ANALYSIS AND PARAMETRIC STUDY OF PILED RAFT FOUNDATION USING FINITE ELEMENT BASED SOFTWARE PLAXIS 3D

Simeneh Abate, Alemayehu Teferra and Ameyu Temesgen

ABSTRACT: The design of group piles depends on either the group or single pile capacity. In conventional design method such foundations, the pile cap is not considered as a foundation element which makes the approach conservative as the contribution of the raft is not accounted for. Taking into account of the interactions between different elements of piled raft foundation, an economic design would be attained. This paper presents analysis and parametric study of the piled raft foundation using finite element software PLAXIS 3D. A number of parameters were investigated from the elements of the piled raft system and their effect on the response of piled raft system is studied with regard to settlement. Accordingly, the result shows that concentrating more piles at the center of uniformly loaded piled raft increase the central settlement while decreasing the differential settlement. In line with the current and previous studies, random/strategic placing of piles (for example, around the edge and at the center) does not provide a consistent reduction of settlement as compared to uniformly distributed piles under the piled raft system.

KEYWORDS: raft, pile, pile raft, interaction, PLAXIS 3D

1. Introduction

A geotechnical engineer, faced with design of foundations, considers shallow foundation for supporting a given simple structure. When the weight of the structure increases and the bearing capacity of the foundation soil compromise the stability or serviceability of the structure, one needs to resort to other foundation types.

Piles are good solution in site conditions where low bearing capacity and significant settlement are expected. In designing piles as foundation support for structures, it is a common trend to include a pile cap for joining of the pile heads. The pile cap is designed for structural section capacity only. The role of the pile cap is in direct contact with the foundation soil.

A piled raft is a foundation which acts as a composite construction consisting of three load bearing elements. These are namely piles, raft and subsoil. According to its stiffness, the raft distributes the total load of the structure as contact pressure and over the piles in the ground. Piled raft is not new from construction point of view. In fact a number of high rise buildings supported by piles are constructed with a foundation system similar to piled raft foundation but the raft is considered as pile cap.

According to Hanisch *et al.* (2002), a piled raft foundation has four kinds of interactions. These

interactions are pile-pile, pile-raft, pile-soil and raft-soil (Figure 1). The design should properly address the influence of these interactions.

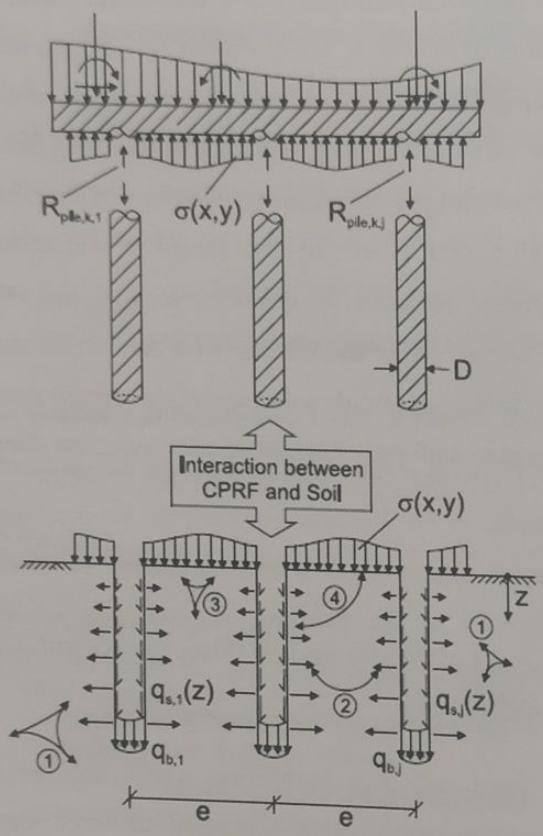


Figure 1 Interaction between pile, raft and soil in piled raft foundation as proposed by Hansich et *al.* (2002)

2. Analysis

Randolph (1994) defines three different design philosophies with respect to piled rafts (Figure 2).

i. The "conventional approach" in which piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft primarily to ultimate load capacity. Curve 1 represents this design philosophy in which the piles take the whole load.

ii. "Creeping piling" in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70 – 80% of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the pre-consolidation pressure of the soil. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety.

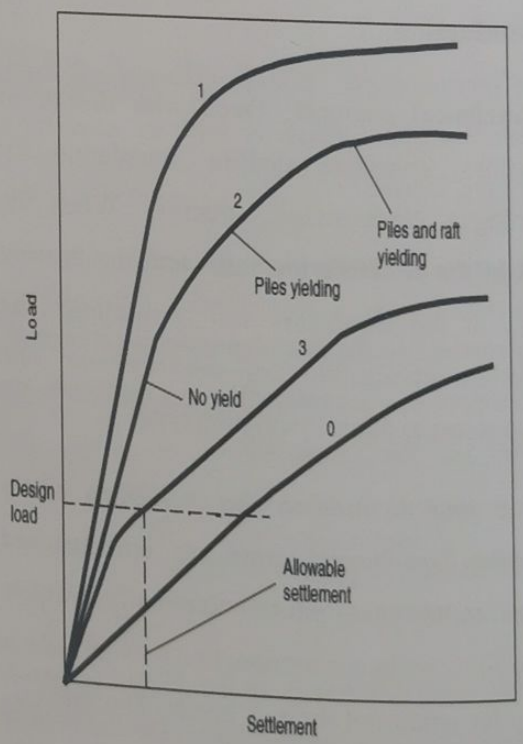


Figure 2: Load settlement curves for piled rafts according to various design philosophies Curve-0: Raft only settlement, Curve-1: Raft with piles designed for conventional safety factor, Curve-2:

Raft with piles designed for lower safety factor, Curve-3: Raft with piles designed for full iii. Differential settlement control, in which the piles are located under the raft where high settlement is expected. This will make the settling area of the raft more stiff which ultimately reduce the differential settlement.

A number of methods can be cited in terms of their ability to predict load-settlement behavior if a piled raft foundation. But three broad classes of analysis methods are identified according to the assumptions, complexity and numerical methods employed. These are:

a. Simplified Calculation Methods
b. Approximate Computer-Based Analysis
c. More Rigorous Numerical Methods of Analysis

In the present paper, a three-dimensional Finite Element Analysis, which is with in category c cited above, is used.

