ENGINEERING RESEARCH JOURNAL (ERJ)
Vol. 1, No. 48 Apr. 2021, pp 85-96
Journal Homepage: http://erj.bu.edu.eg

Behavior of piled raft foundation of piles breakthrough inclined soft clay layer

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

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

Abstract

Piled raft foundations are successfully utilized for supporting structures in different soil layers and can provide safe bearing capacity and serviceability requirements. However, the performance of the piled raft in inclined soft clay layers still remains a challenging problem during analysis. This study aims to investigate the behaviour of piled raft as a foundation system for piles breakthrough an inclined soft clay layer. To achieve this aim, the numerical analysis is conducted on the piled raft foundation through three dimensional finite element modelling. The utilized soil profile in this research consist of four layers the top layer is very loose sand underlain by inclined soft clay layer varied thickness from 3 m to 6 m underlain this layer loose and dense sand. The numerical analyses are applied for studying the effects varied pile length below soft clay, equal pile length below soft clay layer and pile diameter on the settlement and load carrying capacity of piled raft foundation system.. Results show that the settlement is decreased by increasing pile length. Furthermore, the layout of pile has a clear influence on both location and value of maximum settlement for piled raft foundation.

Keywords: finite element method, compressible layer, piled raft foundation, settlement.

1. Introduction

To construct a high rise structure that includes number of basements, raft foundation is usually selected for supporting the entire system. If the soil is very weak, raft on piles foundation structure is utilized to transfer the load to deep bearing layers. To construct a structure on a deeply extended non-bearing layer, it is ineffective and uneconomical way to utilize long piles for reaching the bearing layer. Therefore, a piled raft foundation structure is one of the widely cost-effective foundation structure that can be used. In several countries, piled raft foundation has been utilized for supporting various kinds of structures in several soil layers. Specifically, the utilization of piled raft foundation in the developed urban areas has more common than other public regions. Piled-raft foundations have several benefits such as increasing the bearing capacity and decreasing settlement of the foundations. These benefits are based on the involvement of the raft to the load bearing capacity and to the efficient utilization of the piles for reducing the settlement.

Recently, several types of structures have been established using piled raft foundation such as high-rise building systems and bridges. Piled raft is considered as a composite structure, which integrates the bearing capacity of both pile and raft. Abdel-Azim et al. [1] stated that the behaviour of piled raft depends on the interaction among several conditions including pile with raft, pile with soil, and raft with soil. To achieve an accurate design, the foundation system needs to satisfy two criteria: 1) the foundation should adequate the allowable bearing capacity, 2) the settlement should within allowable limits. Excessive settlement of foundation not only affects the stability of its superstructure but also can damage the already existing surrounding buildings Butterfield and Banerjee [4]. Therefore, the settlement of foundation is usually treated as a secondary design criterion which considers inappropriate in case of a raft foundation, Randolph

[3]. Because of the lack of conventional design methods, the piled raft foundation system adapts the piles to carry the whole superstructure load without considering the contribution of raft which resulting in more appropriate design Horikoshi and Randolph [5]. To understand the performance of piled raft, Cooke [2] reported that the overall settlement has a limited effect on the performance of the building comparing with differential settlement. Horikoshi, and Randolph [5-6] suggested an approach to study the overall settlement and to reduce differential settlement. To date, several research have studied the behaviour of piled raft on stiff soil Poulos et al [7], however the behaviour of piled raft foundation through inclined soft clay soil is limited [8-10].

The present paper investigates the influence of equal and varied pile length below soft clay, piles number on the differential and total settlement behaviour of piled raft. The role of each parameter in controlling the overall settlement and differential settlement of foundation is clearly investigated using a finite element Plaxis program.

2. Methodology

2.1 Finite element modelling

Among several numerical approaches, finite element model is widely used in several geotechnical engineering projects. In this work, Plaxis software package is utilized for the three dimensional finite element approach for piled raft foundation. Through this study, a 20 m × 20 m raft dimension and 0.5 m pile diameter was analysed using PLAXIS-3D software. The finite element analyses were utilized to model the piled raft foundation. To simulate this model, the interaction of structural among the piles and the raft are adapted as rigid connection without sliding in the interface. Through the analysis, piles and raft are modelled as a linear elastic material. The elastic ideal plastic constitutive approach with a Mohr Coulomb yield criterion is selected for modelling the nonlinear stress-strain performance of the soil element. A multi-layer of soil with -3.5 m ground water table was utilized in this study. The soil properties that used in this study are indicated in Table 1. This table shows the properties of four layers including very loose sand, soft clay, loose sand, and dense sand.

