ENGINEERING RESEARCH JOURNAL (ERJ)

Vol. 1, No. 48 Apr. 2021, pp 74-84

Journal Homepage: http://erj.bu.edu.eg

3D NUMERICAL STUDY ON THE BEHAVIOUR OF PILED RAFT FOUNDATION SYSTEM

Amr A. Radwan[1], Abdrady A. Hasen[2], Samir A. Gad[3], Kariman S. Deef[4]

[1]Professor, of soil mechanics and foundation, Faculty of Engineering, Helwan University, Cairo
[2, 3] Professor, of soil mechanics and foundation, Faculty of Engineering, Al- Azhar University, Cairo
[4] Assistant lecturer, Department of Civil Engineering, High Institute of Engineering, 15 May, Cairo

Abstract.

The piled raft system has proved to be a reasonable foundation system compared with the traditional pile foundation systems. However, there is a hesitation for considering the utilization of piled rafts on very loose sand underlain by inclined very soft soil due to limitations concerning insufficient bearing capacity and excessive settlement. Therefore, this study aims to describe the behavior of piled raft on very loose sand underlain by inclined soft clay layer varied between 3 m and 6 m using a 3D finite element approach. A series of numerical analysis was performed to study the behavior of the piled raft foundation system using various factors including raft thickness, pile length, and pile spacing, which are considered for an economical and effective design. The results showed that the length and spacing of piles might affect both bearing capacity and the settlement performance of the raft. In addition, increasing the pile length can decrease the settlement, but after reaching a certain length, the increase in pile length demonstrated the settlement tended to be insignificant. Therefore, to achieve an economic design, it is vital to consider the optimal pile length in the design of raft foundation model according to the allowable settlement.

Keywords: settlement; soft soil; pile length; 3D finite element approach; piled raft foundation.

1. INTRODUCTION

A piled raft is a system that serves as a composite structure including three load bearing elements such as raft, piles, and subsoil. Based on the piled raft foundation stiffness, the raft distributes the overall load of the structure as contact pressure, and over the piles at the ground. The concept of piled raft requires investigating several variables for studying the analysis behavior of models which simulate the real site conditions. The utilization of piled raft model can lead to reduce the differential and total settlement. Recently, in several applications, the utilization of raft foundation can induce high settlement which consider not applicable according to serviceability requests. Actually, placing piles in a regular way under the raft decreases the allowable settlement values and the bearing capacity of the whole foundation system can be improved (Maharaj and Gandhi, 2004). To date, the classical design approaches are utilized for pile groups leading to a higher piles numbers under the raft. According to the piled raft concept, the number of piles could be decreased.

Several scholars observed various methods for forecasting load-settlement behavior for the piled raft foundation (Poulos 2001; Horikoshi and Randolph 2001; Ta and Small 2006; Poulos and Bunce, 2008). Among these approaches, three classical methods are widely applied including: i) simplified analytical method, ii) approximate computer-based model, and iii) rigorous computer-based approach. Generally, the pile raft analysis is related originally to the pile group analysis. Reul (2004) suggested a numerical approach for studying the bearing performance of the piled raft on clay soil. Prakoso and Kulhawy (2001) implemented plane-strain analysis for studying the influence of foundation geometry on the differential and total settlement. Poulos (2001) performed two-dimensional numerical simulation by plate-on-spring theory for examining the effect of the piles numbers in a piled raft group, the pile length, and raft thickness on the bending moment in the raft. For understanding the design of piled rafts, numerical researches have been performed on the settlement behavior (Lee et al.2010: Cho et al.2012). However, the observed methods still have some limitations based on its accuracy and applicability in soft soil. Therefore, this work is performed for investigating the piled raft behavior on very loose sand underlain by inclined soft clay layer varied between 3 m and 6 m using a 3D finite element approach. To achieve this aim, several parameters related to pile group configuration such as pile length, pile spacing, and raft thickness are considered.