3. Validation of 3D-Plaxis Software

Before conducting the intended parametric studies, it is necessary to examine the accuracy of the software. For the validation of the result, two buildings located in Frankfurt, Germany, were considered. The two buildings are Westend and Torhaus, respectively (Figure 3a and b)

Then, the results obtained by the Plaxis software are compared with those obtained by other methods in Figure 4. The results of all methods considered are then compared with measured data.

utilization of capacity (Paulos, 2001)

For comparison, the following quantities are used

i. Center settlement
ii. Maximum and minimum pile loads
iii. Piled raft coefficient $a_{pr.}$

$a_{pr.}$ is defined as the ratio of reaction from piles to the total piled-raft system reaction. The values of a_{pr} varies from 0, for the case where the load is totally supported by the raft, to 1 for the case where the load is supported by piles.

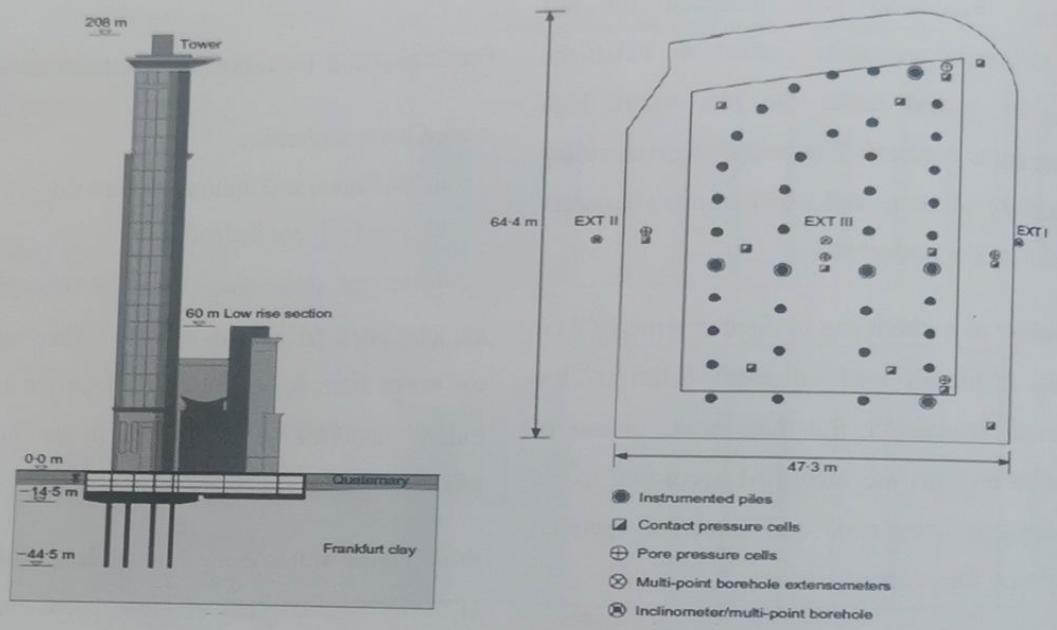
From Figure 4, it is demonstrated that software 3-D PLAXIS results that are close to the measured quantities for Westend. For Torhaus, the measured center settlement is 124mm compared to 92mm obtained by the software. As indicated by the comparative bar charts, it may be stated in general that the software gives acceptable values.

4. Analysis and Parametric Study

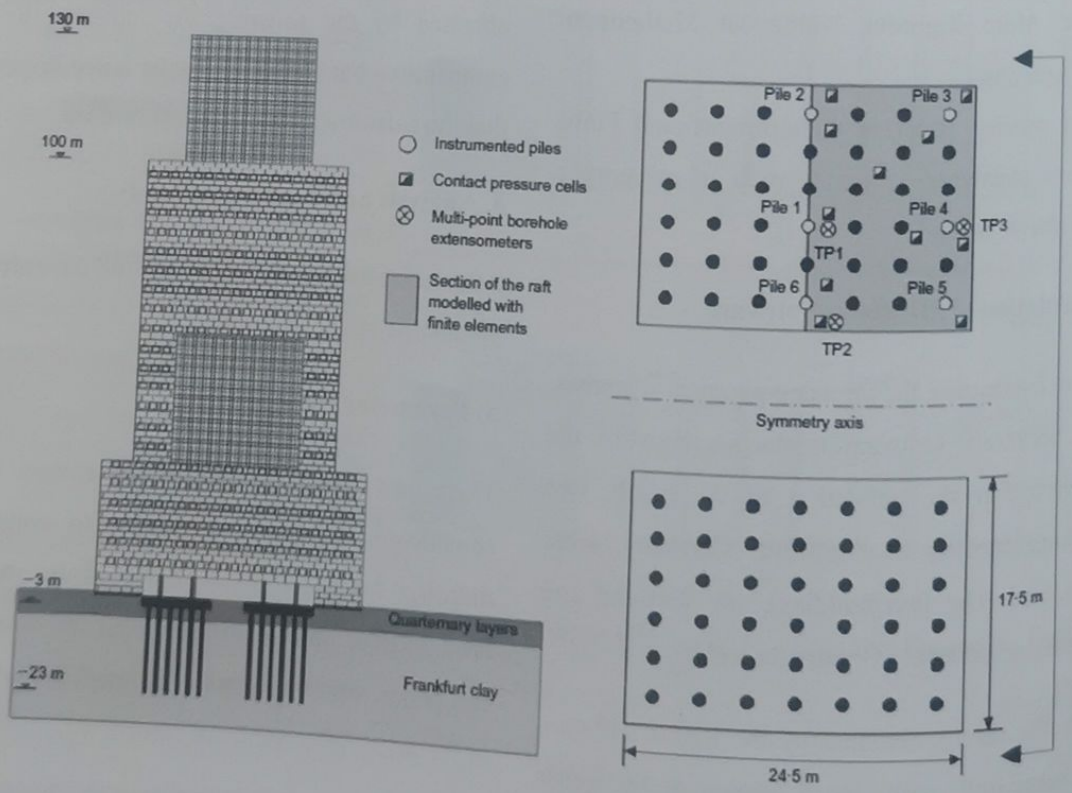
After establishing the reliability of the software, parametric study are conducted.