Table1. Soil properties that used in this study

Parameter	Symbol	Unit	Layer one	Layer two	Layer three	Layer four
Layer description	---	---	Very loose sand	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

The raft was simulated as a plate with isotropic stiffness and the input parameters of the established model are presented in Table 2. Moreover, the piles were modeled as embedded piles with layer dependent shaft resistance and the related input parameters are presented in Table 3.

Table 2. Raft properties used in this study

Parameter	Symbol	Unit	Raft

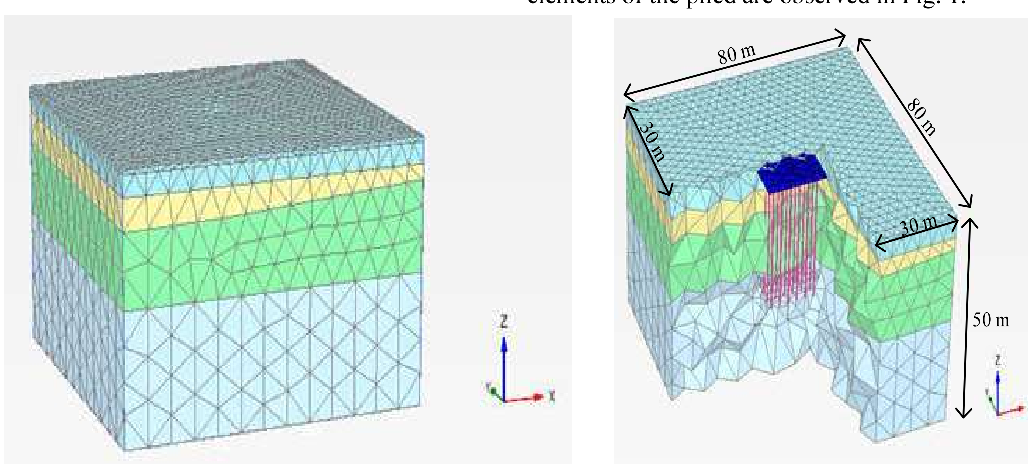
Material Model	--	Linear-Isotropic	
Unit weight	ɣ	kN/m³	25
Young's Modulus	E	kN/m²	3×10^7
Possion's ratio	υ	---	0.2
Thickness	T	m	2
Width-Breadth	L × B	m²	20 × 20

Table 3. Embedded pile properties used in this study

Parameter	Symbol	Unit	pile
Material Model	---	---	Linear-elastic
Unit weight	ɣ	kN/m³	25
Young's Modulus	E	kN/m²	3×10^7
Possion's ratio	υ	---	0.15
Diameter	D	m	0.5

2.2 Mesh design and boundary condition

To design the mesh pattern, the raft and soil elements are simulated as 15 node wedge elements and the circular pile is simulated by way of the triangular prism element. Recent researches on finite element techniques illustrated that the mesh pattern and the element size could obviously effect on the results and accuracy that need to be considered while adapting the finite element area. To analyse our work, Also, the reasonably medium mesh is used. With regard to the boundary condition, all nodes in the bottom of the soil are constrained for any type of rotation and translation. Furthermore, for minimizing the influence of the boundary conditions on the distribution of stresses, the horizontal boundary is preserved four times the width of the raft. Also, the vertical boundary condition is preserved two times the width of the raft and from one to third times the length of the pile (L/3). The mesh pattern adapted at various elements of the piled are observed in Fig. 1.



(a) (b)

Figure 1. Finite element mesh of model system: (a) soil layers before adding pile raft foundation; (b) the soil layers with the pile raft foundation.