2. Methodology

In this study the parametric study and the analysis of piled raft foundation have been performed. The research is conducted based on an effective finite element model (Plaxis 3D software). Several parameters are considered from the features of the piled raft system. Based on their influence on the reaction of piled raft system, some parameters are chosen to be constant while others are changed. The soil properties that used in this study are observed in Table 1. Based on the changed parameters, raft thickness, pile length, and pile spacing were taken into consideration. This study includes a static analysis of a piled raft assistant high rise buildings and embedded in soil layers. The influence of pile group formations on the features of settlement for a piled raft are also considered. The pile group formation contains several factors such as the pile diameter, pile embedded length, the arrangement and number of piles, and the pile spacing. The process followed in the current study can be illustrated as follows:

- Physical characteristics of the model structural: establishment of three-dimensional numerical model of the structural system that includes (i) piles; (ii) raft and; (iii) soil. The superstructure is impassive and changed with the related uniformly load. Every portion in the system has been separately modeled. Then, every part was discretized into different finite element numbers.
- Load: The overall load performed on the model of structure is supposed to be uniformly distributed over the entire surface area of the raft. This kind of spread load is assumed for a rigid raft.
- Output: The modeling was established by the above mentioned conditions and analyzed through the finite element system (Plaxis 3D foundation) to determine and estimate the settlement of the structural system.

In this study a 20 m × 20 m raft with 0.5 m diameter piles was analyzed using software PLAXIS-3D. A finite element model was utilized to model the piled raft foundation. The piles and raft were proposed to be linearly elastic. The Mohr-Coulomb yield criteria was used to represent soil as elastic- perfectly plastic material. A multi-layer of soil with -3.5 m ground water table was assumed for this study. A drained condition was assumed and the total stress analysis was carried out. The various soil layers and material properties are tabulated in Tables 1. In addition, Figure 1 has been added to show the geometry of the applied piled raft foundation. Based on Figure 1, the soil material model for layers number 1, 3, and 4 were Mohr Coulomb, while layer 2 was Modified Cam Clay soil.

Table 1. The soil properties of this study

Parameter	Symbol	Layer one	Layer two	Layer three	Layer four
Layer description	---	Very loose sand	Very soft clay	Loose sand	Dense sand
Unsaturated unit weight	γ_{unsat}(kN/m^3)	15	15	18	19
Saturated unit weight	γ_{sat} (kN/m^3)	18	16	20	20
Young's Modulus	E (kN/m^2)	5000	---	15000	90000
Cohesion	C (kN/m^2)	0	12.5	0	1

Friction angle	ϕ	28°	0	30	40
Possion's ratio	υ	0.25	0.3	0.3	0.25
Dilation angle	----	0	0	0	10
Drainage Type	---	Drained	UnDrained	Drained	Drained
Material Model		Mohr-Coulomb	Modified Cam Clay	Mohr-Coulomb	Mohr-Coulomb