a) Parameter Identification

There are large number of parameters to be considered if one is interested to conduct a thorough study. However, some of the variables have little or no effect in the piled raft system. In this paper, variables that have significant influence in the piled raft system are considered.



a) Westend 1 building



b) Torhaus

Figure 3. Raft Layout and finite element model (Reul and Randolph, 2003)

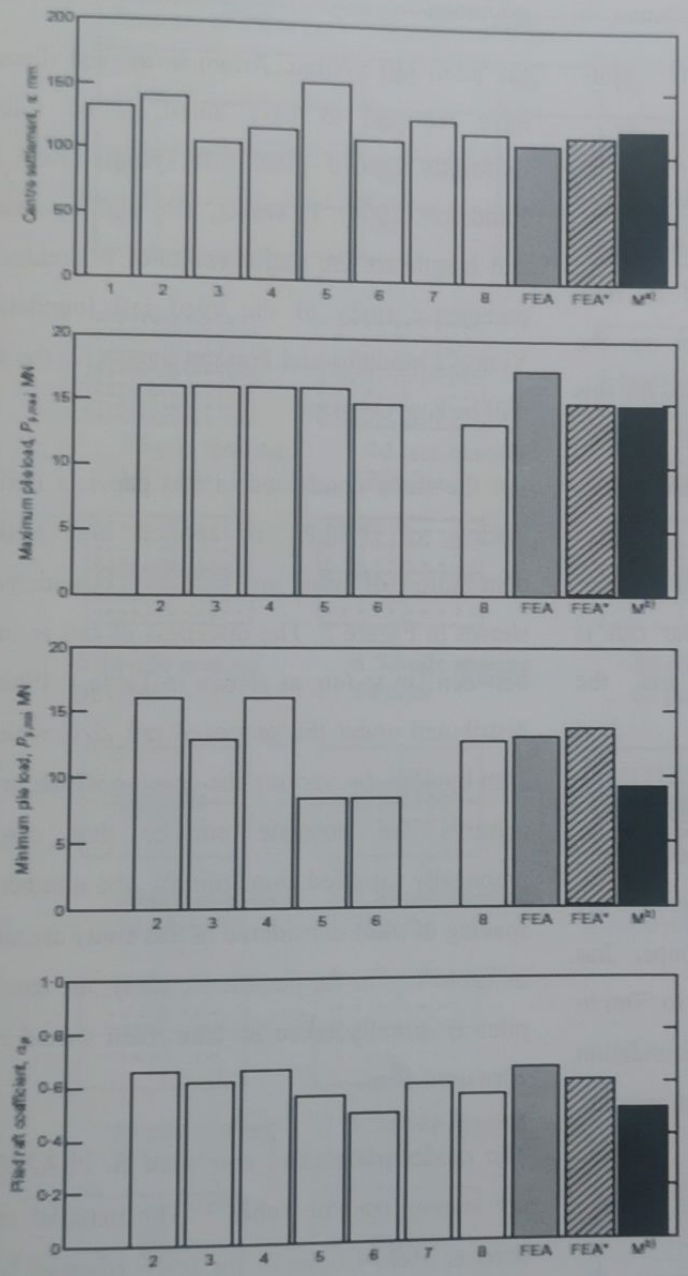


Figure 4: Westend 1: Comparison of different methods and measurements (Reul and Randolph, 2003)

The main parameter that influences the response of piled raft system is its stiffness. But the stiffness of a piled raft system depends on the elements in the system. The elements of the system are the soil, piles and superstructure (columns) and the

raft. The stiffness of a piled raft system is governed by individual stiffness of the elements. Thus, parameters are identified accordingly.

The thickness, shape and dimension of the raft can be considered as variables in the parametric study. Shape and dimensions are not most of the time design parameters. They are related to the architectural aspect of the structure. Thus, for this study, only the thickness of the raft shall be taken as one of the variables in the parametric study. The shape is specified as rectangular while an aspect ratio of 1.5 (width/length) is taken for the raft dimensions. A 45m by 30m rectangular raft is assumed. The Young's modules and the Poissons's ratio are also kept constant.

The soil also contributes to the stiffness of piled raft system through Young's modulus and Poissons's ratio. The strength parameters of the soil can also be considered. This paper has assumed a uniform soft/medium clay up to 70m in which the ground water is found at the foundation level. All parameters of the soil are kept constant throughout the analysis.

The geometric arrangement, number, spacing, diameter and length of piles are among the physical factors that contribute to the stiffness of the piled raft system. Arrangement and diameter have reported to have small or no role in uniformly loaded piled raft system (Reul and Randolph, 2004). However, pile number spacing and length are the major variables in conducting parametric study of the piled raft foundations. Young's modulus and Poisson's ratio for the piles will be kept constant.

For the study conducted in this paper, a uniform loading of 150kPa is applied and uniform distribution of piles are basically considered as shown in Figure 5. The thickness of raft is varied between 1m to 6m, as shown in Table 1. Piles are distributed under the proposed raft size, which is 30m by 45m, by varying the spacing which in turn controls the possible number that can be practically installed. Accordingly, the number and spacing of piles considered in this study are shown in Table 2. In the parametric study, the length of piles is initially taken as 10m, then varied every 10m until 50m.

The model parameters employed in PLAXIS 3D are summarized in Table 3. The material model used is Mohr-Coulomb for soils, whereas Linear Isotropic model is used for piled raft structural member.