3. Validation of the model

The major benchmark that requires to be achieved while conducting any numerical analysis is to examine the compatibility of the proposed approach with a numerical or experimental model. To verify the results, the applied numerical models using Plaxis is matched with an available work on numerical analysis performed by Karim et al. [11]. Thus, in order to give support to the results obtained by the computer program (PLAXIS 3D), four cases are taken for verification between Plaxis results of this study and the previous numerical results given by Karim et al. [11]. The material properties and pile model for the numerical model are shown in Table 4. The established models are performed in Mohr coulomb model and the raft (concrete) dimensions are 10 m ×10 m ×1 m. The soil at the site consists of soft clay with cohesion 25 kN/m^2, Poisson's ratio of 0.45 and modulus of elasticity 15000 kPa. After reviewing the results of the analysis (Fig. 2), it can be concluded that the results of this study are in acceptable range with the previous study indicating the good ability of the established models. The models which are performed by the finite element program with different configuration of piles are shown in Fig. 2. As shown, four models are analysed by the finite element program including (a) Raft only, (b) Raft with single pile, (c) Raft with two piles (2×1), and (d) Raft with eight piles (4×2). The soil is modelled as Mohr Coulomb. One layer of soft clay is used. A shown in Fig. 2, the relations between the load and settlement for un-piled, single pile, two piles, eight piles with raft with size (10 m×10 m) and (L=24 m and D=0.6 m) is observed. It is noteworthy to mention that the relation between the analyses of current study and previous literature is satisfied.

Table 4. Material properties and pile model used for the verification of the numerical model.

Material properties	Type of Layer	Cu(kN/m^2)	υ	E(kN/m^2)	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

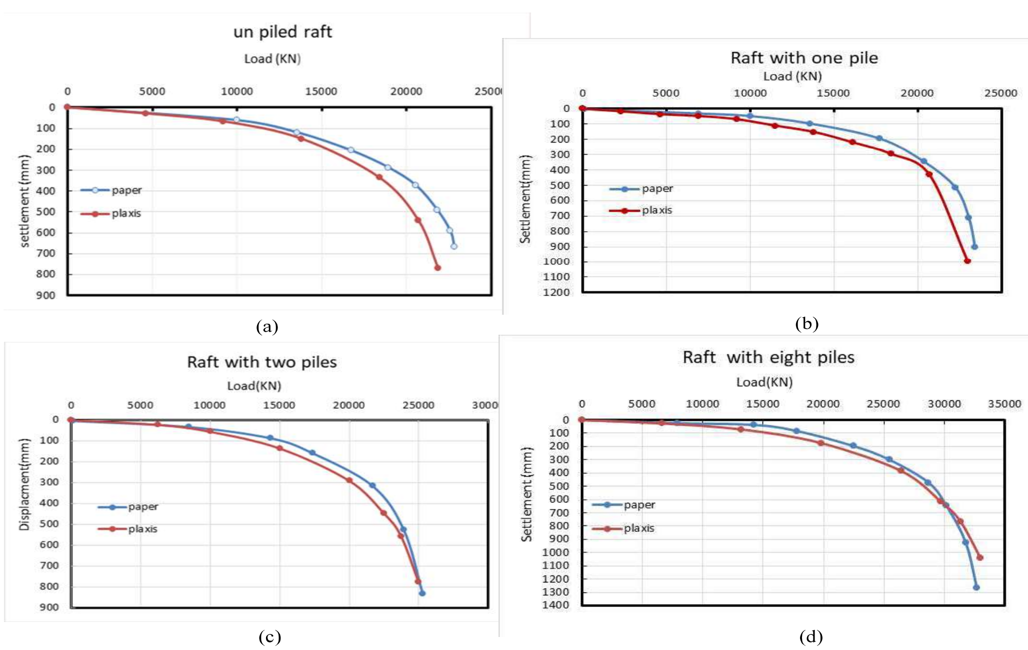


Fig. 2, The relations between the load and settlement: (a) un-piled, (b) single pile, (c) two piles, (d) eight piles with raft with size (10 m×10 m) and (L=24 m and D=0.6 m).

4. Parametric study

The major aim of the parametric study is for investigating the piled raft behaviour under changing the geometry dimensions. Therefore, several cases for parametric study are observed. Specifically, the varied and equal pile length below soft clay, pile diameter , and type of soil . Details of piled raft and pile groups in this study are described below and summarizes in Table 5.

Table 5. Details of piled raft and pile groups.