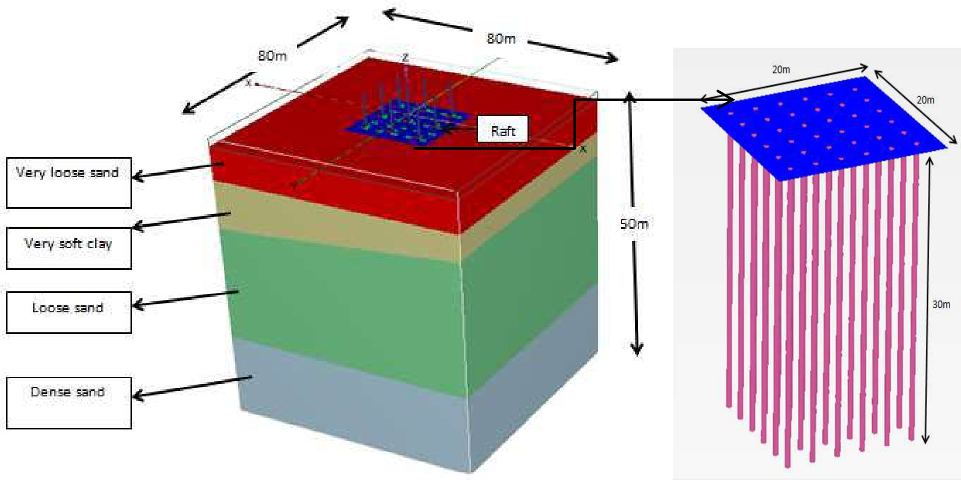

FIGURE1. 3D model of piled raft foundation

3. MATERIAL PROPERTIES

The elasticity modulus of raft and piles, E, was taken equal 3.0 x 10^7 kN/m^2. As shown in Table 2, the raft was modeled as a plate, with isotropic stiffness and the related input parameters were carefully considered. In addition, the piles were modeled as embedded piles with layer dependent shaft resistance and the input parameters are tabulated in Table 3. The procedure steps of the performed model are consist of four stages. These stages including initial stage, excavation stage, construction stage, and loading. The four stages are clearly described in in Table 4. To adapt these analyses, the geometry parameters are indicated in Table 5. As shown in this table, the raft thickness was varied from 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m.

TABLE 2. Raft properties used in this study

Parameter	Symbol	Raft
Unit weight	ɣ S(kN/m^3)	25
Young's Modulus	E (kN/m^2)	3 x 10^7
Possion's ratio	υ	0.2

Thickness	T (m)	2
Length-Breadth	L×B (m×m)	20×20

TABLE 3. Embedded pile properties that used in this study

Parameter	Symbol	pile
Unit weight	ɣ (kN/m³)	25
Young's Modulus	E(kN/m²)	3×10^7
Passion's ratio	ʋ	0.2
Diameter	D(m)	0.5
Length	L(m)	30

TABLE 4. Steps of the finite element analyses

Step	Description	Type
1. Initial phase	Initial stress state calculated	$K_{\circ}$ procedure
2. Excavation	Excavated up to -2m.	Plastic
3. Construction	Raft and Pile activated(i.e. constructed)	Plastic
4. Loading	500kPa distributed load is applied on raft	Plastic

TABLE 5. Geometry parameters that used in this study

Raft Size(L_R×B_R)	Raft Thickness (m)	Pile Diameter (m)	Pile Length (m)	Pile Spacing (m)
20m×20m	0.5,1.0, 1.5,2.0and 2.5	0.5	25,30 and 35	4d,6d,8d and 10d

4. MODEL VALIDATION

As the computer concerned with finite element approach has become one of the best satisfactory tools for analyzing the engineering problems using numerical methods of the structure response, it is essential to verify these analyses. Thus, in order to give support to the results obtained by the computer program, PLAXIS 3D software, three cases are taken for verification between Plaxis results with that of numerical result given by Karim et al. (2013).

The paper chosen for this comparison is performed on the results for piled raft analysis carried out by Karim et al. (2013). The performed simulation is implemented based on Mohr coulomb model, as shown in Figs. 2 to 4. The models which are accomplished by the finite element program with different formation of piles are shown in Figs 2, 3, and 4. Three models are analyzed by the finite element program which including raft only, raft with single pile, and raft with eight piles. As shown, the raft (concrete) is 10 m ×10 m with a thickness of 1 m. The soil at the site consists of soft clay with cohesion value of 25 kN/m², Poisson's ratio of 0.45, and modulus of elasticity value equal to 15000 kPa. After reviewing the results of the analyses (Figs. 2 to 4), it can be concluded that the results obtained from this study are close to the previous study which indicate that the PLAXIS results are applicable. To give a visual sense for the applied models, Table 6 has been added.

TABLE 6. The material properties and pile model for the verification numerical model

Material properties	Type of Layer	Cu(kN/m²)	υ	E(kN/m²)	ϕ(˚)
	Soft Clay	25.0	0.45	15000	0.0
Pile Model	Pile Diameter (D_p) (m)	Pile Length (L_p) (m)	Raft Width (B_r)(m)	L/D_p	L/B_r
	0.6	24	10	40	2.4