Table1: Raft Thickness variation:

Thickness (m)	1.0	1.5	1.75	2.0	2.5	3.0	4.0	5.0	6.0

Table 2: Spacing and Number of Pile Variation

Spacing of Piles (m)	Number of Piles					
3.0	140	96	80	60	32	16
3.5	96	-	80	60	32	16
4.0	80	-	-	60	32	16
4.5	60	-	-	-	32	16

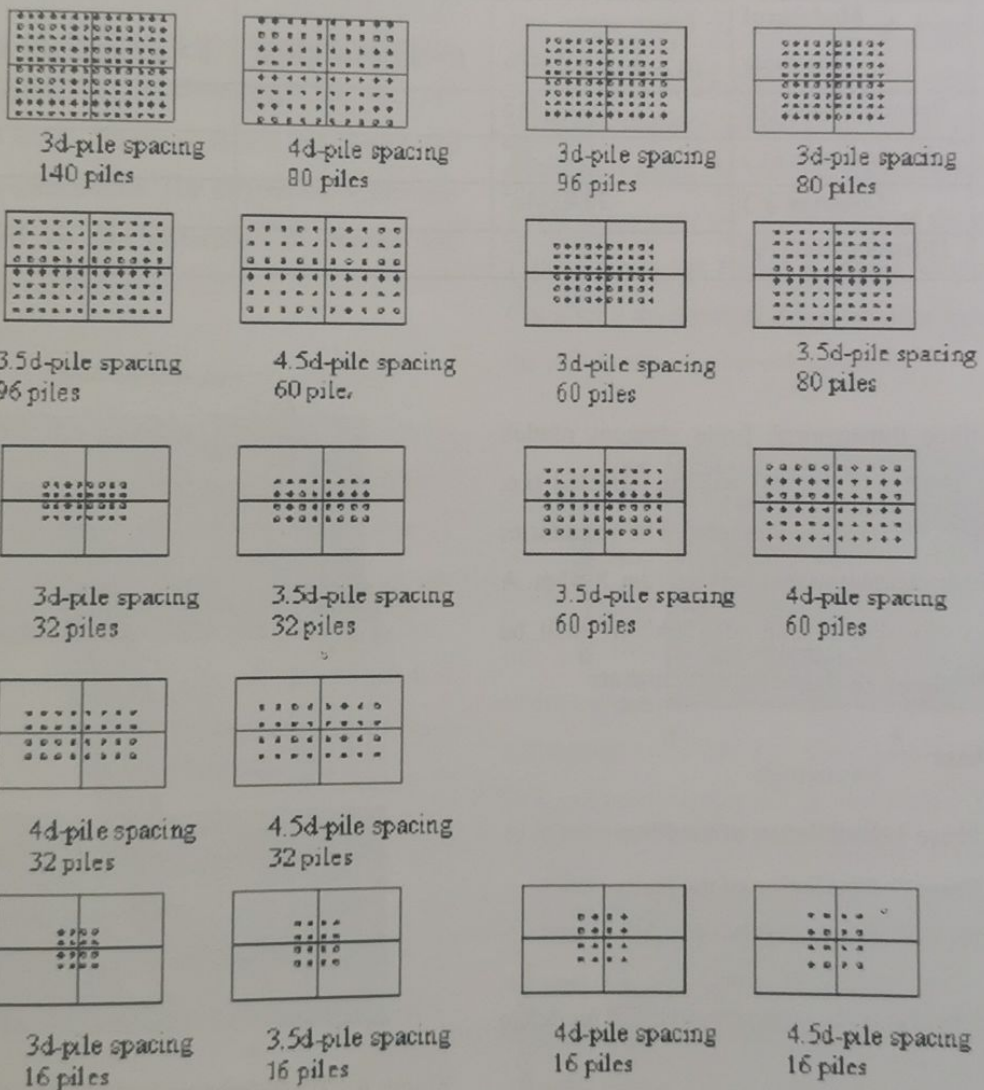


Figure 5: Pile foundation layout with uniform pattern

Table 3: Relevant Soil, Raft and Pile.Parameters for Finite Element Analysis

Description	Soil	Raft	Pile
Type	Medium/Soft Clay	Concrete Grade C30 (EBCS-2)	Concrete Grade C30 (EBCS-2)
FE Model	Elasto-Plastic (Mohr-Coulomb)	Linear Isotropic	Linear Isotropic
Unit Weight	$\gamma_{sat} = 18$ KN/m^3 $\gamma_{unsat} = 17$ KN/m^3	$\gamma = 24$ KN/m^3	$\gamma = 24$ KN/m^3
Modulus of Elasticity	$E_s = 8.0$ MPa	$E = 3.2 \times 10^7$ KN/m^2	$E = 3.2 \times 10^7$ KN/m^2
Poisson's Ratio (ν_s)	0.3	0.2	0.2
Friction angle (ø')	20°	-	-
Cohesion (c')	10 KN/m^2	-	-
Dilatancy angle (ψ)	0°	-	-

In the three dimensional finite element model, only the quarter of the raft will be modeled (i.e. 22.5m X 15.0m) due to symmetry. The boundaries of the finite element model will be 70m X 45m. A uniformly distributed load of 150kN/m^2 will be used. The phases in staged construction are

Initial Phase

- Phase 1: Installation of the Piles
- Phase 2: Installation of the Rafts
- Phase 3: Loading of the system

Figure 6 below gives representative 3D model in Plaxis

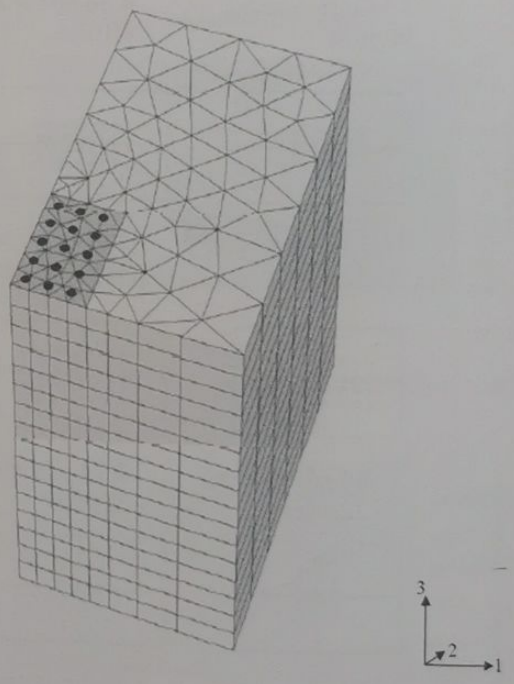


Figure 6: 3D finite element model in PLAXIS for a piled raft foundation

5. Analysis of Result and Discussion

The parametric study conducted included a number of alternative arrangements of piles. The comparison criteria for ultimate design have been set to be the differential settlement, total settlement and maximum moments.

a) Effect of Raft Thickness

In order to examine the effect of raft thickness on magnitudes of settlements and bending moments, an initial analysis is conducted on the raft foundation alone. Figure 7 shows the central and differential settlements. The differential settlement is measured by the difference of central and middle edge settlements.

