the piled raft foundation while it can significantly affect the bending moment in the raft. When the raft thickness increases, the bending moment in the raft also increases.

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