EFFECT OF CHANGING CONFIGURATIONS AND LENGTHS OF PILES ON PILED RAFT FOUNDATION BEHAVIOUR

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ABSTRACT

Piled raft foundation is an economical foundation system where the bearing capacity of the raft is taken into consideration in supporting the loads from superstructure. The piles in a piled raft system are used to enhance the bearing capacity of the raft and also to control settlement, especially differential settlement and hence, these piles are commonly known as ''settlement reducing piles''. Therefore, piled raft is a technically competent foundation system and offers significant savings in terms of overall foundation cost as compared to conventional piled foundation. This is because conventional piled foundation usually ignores the contribution of the raft and assumes the loads are supported entirely by the piles. However, the use of piled raft foundation system requires careful design and analysis as it involves complex interactions. In this paper nonlinear 3D finite difference analysis was carried out to model the piled raft problems using the commercial software FLAC3D. In order to check the validity of the proposed numerical modelling a back-analysis was made for a case study. A comprehensive parametric study was performed on a hypothetical square piled raft over three clay soil profiles with different degrees of stiffness. The variation was made in number of piles, length of piles and distribution of piles over the raft area. The effect of these variables upon the average settlement and differential settlement was studied.

KEYWORDS

Piled raft foundation, clay soil, 3D modelling, finite difference analysis

1. INTRODUCTION

Piled raft foundation is a piled foundation that implements the piles as elements used for enhancing the behaviour of the raft to satisfy the design requirements, and they are not considered as carriers for the total structural load. The design requirements may be related to the settlement control or increasing the ultimate bearing capacity of the foundation. Since the main purpose of the piles in the majority of piled foundations is to limit settlement, then the piles in the piled raft will serve mainly as settlement reducers. The concept of settlement reducing piles firstly proposed by Burland et al. [1] leads to the use of limited number of piles beneath the raft to reduce settlement (total and/or differential) with a low cost compared to traditional pile foundation. Randolph [2] has discussed the importance of focusing upon settlement issues rather than capacity in the design of piled foundations. Also Randolph [2] has reviewed some analytical approaches for estimating the stiffness of pile foundations systems. The piled raft foundation has a complex behaviour involving different interactions between its various components. Therefore, a proper analytical model is needed to evaluate these interactions. Numerical methods, which are approximate, have been developed widely in the last two decades because numerical methods are less costly and may be used to consider many kinds of different soil and foundation geometries compared to field and model tests.

According to Poulos [3], there are three broad classes of numerical analysis methods: (1) simplified calculation methods, (2) approximate computer-based methods and (3) more rigorous computer-based methods. He also noted that the most feasible method of analysis is the 3D linear/nonlinear finite element or finite difference methods. Recently nonlinear 3D finite element and finite difference analyses have been conducted [4,5,6,7,8]; however, modeling problems related to the soil–structure interface still remain in the 3D finite element and finite difference analysis. The great challenge in the numerical methods is the choice of proper input parameters to give reasonable output results. The procedure of choosing right values for the input parameters can be adjusted by making back analysis for well documented case histories.

Therefore, the overall objective of this study focuses on investigating the behaviour of the piled raft foundation system in clay by changing of some parameters as:- Piles' number, length and configuration (distribution of piles over the raft). The change in the piles' number, length and configuration in addition to the change in subsoil properties produces a wide variety of cases to be studied. From this variety we may see the effect of changing each variable separately in a condition that may be close to a real one. The concluded observations from the parametric study aims at helping the engineers in taking a logical path in an iterative design process for a piled raft foundation.

2. FINITE DIFFERENCE MODELLING

The behavior of the piled raft was investigated by carrying out 3D numerical analyses using the finite difference software FLAC3D [9]. The basics of 3D modelling of piled raft foundation include the method of modelling the subsoil conditions and the elements used for representing the raft and the piles showing how they interact with the surrounding soil.

The subsoil conditions includes three components which are: grid geometry, boundary conditions, and constitutive behaviour. The grid geometry is composed from solid elements named zones having grid points at the vertices of these zones. The grid geometry was generated using primitive mesh shapes available in FLAC3D and dividing these shapes into suitable number of elements to match the problem modeled. The boundary conditions in the current study were the displacement boundary conditions which were set to roller supports at the lateral faces of the numerical model while the bottom face of the numerical model was set to hinge support. The constitutive behaviour used in this study was Mohr-Coulomb elasto-plastic constitutive model.