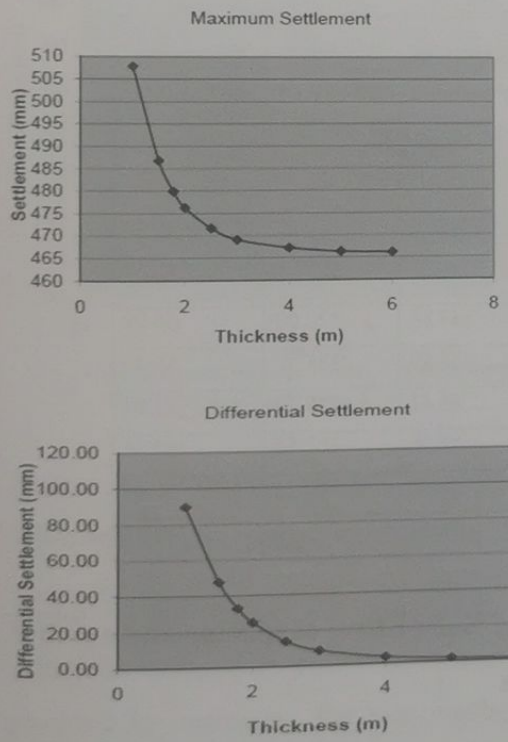
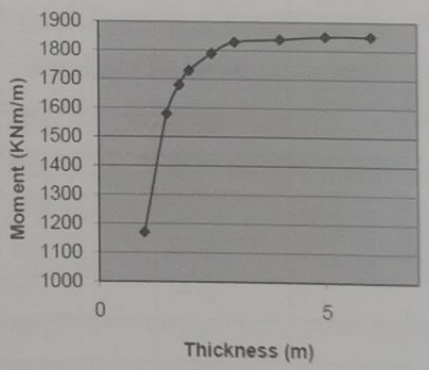


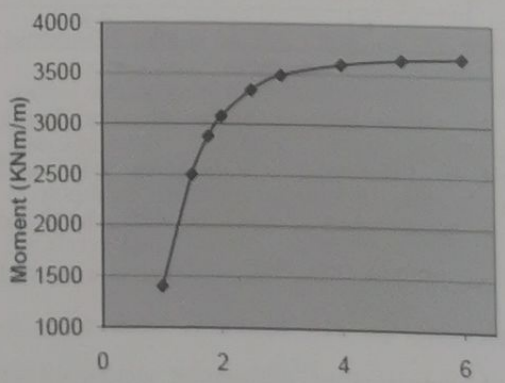
Figure 7: Variation of central and differential settlement with thickness of raft

The above figures show a well-known trend that's as the raft thickness increases both the total and differential settlement decrease. One major point that is observed from the Figure 7 is that after a thickness of 2.5m there is a little or no advantage increasing the raft thickness for the case under consideration.

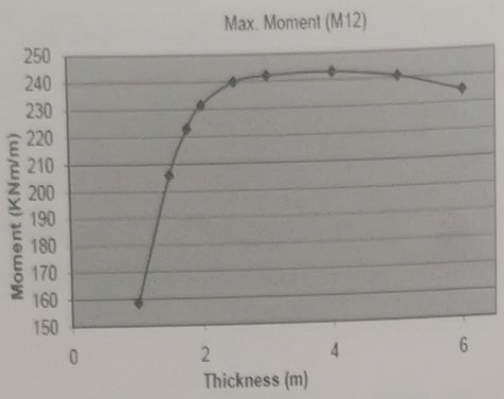
The same trend is illustrated in Figure 8 for maximum bending moments. Local axis 1 runs along the length of the raft (+ve x-axis) while local axis 2 runs along the width of the raft (-ve z-axis). Local axis 3 runs out of the plane of the raft (+ve y-axis). From the Figure 8 shown, one observes that after a thickness of 2.5m, bending moments in the raft do not increase substantially.



a) Maximum moment in local axis 1



b) Maximum moment in local axis 2



c) Maximum moment in local axis 3

Figure 8: Variation of Maximum moments in along the three axis

From the output of the above analysis, one observes that a reduction in differential settlement is accompanied by an increase of bending moments. As the raft stiffness increases, both the total and central settlement decreases significantly, but with an increase of bending moments. The rate of decrease in settlement and increase in moment become negligible after a raft thickness of about 2.5m. From this point on, an increase in thickness of raft will not bring any significant change on both the settlement and moment of the raft. Table 4 shows the effect of the thickness of the raft on settlement and bending moment.

Table 4: Effect of thickness of raft on settlement and bending moment

Raft thickness (m)	*Diff. Settlement (mm)*	*Percentage of Differential Settlement*	*Percentage of Decrease of Differential Settlement*	*Percentage of Increase of M11*	*Percentage of Increase of M22*	*Percentage of Increase of M12*
1	89.60	17.64				
1.5	47.65	9.79	44.51	35.04	78.57	29.85
1.78	32.97	6.87	61.06	43.59	105.71	40.68
2	24.94	5.24	70.32	47.86	120.00	46.09
2.5	13.91	2.95	83.28	52.99	138.57	51.40
3	8.42	1.80	89.82	56.41	149.29	52.74
4	3.69	0.79	95.52	57.26	157.14	53.34
5	1.93	0.41	97.65	58.12	160.71	51.86
6	1.14	0.24	98.61	58.12	162.14	48.11

From the above table, one can observe that a decrease in differential settlement by 84% will result in an increase of M11 by 53%, M22 by 140% and M12 by 52%. This of course achieved by increasing the raft thickness from 1.0m to 2.5m. A reduction of differential settlement of almost 100% can be achieved at 6.0m for a little increase in moment in the raft.

b. Piled Raft: Effect of spacing and number of piles

Here piles are introduced under the raft to conduct the parametric study. The length of pile considered in this section is 10m and a mat thickness of 2.5m is considered in this study. The output of the analysis is presented in Figure 9 to 12.