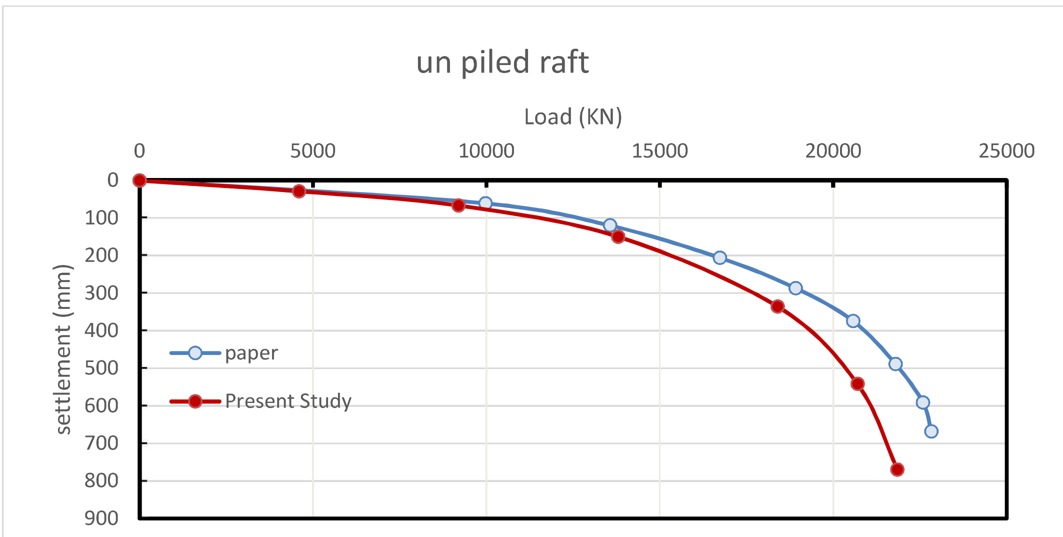

FIGURE 2. Comparison between load and settlement for un piled raft with size (10m x 10m) & (L=24m and D=0.6m).

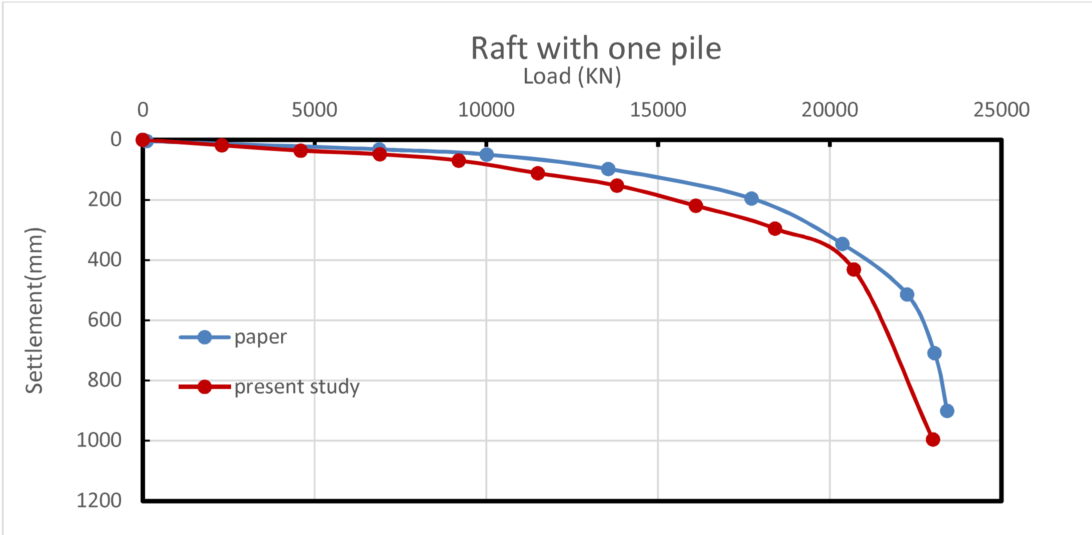

FIGURE 3. Comparison between load and settlement for piled raft (single pile) with raft size (10 m x 10 m) & (L=24 m and D=0.6 m).