Case	Varied Geometry	Raft Dimensions		Pile Group Geometry		
		Width× Length(m)	Thickness(m)	Pile spacing	No. of piles	Pile length(m)
1	Pile length	20×20	2	4D	10×10 = 100	25, 30, 35
				6D		
				10D		
3	Variable and equal pile length below soft clay	20×20	2	6D	5×5 = 25	10D
						20D
						25D
						30D
4	Pile diameter	20×20	2	6D	5×5=25	0.5
						0.6
						0.7
						0.8

D is the pile diameter = 0.5 m

5. Results and discussion

In the present study, the behavior of piled raft foundation system has been studied and the influence of the essential factors including pile length, and number of piles breakthrough compressible layer is studied. These parameters have been adapted to develop an economical and effective design methodology for reducing differential settlements with an eventual increase of total settlement. Therefore, the numerical analyses have been conducted to study the maximum and differential settlement of pile-raft foundation through inclined soft clay soil.

5.1 Effect of pile length

The effect of pile length on the piled raft was studied for the settlement of raft for three different lengths of piles including 25 m, 30 m, and 35 m. Through this analysis, the pile diameter was taken 0.5 m for all pile lengths and raft thickness was taken as 2 m. Allowable load intensity of 500kN/m^2 was applied for pile groups of length 25m, 30m and 35 m. The effect of pile length on settlement of piled raft under allowable load is shown in Figure 3. It can be seen that the settlement of foundation decreased as the pile length was increased at various pile spacing. The maximum settlement at centre of piled raft decreased from 6.2 cm to 3.1 cm representing 50% of 4D pile spacing. The decreased value 4.7 cm as percentage of 40.5% at pile spacing 6D and 21% at pile spacing 10D can also be observed. This is as a result of the increase in the number of pile, where in case of a distance 4D, 6D, 10D the number of piles was 100, 36 and 16 respectively .Fig. 4 shows the relation between the pile length and the differential settlement for different spacing. As seen from this figure, by increasing the pile length, the settlement obviously decreased. Then, the differential settlement becomes negligible for the lengths between 30 m and 35 m.

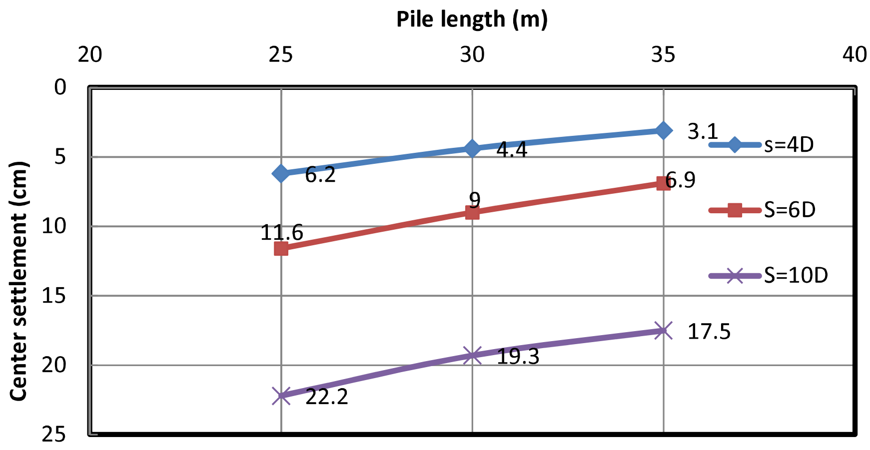


Figure 3. Raft settlement at center for various pile lengths for spacing (4D, 6D, and10D).