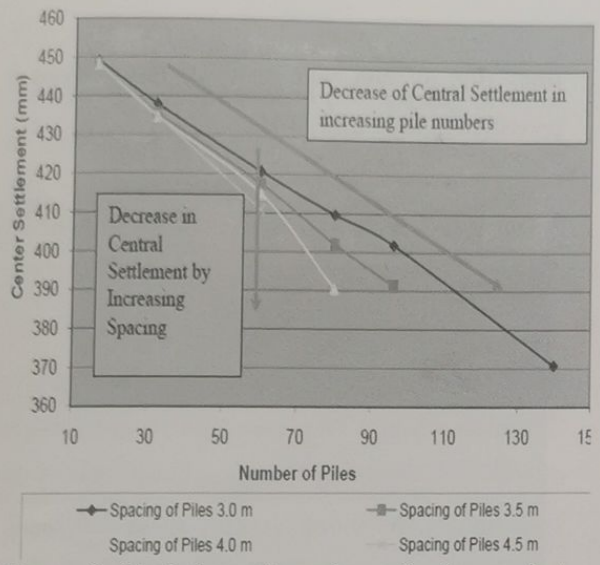


Figure 9. Variation of number of piles against center settlement

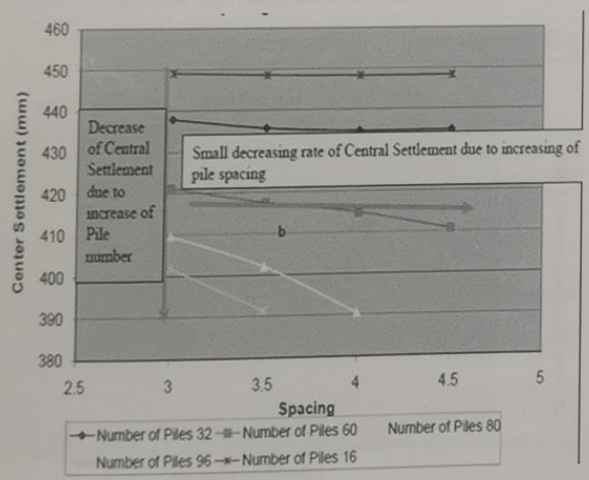


Figure 10: Variation of spacing with center settlement

Figure 9 and Figure 10 demonstrate that a significant decrease in central settlement van be observed by increasing the pile number while gradual decrease is seen by increasing the number of piles. One can reduce the settlement by 50mm, for example, by increasing the number of piles from 16 to 96. The major reason for a decrease in central settlement is increasing spacing may be due to stress overlap in closely spaced piles. For closely spaced piles, the stress overlap area will be large leading to higher settlement. Whereas for the case of widely spaced piles, the stress overlap between adjacent piles will be lower and the settlement will also be lower.

Figure 11 and Figure 12 illustrate that there is an optimum pile number which corresponds to minimum differential settlement for a given loading, spacing of piles and thickness of raft. In Figure 11, for example, the 3.0, 3.5 and 4.0m spaced piles have minimum differential settlement for the case of 80 piles.

In piled raft foundation design practice, one tries to decrease the differential settlement by keeping the central settlement to the accepted values of the prevailing codes. With the conventional method of design, a designer has to put a higher number of piles under the raft in order to meet the differential settlement requirement. Simply putting piles under the raft leads to a decrease of both total and differential settlement. But allowing a higher total settlement that is in the range of the prevailing codes, one may obtain a lower number of piles. The white dots in Figure 12 show the intersection of graph of different number of piles illustrating the above fact.

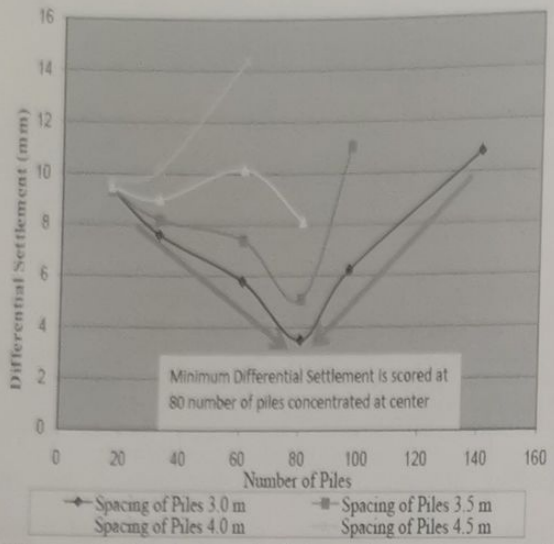


Figure 11: Variation of differential settlement with number of piles

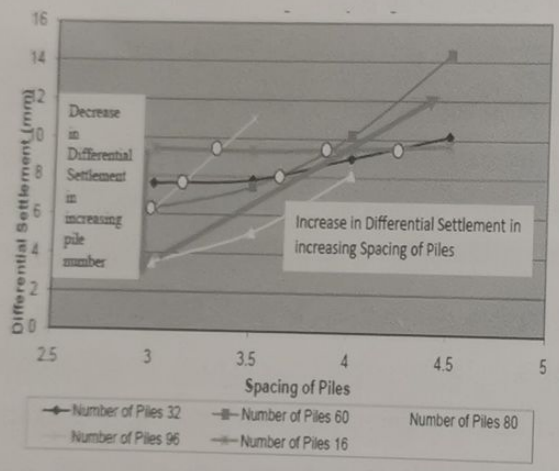


Figure 12: Variation of differential settlement with spacing of piles

c. Piled Raft Foundation: Effect of length of piles

In order to study the effect of length of piles, two spacing of piles: namely the widest (4.5m) and the closest (3.0m) are taken. The pile numbers considered are limited to 60 and 80 for pile spacing of 3.0m and pile numbers of 16, 32 and 60 for spacing of 4.5m. The length has been increased from 10m to 50m. The result of the analysis is presented in Figure 13 to 16.