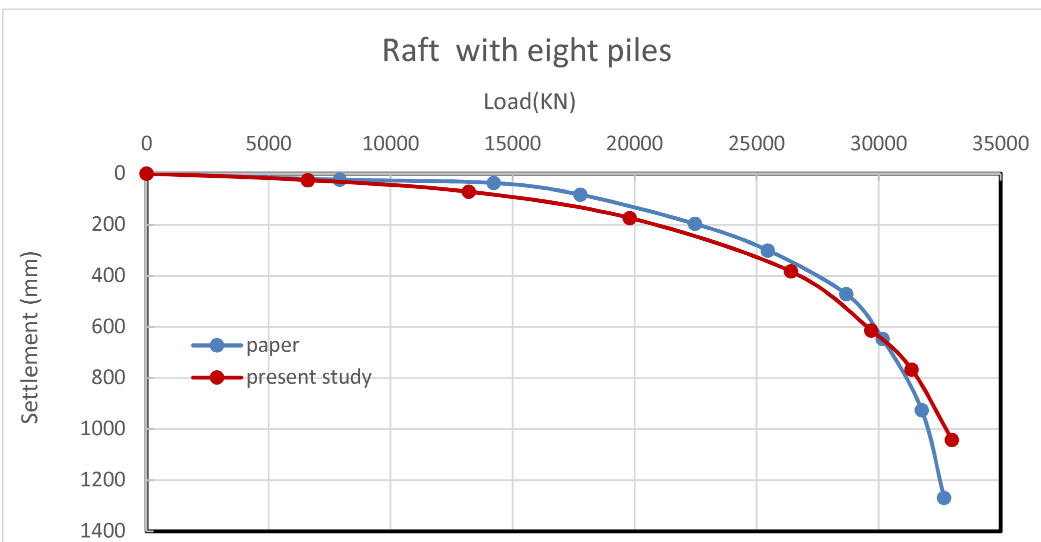

FIGURE 4. Comparison between load and settlement for piled raft (eight piles) with raft size (10m x 10m) & (L=24m and D=0.6m).

5. RESULTS AND DISCUSSION

5.1 Effect of Raft Thickness

In this model, the piled raft with 6 × 6 pile group was modeled for pile spacing 6 D from center to center and length equal 30 m. The applied load on the raft was 500kN/m^2. Based on Fig. 5, as the raft thickness was increased, normalized settlement was nearly constant. The decrease is more pronounced in case of differential settlement. The differential settlement between center to edge of piled raft decreased from 50 mm to 12 mm as the raft thickness changed from 0.5 m to 2.5 m respectively. Moreover, the settlement at the center increased from 66 m to 93 mm.

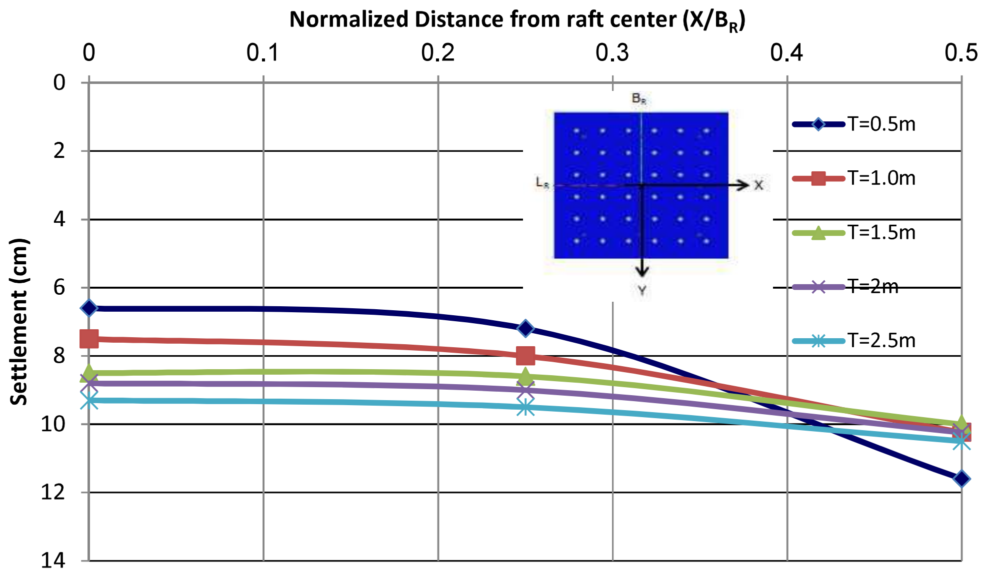

FIGURE 5. The settlement of piled raft foundation along the width of raft for various values raft thickness