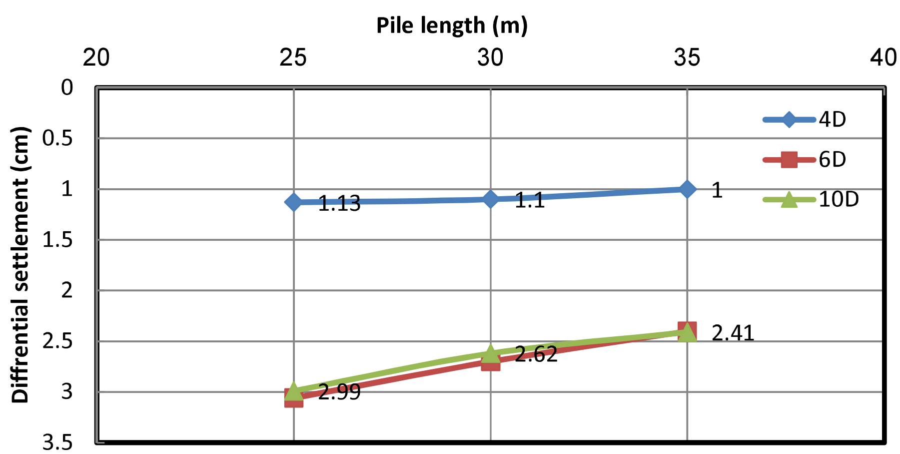


Figure 4. Raft differential settlement for various pile length at spacing (4D, 6D, and10D).

Figure 5 shows the load distribution percent between pile and raft based on various pile lengths. As seen, the piles have been taken more percent of load because piles have more pile load by increasing the pile length. But it was recognized that even pile length increased from 25m to 35m the load carrying percent increased about only 4.5 percent.

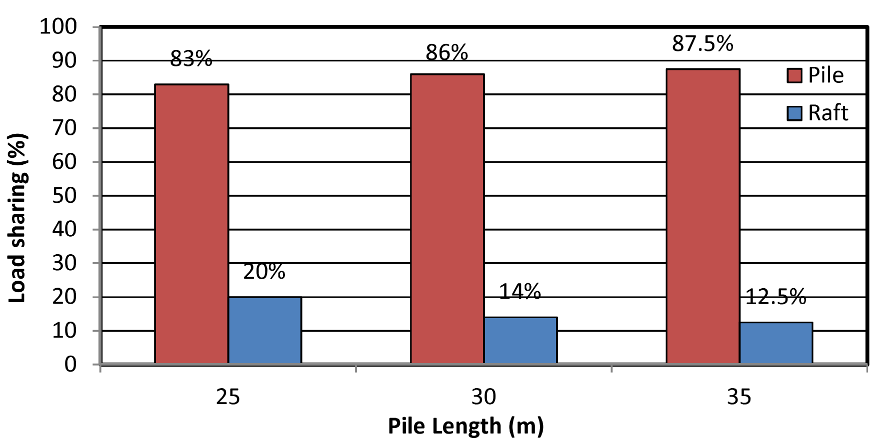


Figure 5. Distribution percentages of load between raft and pile due to pile length

5.2 Effect of the variable pile length under soft clay layer

The location of soft clay layer could also have a significant effect on the behavior of the piled raft. Figure 6 shows the settlement of raft for different embedded pile lengths below soft clay including 10D, 20D, 25D, and 30D where D represents the pile diameter which is taken as 0.8m. When the embedded pile length increased from 10D to 30D, the settlement decreased from 42.3 cm to 7.3 cm, respectively. Eventually, it can be concluded that the settlement reduces by increasing the pile length beneath the soft clay layer. Furthermore, after the embedded pile length reaches 25 D there is no effect on the settlement this is due to the penetration of piles into the layers of dense sand, which lead to an increase in the bearing capacity of the pile due to the increase in friction and end bearing.

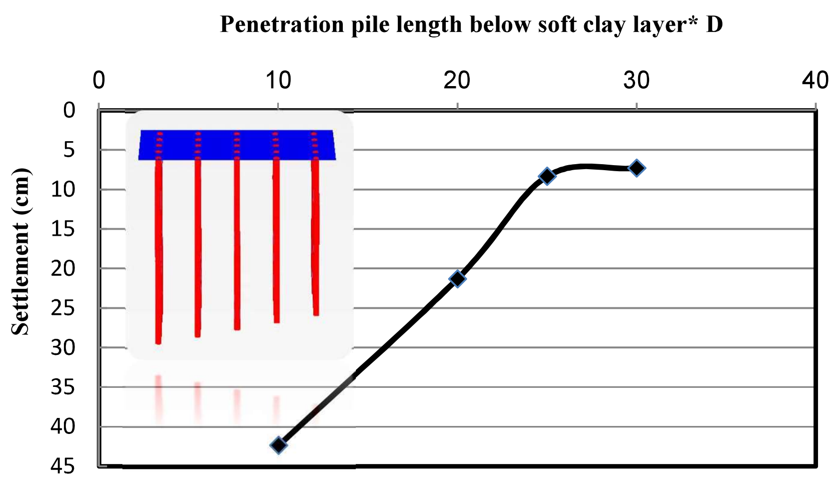


Figure 6. The relation between the settlement and the penetration pile length below soft clay layer at center of raft.