In the current study, the raft was modelled using shell elements. The modelling of piles was performed using pile structural element available in FLAC3D such that the pile element is embedded inside the grid representing the soil. The interaction between the pile element and the grid is achieved via shear and normal coupling springs. These coupling springs transfer forces and motion between the pile element and the soil grid at the pile elements' nodes through links formed at these nodes.

3. NUMERICAL VERIFICATION USING BACK ANALYSIS PROCEDURE

Numerical analyses are performed on one piled raft case study using FLAC3D software to prove the validity of the modelling procedure done in this study . The case study was the 30 storey

Messe-Torhaus building constructed in Frankfurt and was the first building in Germany with foundation designed originally as a piled raft (Sommer et al. [10] and Sommer [11]).
The building is a 30 storey (130 m height) building constructed between 1983 and 1986. The foundation of the building consists of two piled rafts 10 m apart. Each piled raft has dimensions of 17.5 m x 24.5 m and a 2.5 m thickness supported upon 42 bored piles of 0.9 m diameter and 20 m length. Figure 1 shows the geometry of the building and its foundation including the instrumented measuring devices. The Young's modulus of the Frankfurt clay layer varies with depth according to the empirical formulation presented by Reul [12]:

$$E = 45 + \left(\tanh\left(\frac{z-30}{15}\right) + 1\right) * 0.7z \tag{1}$$

Where,

E: Young's modulus (MPa)
z: Depth below the surface of the Frankfurt clay layer (m)

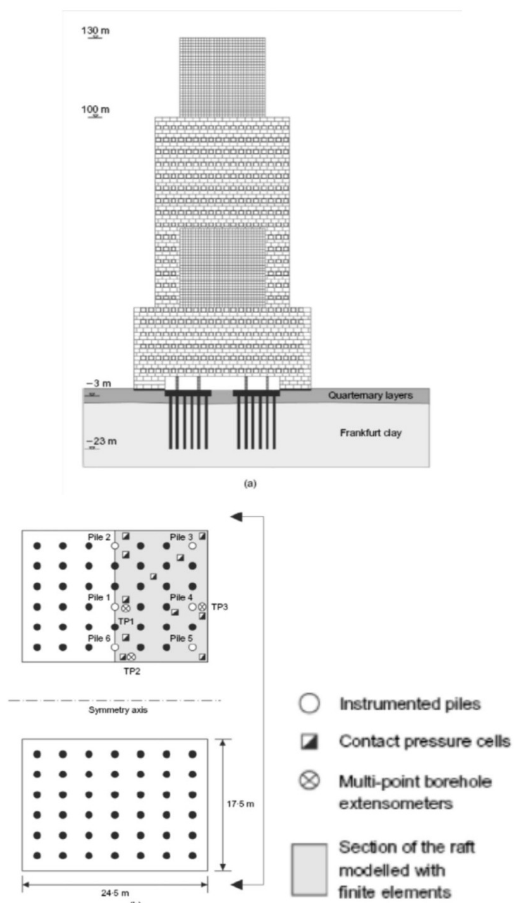


Figure 1. Torhaus building geometry: (a) profile view of the building; (b) plan of the two piled rafts showing the positions of the instrumented measuring devices

Table 1. summarizes the material parameters for the soil layers, the concrete raft and piles.

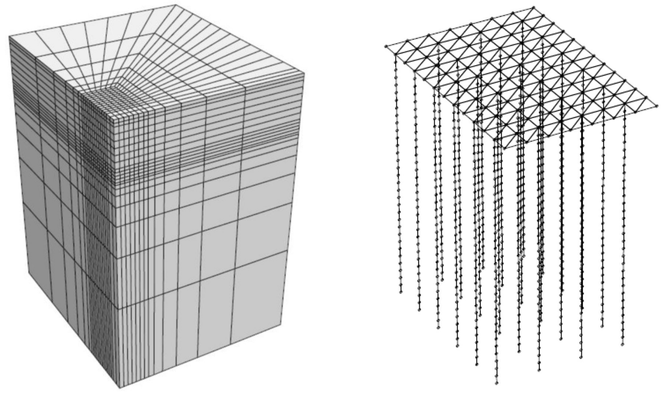
Table 1. Material parameters used in the analysis for Torhaus building.