5.2 Effect of Pile Spacing

The influence of pile spacing was analyzed for the piled raft foundation with fixed dimension of 20 m and pile length 30 m. The piles were 0.5 m in diameter. The pile spacing was taken as 4D, 6D, 8D, and 10D for the load intensity of 500kN/m^2. When the load was applied, the decrease in pile spacing had a clear effect on reducing the raft settlement. From Fig. 6, the variation in settlement with the change in pile spacing was observed. The settlement at the center of the raft was increased from 43 mm to 194 mm when the pile spacing increases from 4D to 10D, respectively, resulting in a significant variation.

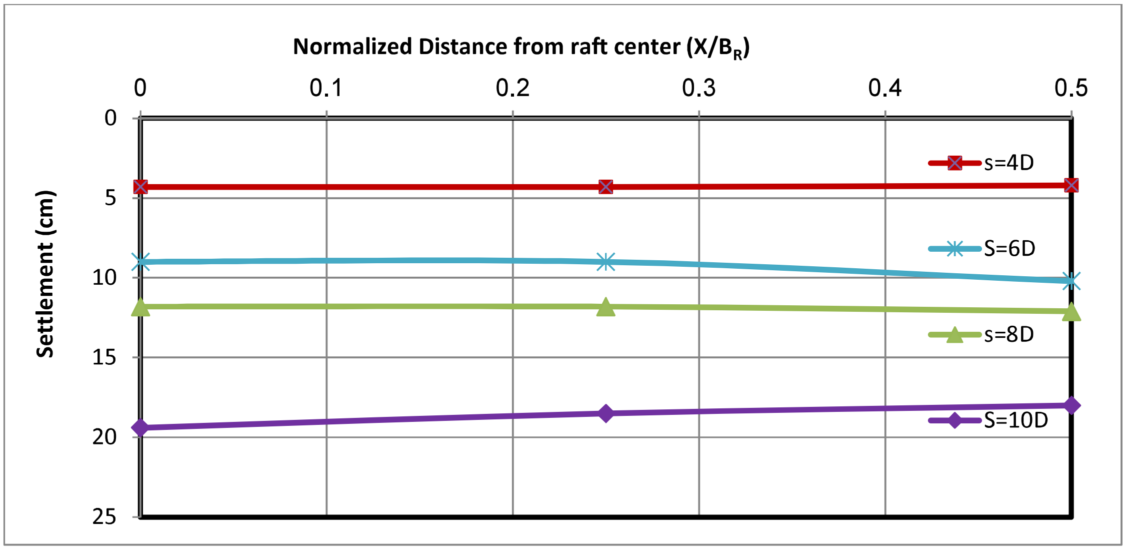

FIGURE 6. The settlement of piled raft foundation along the width of raft for various pile spacing

5.3 Effect of Pile Length

The influence of pile length on the piled raft was analyzed for the settlement of raft for three different lengths of piles including 2 5m, 30 m, and 35 m, respectively. In this analysis, the raft thickness was 2 m and the pile diameter was taken as 0.5 m for all pile lengths. Allowable load intensity of 500kN/m^2 was applied for all lengths. The effect of pile length on the settlement of piled raft under allowable load is shown in Figs. 7 to 9. It can be observed that the overall settlement of the foundation can be decreased as the pile length was increased for all pile spacing. As shown from Figs. 7-9, it can be illustrated that the settlement at center of piled raft was decreased from 62 mm to 31 mm when the pile length increased from 25 m to 35 m, respectively. In addition, a significant change is observed in settlement but a similar trend was not found out for the center-edge differential settlement. The differential settlement was negligible as the pile length increased from 25 m to 35 m. It can be concluded that by increasing pile spacing the settlement increase at the same pile length.