5.3 Relation between the equal and variable pile lengths below raft foundation

Figure 7 shows the effect of the equal and variable pile lengths below raft foundation on the settlement values, where the distance between piles are 6D. As seen from this figure, the fixed length of the pile are considered in the first stage where the embedded equal pile lengths below soft clay of 10D, 20D,25D and 30D. and the second stage is considered for the variable piles lengths of 10D, 20D, 25D, and 30D, below soft clay soil. It can be concluded that after penetration pile length equal 25 times of pile diameter there is no effect in decreasing settlement between the variable and equal pile length, thus due to the breakthrough of the piles into the dense sand Layer.

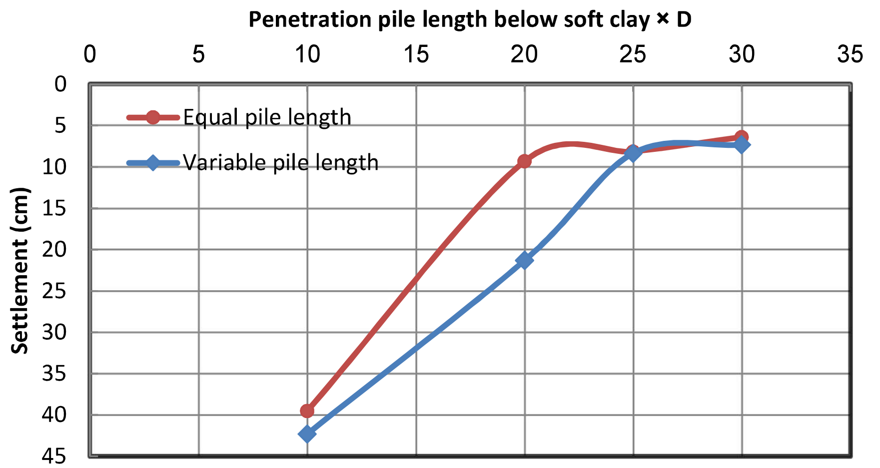


Figure 7. The relation between the settlement and the penetration pile length below soft clay layer and equal pile lengths.

5.6 Effect of variable and equal penetration pile length for different type of soils below soft clay

In this section, the effect of penetration pile length was conducted on piled raft foundations for different densities of soils including loose, medium and dense sand and. These types of soils were adapted for different angles of internal friction including 30, 34 and 40 ° respectively, which underlain below soft clay layer. The properties of layers including very loose sand, loose sand, and dense sand are presented in table 6. The raft thickness was fixed as 2m while the remaining parameters and geometry were remained as same as described in previous section. Figure 8 presents the result of these different densities in the form of the penetration pile length below soft clay. Based on this figure, it can be noted that the settlement decreased rapidly by increasing the angle of shearing resistance from 30˚ to 35˚, respectively. As seen from the curves at 25D of the pile that the same value of settlement is observed in all cases, which the pile diameter (D) is taken as 0.8m. Furthermore, there is no clear effect on settlement values in case of variable and equal lengths, and thus the use of variable length is more economically, especially on large scale.

Table 6. Soil properties that used in this study

Type of soil	Unsaturated unit weigh (KN/m^3)	saturated unit weigh (KN/m^3)	Young's Modulus (KN/m^2)	Cohesion (KN/m^2)	Friction angle	Possion's ratio
Loose sand	18	20	15000	1	30	0.3
Medium dense sand	18	19	40000	1	34	0.3
Dense sand	19	20	90000	1	40	0.25