Parameter	**Quaternary sand and gravel**	**Frankfurt clay**	**Raft**	**Piles**
Young's modulus, E: MPa	75	Equation (1)	34000	23500
Poisson's ratio, ν	0.25	0.15	0.2	0.2
Total unit weight of moist soil, γ: kN/m^3	18	19	25	25
Buoyant unit weight of moist soil, γ': kN/m^3	-	9	-	-
Coefficient of earth pressure at rest, K_o	0.72, $(0 \leq z < 25)$ 0.57, $(z \geq 25)$	0.46	-	-
Angle of internal friction, φ' : degrees	32.5	20	-	-
Cohesion, c': kPa	0	20	-	-
Material model	Elasto-Plastic Mohr Coulomb		Linear elastic	
Analysis Type	Effective drained		-	

In the present study, a 3D finite difference model was constructed for one quarter of the building's foundation (i.e. half one of the two rafts) using FLAC3D software. In this model, the subsoil was modelled using elasto-plastic Mohr Coulomb material model. The raft was modelled using shell structural elements while the piles were modeled using pile structural elements. Figure 2 shows the geometry of the FLAC3D model used in this study to simulate the foundation of the Torhaus building. The analysis type of the numerical model was effective drained analysis to get the long term behaviour for the foundation system.

From the last documented measurement of the settlement after two years from the completion of the construction of the building (Sommer [11]), the average centre settlement for the two rafts was 124 mm and the maximum settlement was 140 mm. The finite difference analysis in the present work gave a value of 106 mm for the centre settlement of the raft and a value of 112 mm for the maximum settlement of the raft which compare well with the measured settlement values.

From the last documented pile measurement in February 1986 (Sommer [11]), a piled raft coefficient a_{pr} was derived to be 0.67. This coefficient was calculated in the current finite difference analysis to be 0.79 lying near the value obtained by Reul and Randolph [7] using finite element analysis which is equal to 0.76. Also, the value of the coefficient a_{pr} calculated by Hemaida [13] using finite element analysis was equal to 0.7. Figure 3 shows a comparison between the measured pile loads (sommer [11]) and the calculated pile loads using the present method, the finite element analysis of Reul and Randolph [7] and the finite element analysis of Hemaida [13] and it shows that the values of pile loads obtained from the present numerical work indicate a more flexible behaviour of the raft compared with the previous numerical work.



(a) (b)

Figure 2. Geometry of the FLAC3D model for the foundation of the Torhaus building: (a) finite difference grid representing the soil; (b) shell and pile structural elements representing the raft and the piles