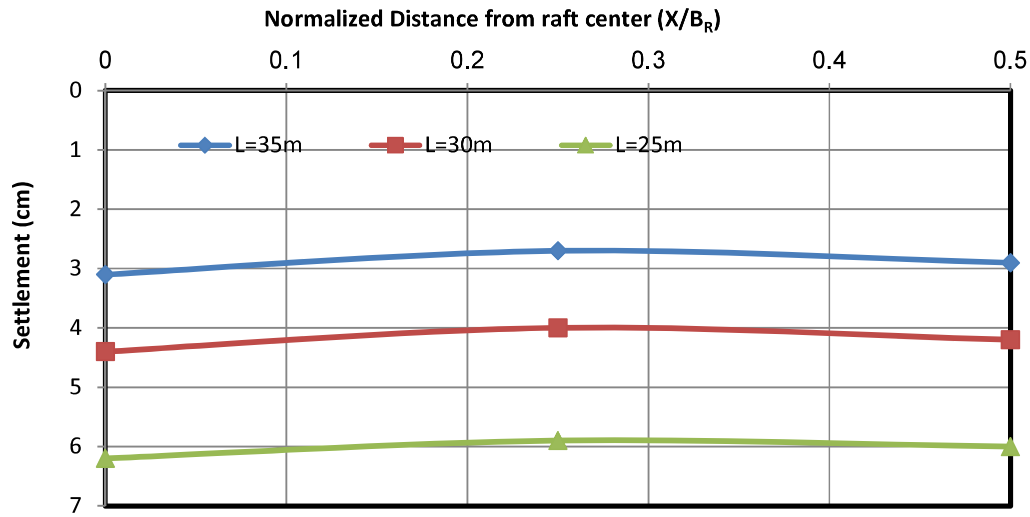

FIGURE 7. The settlement of piled raft foundation along the width of raft for various pile length at pile spacing 4D

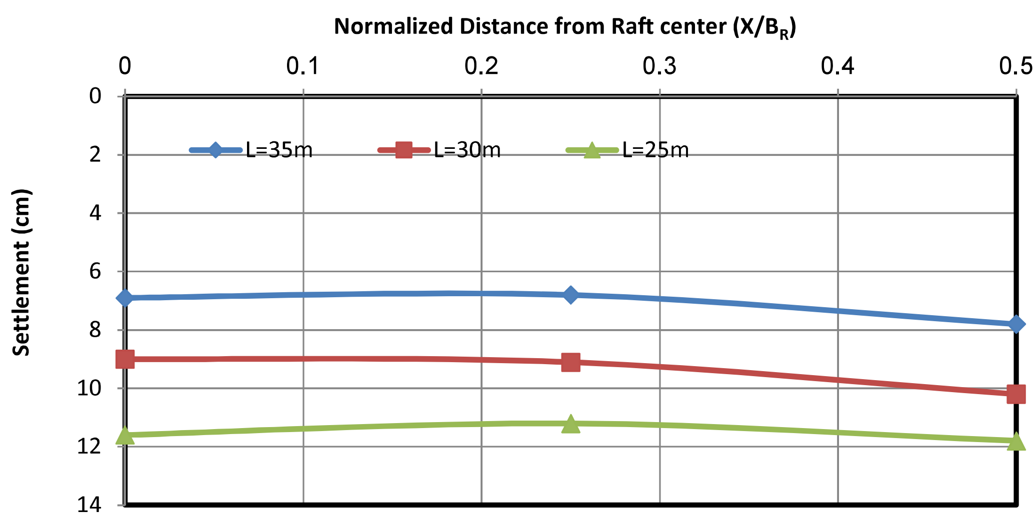

FIGURE 8. The settlement of piled raft foundation along the width of raft for various pile length at pile spacing 6D