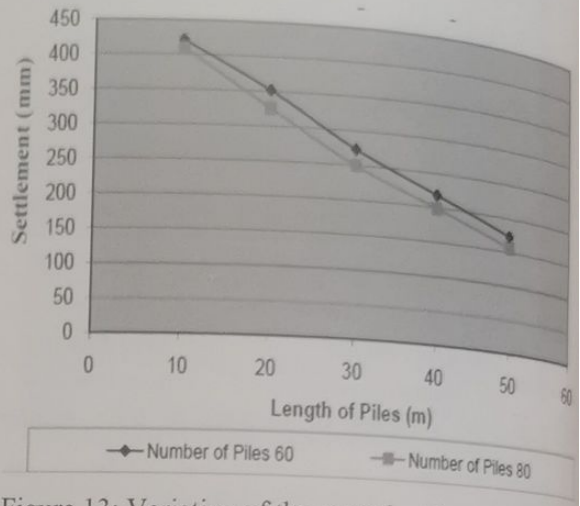


Figure 13: Variation of the central settlement with pile length at pile spacing of 3m

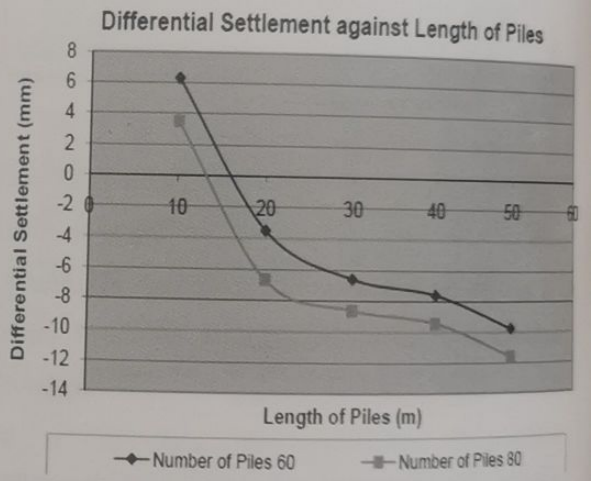


Figure 14: Variation of the central settlement with pile length at pile spacing of 3m

The increase in length of piles brings significant change in both the central settlement as well as the differential settlement. A similar decreasing pattern is observed for both spacing (3.0m and 4.5m). From Figure 14 and Figure 16, one observes an increase in length above 20m yields differential settlement that is either negative or

constant. For 32 piles with pile spacing of 4.5m, an increase of the length of pile did not reduce the differential settlement.

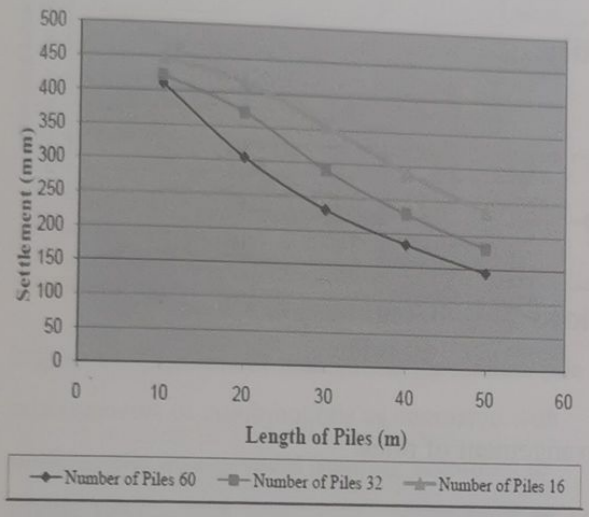


Figure 15: Variation of central settlement with length at the spacing of 4.5m.

Negative values of differential settlement are observed for 3.0m pile spacing for a pile number 60 and 80 (Figure 14). Figure 16 indicates that a negative differential settlement is observed for a pile number of 16 and spacing of 4.5m. Negative differential settlements are observed as a consequence of the raft and pile system. As the pile length increases, the raft area where piles are located becomes stiffer. If the piles are closely and have significant length, the unsupported raft that is around the edge act like a cantilever. Thus the edge of the raft settles more that the central part.

The load share between the raft and the piles as the length of piles increases was also studied. A maximum pile raft coefficient value of 67.75 was obtained for pile raft with 80piles which are spaced 3.0m. The study indicated that the coefficient increases with the length of piles.

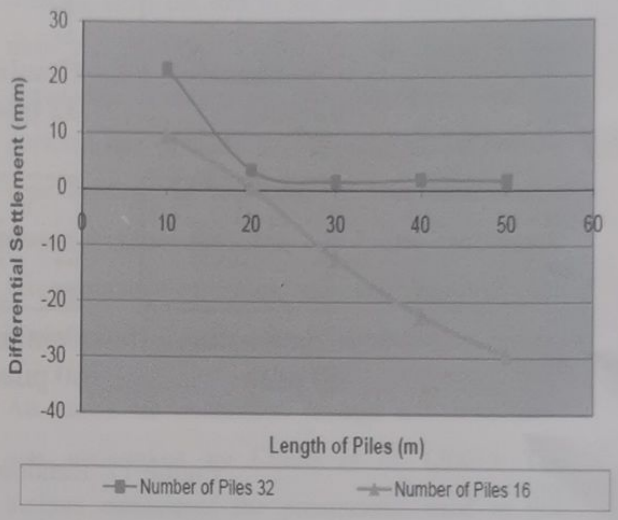


Figure 16: Variation of differential settlement with length at spacing of 4.5m.

d. Effect of geometric arrangement of piles on settlement.

In this part of the analysis, the settlements resulting from uniform and random arrangements of piles are investigated. Uniform and random arrangements of piles are defined as indicated pictorially in Figures 5 and 17.

Figures Figure 18 and Figure 19 show the results of the above combinations. For uniformly distributed piles, previous sections of analysis results are taken. These are the line graphs with spacing of piles 3.0, 3.5, 4.0 and 4.5. On the other hand, the results for randomly distributed piles are shown as dots on the same graphs.