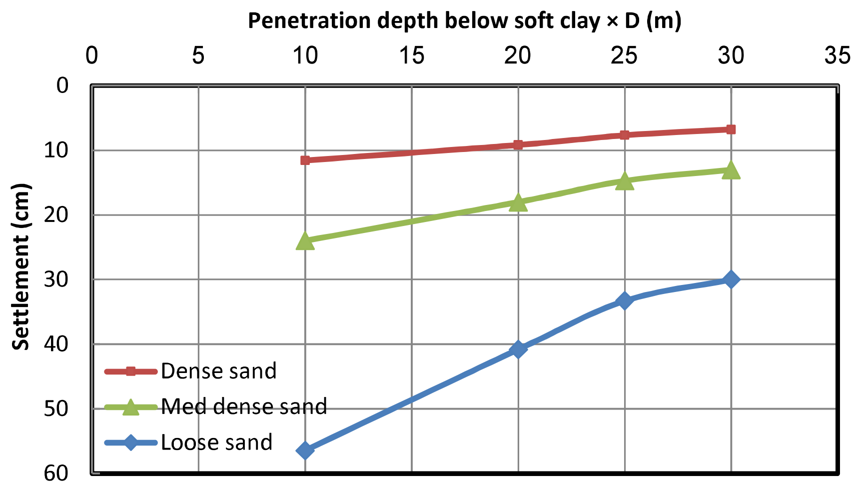


Figure 8. Effect of penetration pile length below soft clay layer on the settlement at loose, medium sand and dense sand.

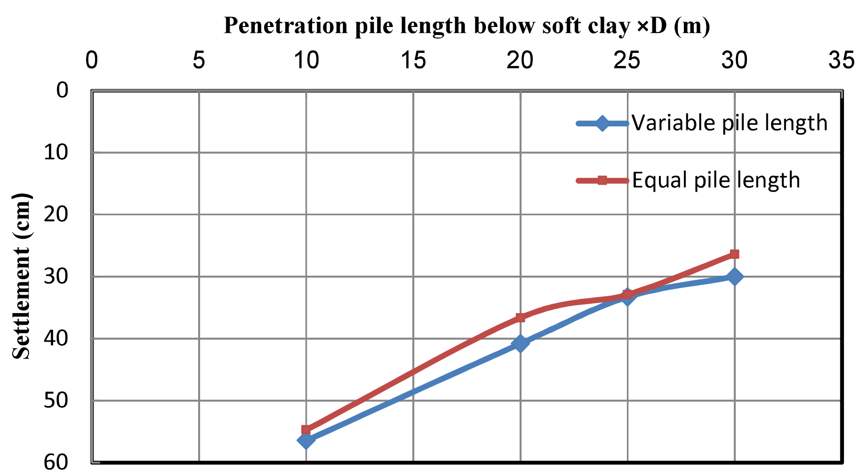


Figure 8(a). Effect of penetration pile length below soft clay layer on the settlement ***in case of loose sand***

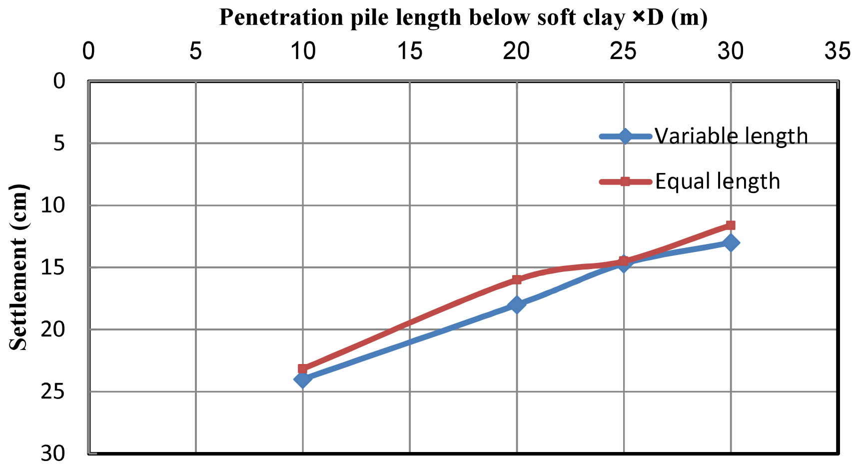


Figure 8(b). Effect of penetration pile length below soft clay layer on the settlement ***in case of medium dense sand***