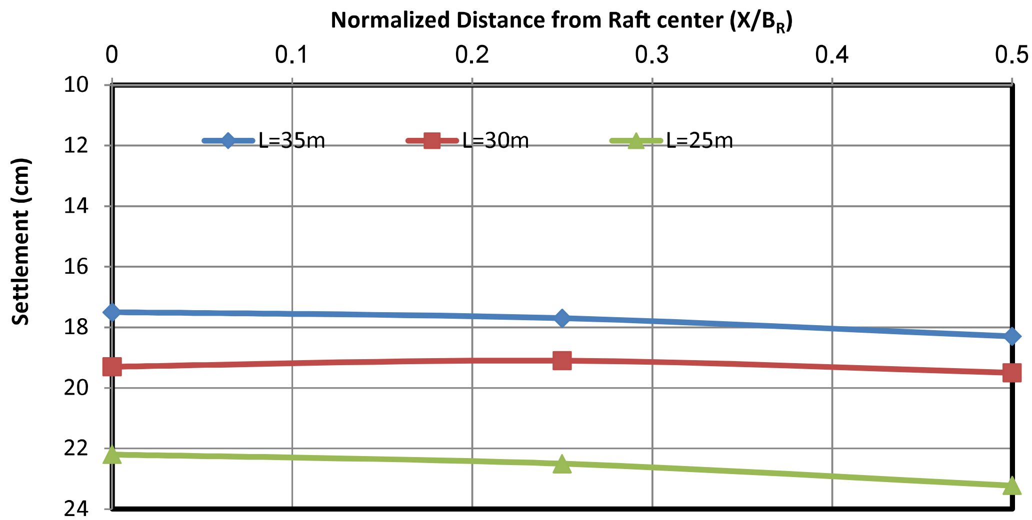

FIGURE 9. The settlement of piled raft foundation along the width of raft for various pile length at pile spacing 10D

6. CONCLUION

This paper discussed the displacement based design approaches for piled raft foundation where the piles are used to minimize the settlement. The analysis of the vertically loaded piled raft has been conducted using the nonlinear plane strain finite element models. From the result of analysis the main conclusion are as follows.

1-Increasing the raft thickness from 0.5 m to 2.5 m increases the settlement at the center of the piled raft from 66 mm to 93 mm with percentage of 29%.

2-The thickness of raft has a significant influence on the differential settlement. The increase of raft thickness decreases the differential settlement.

3-The pile spacing is a factor which has a major influence on both settlement and differential settlement. The results showed that the settlement increases by increasing the pile spacing from 43 mm to 194 as percentage of 77.8%. The differential settlement increased from 1 mm to 14 mm in case of center to edge differential settlement as the pile spacing changed from 4D to 10D, respectively.

4-The settlement of the piled raft foundation decreased with increasing the pile length. When the pile length varied from 25m, 30m, and 35m, the overall settlements were 62 mm, 44 mm, and 31 mm, respectively.

7. REFERENCES

Cho, J., Lee J., Jeong, S., and Lee J. (2012). The settlement behavior of piled raft in clay soils, Ocean Eng., pp. 153 - 163.

Horikoshi, K., and Randolph, M.F. (2001). Optimum Design of Piled Raft Foundations. Proceeding of International Conference on Soil Mechanics and Foundation Engineering, 2, 1073-1076.

Karim, H. H, AL-Qaissy M. R., and Hameedi, M. K. (2013). Numerical analysis of piled raft foundation on clayey soil. Eng. &Tech .journal , vol. 31, no. 7, pp. 1297-1312.

Lee, J., Kim, Y., and Jeong, S. (2010). Three-dimensional analysis of bearing behavior of piled raft on soft clay,Computers and Geotechnics, 37, pp. 103-114.

Maharaj, D. K., and Gandhi, S. R. (2004). Non-linear finite element analysis of piled-raft foundations, Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 157, pp.107-113.

Prakoso, W. A., and Kulhawy, F. H. (2001). Contribution to piled raft foundation design, J. of Geotech. Geoenv. Eng., 127(1), pp. 17-24.

Poulos, H. G. (2001). Methods of analysis of piled raft foundations. TC 18 Rep., International Society of Soil Mechanics and Geotechnical Engineering, London.

Poulos, H.G., and Bunce, G. (2008). Foundation design for the Burj Dubai – the world's tallest building, 6th International Conference on Case Histories in Geotechnical Engineering, 1-47.

Reul, O. (2004). Numerical study of the bearing behavior of piled rafts, Int. J. Geomechanics, 4(2), pp. 59-68.

Ta, L.D., and Small, J.C. (2006). Analysis of piled raft systems in layered soils. International Journal for Numerical and Analytical Methods in Geomechanics, 20(1), 57.