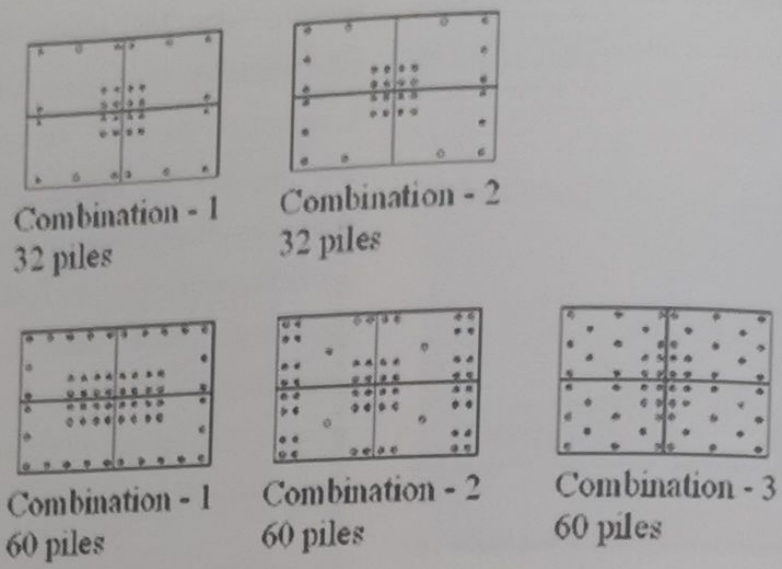


Figure 17: Random arrangement of piles

The results for randomly distributed piles cluster at one place for central settlement and are located lower than for uniformly distributed piles. For the differential settlement, however, the results are located above the uniformly distributed piles.

6. Comparison of results with literatures

According to the present investigation, an increase of raft stiffness results in reduction in both total and differential settlements. The maximum moment is observed to increase with raft thickness. Rabiei (2009) has studied and found out similar curves to that of Figure 8. Similar comments were made by Reul and Randolph (2004) where they clearly stated that increasing the thickness of the raft improves the performance of the raft with respect to settlement.

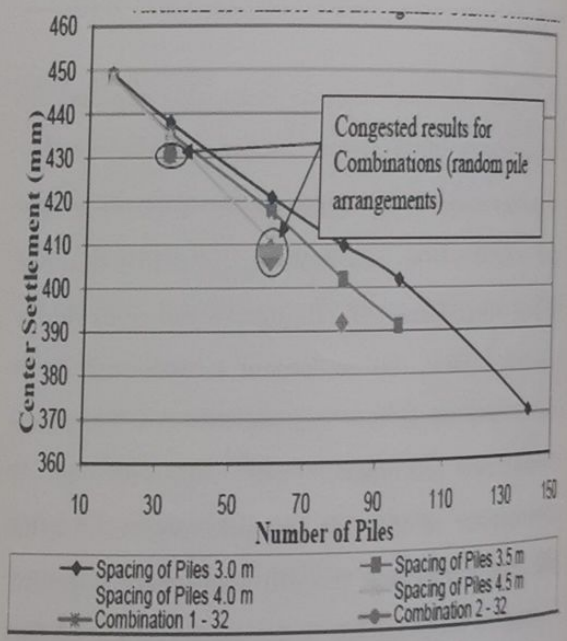


Figure 18: Central settlements for random pile arrangements or combinations as compared with uniform pile arrangement (naming according to Figure 17)

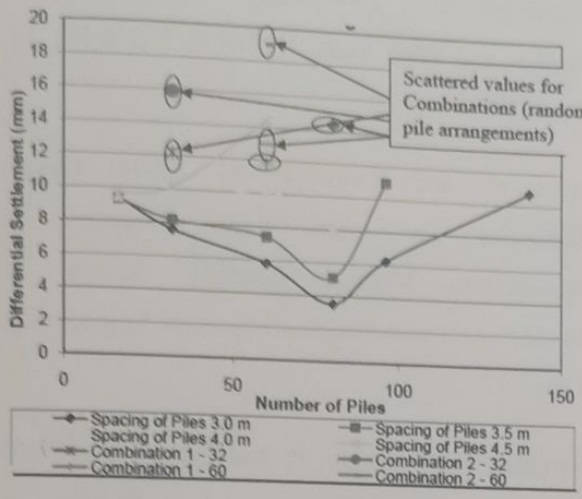


Figure 19: Differential settlements for random pile arrangements or combinations as compared with uniform pile arrangement (naming according to Figure 17)

The effect of pile number was also studied by investigation cited above. Increasing the number of piles results in reduction of the total settlement and differential settlement. Regarding the differential settlement, it was found out in the presented study, that a specified number of piles give minimum differential settlement for a given loading and thickness of raft. The variation in spacing also determines the stiffness in the piled raft system. But as predicted in this work and other literature, closely placing piles around the central area of the raft reduces the differential settlement significantly.

The effect of pile lengths is also studied by various investigators. Reul and Randoplh (2004), Sommers et al. (1995), Wittman & Ripper (1985) and Rabiei (2009). The results show that an increase in length of piles significantly reduce the total and differential settlements. It has been reported that the load transfer from the raft to the piles increases. It is also reported that the load transfer from the raft to the piles increases. It is also reported by Cunha, *et al.* (2001) that systematic arrangement of piles improves the performance of piled raft foundation for column type loading. In this study, it was clearly seen from Figure 18 and 19 that systematic arrangements of piles do not improve the performance of the piled raft foundation.

An economic evaluation though not conclusive was undertaken by Cunha *et al.* (2001). The authors considered the parameters, used in this investigation (number, spacing and length of pile, raft thickness, *etc*) for design options. The outcome of the work from these authors showed that reducing the number of piles or thickness of the raft has effect in the total cost of the piled raft system. The authors recommend that detail investigations to be made in order to come up with conclusive results with respect to the economics.

7. Conclusions

From the investigations conducted, the following conclusions could be made:

1. Both the stiffnesses of the raft and pile group have a major role in determining the total and differential settlement of the piled raft system.
2. Within the framework of this study, increasing the thickness of a raft has made a significant reduction both in total and

differential settlement but up to a thickness of 2.5m

3. There is a clear indication that central settlement decreases with an increase in pile length while the decrease in differential settlement is not sustained beyond a length of 20m.
4. From a uniformly loaded piled raft system, concentrating the piles at center gives small differential settlement but would increase the central settlement.
5. In line with the current and previous studies, random/strategic placing of piles (for example, around the edge and at the center) does not provide a consistent reduction of settlement as compared to uniformly distributed piles under the piled raft system.

8. References

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