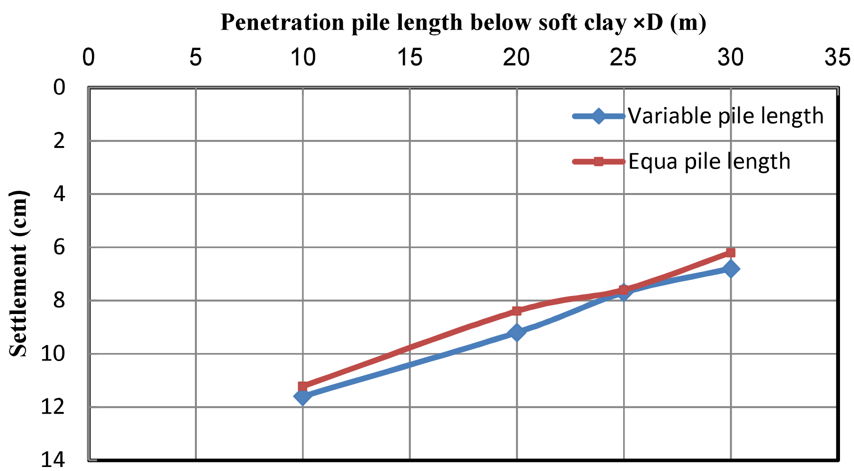


Figure 8(c). Effect of penetration pile length below soft clay layer on the settlement ***in case of dense sand***

5.7 Effect of pile diameter

The effect of the pile diameter on the settlement of piled raft foundation supported by 5×5 pile group was observed in Figure 11. It can be seen that by increasing the pile diameter from 0.5 m to 0.8 m, the settlement decreased from 13.8 cm to 8.1cm, respectively. This small effect on the piled raft foundation supported by 5×5 pile group is similar to the previous study of Seo et al [12]. Thus, it can be concluded that the pile diameter has a small effect on the settlement behaviors.

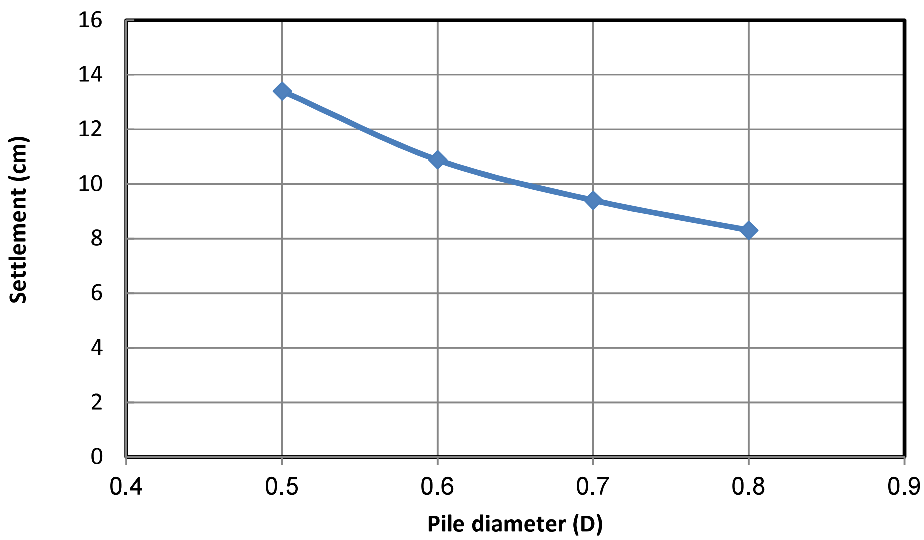


Figure 11.

Effect of pile diameter on the settlement.

6. Conclusions

This study investigates the performance of numerical analyses of the piled raft foundation on inclined soft clay layer using three dimensional analysis. The conclusions of this study are indicated as follows:

1- Results indicated that the settlement reduces by increasing the pile length beneath the soft clay layer. Otherwise after penetration pile length equal 25 times of pile diameter there is no effect in decreasing settlement between the variable and equal pile length, thus due to the breakthrough of the piles into the dense sand Layer.

2-The settlement behavior of pile raft foundation is also affected by pile spacing. Therefore, the increase of pile spacing resulting in increased the settlement. When, the pile length increases from 25 m, 30 m, and 35 m, the settlement decreases as parentage of 50%, 40.5%, and 21%, at pile spacing 4D, 6D, and 10D, respectively.

3- The settlement of the raft decreases with the increase of the angle of shearing resistance and pile diameter

4- The results showed that when using a different density of sand, it is at 25 penetration pile length below soft clay which gives the same value in settlement in case of equal and variable length this due to the same value of the load distribution between raft and piles.

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