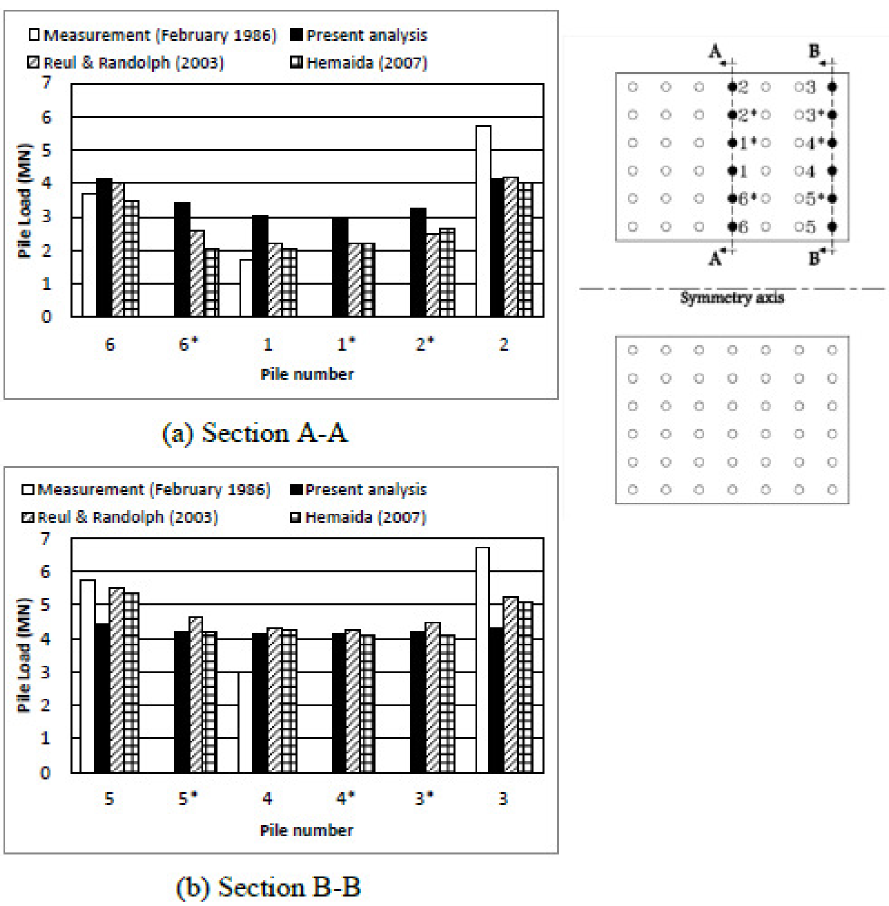


Figure 3. Comparison between measured and calculated pile loads for the piled raft foundation of the Torhaus building

4. PARAMETRIC STUDY

A comprehensive parametric study was performed to study the behaviour of piled raft foundation founded on different subsoil conditions and using variable pile configurations and lengths under a square hypothetical raft. The pile configurations involved three different distributions of the piles over the raft area which are: uniform, concentrated at raft edges and concentrated at central part of the raft. The number of piles ranged from 64 to 121 piles. The piles' lengths used in the study were: 12, 16 and 20 m. Table 2.0 shows the cases studied in the parametric study, where each combination between a pile configuration and a specific pile length was tested upon the three given soil profiles.

Three soil profiles are used in the parametric study. Each soil profile is 30 m in depth consisting of two layers as follows: (1) Top medium dense sand layer having thickness equal to 4 m. The properties of this layer are the same for the three soil profiles. (2) Bottom clay layer of thickness equal to 26 m. For this layer, three different clay types were used which are: soft clay, medium clay, stiff clay. Each soil profile is named according to the clay type composing its bottom layer (e.g. Soft clay profile means that the top soil layer is medium dense sand and the bottom soil layer is soft clay). Both the foundation level of the raft and the ground water table are located at the same level of 1.5 m below the natural ground level as shown in Figure 4. Table 3. presents the soil parameters used in the analyses.

Table 2. Program of the parametric study.

Pile Configuration	**Pile Length (m)**			**Soil Profile**		
Unpiled	NA			Soft clay	Medium clay	Stiff clay
A	12	16	20	Soft clay	Medium clay	Stiff clay
B	12	16	20	Soft clay	Medium clay	Stiff clay
C	12	16	20	Soft clay	Medium clay	Stiff clay
D	12	16	20	Soft clay	Medium clay	Stiff clay
R	12	16	20	Soft clay	Medium clay	Stiff clay

Table 3. Material parameters of the soil types used in the parametric study.

Parameter	**Medium dense sand**	**Soft clay**	**Medium clay**	**Stiff clay**
Young's modulus, E (MPa)	35	8	15	25
Poisson's ratio, ν	0.3	0.45	0.45	0.45
Total unit weight of moist soil, γ (kN/m^3)	18	18	18	18.5
Coefficient of earth pressure at rest, K_o	0.46	0.6	0.5	0.75
Angle of internal friction, φ' (degrees)	33	30	30	25
Cohesion, c' (kPa)	0	10	0.1	15
Material model	Mohr-Coulomb			
Analysis Type	Effective drained			

The raft used in the parametric study is square in plan with dimensions of 20 * 20 meters and thickness equals 1 meter which is kept constant throughout the study. Five pile configurations were used with number of piles ranging between 64 and 121 circular piles involving three ways for distributing the piles upon the raft surface area: uniform, concentrated at raft edges and concentrated at central part of the raft. The pile diameter used was 0.60 meter for all cases in the study. In order to examine the effect of variation in pile length upon the foundation behaviour, three different pile lengths were used which are 12, 16 and 20 meters. Figure 5 shows the pile configurations used in the study. Both the raft and the piles are made from reinforced concrete which is modelled as a linear elastic material having Young's modulus of 22000 MPa and Poisson's ratio of 0.15. In order to reduce the large time needed for running such a complex three dimensional problem, only one quarter of the piled raft was modelled which gives an exact result as the complete model due to the symmetry in the problem. In order to get the maximum values of settlement and straining actions, all the analyses throughout the present study were effective drained analyses.

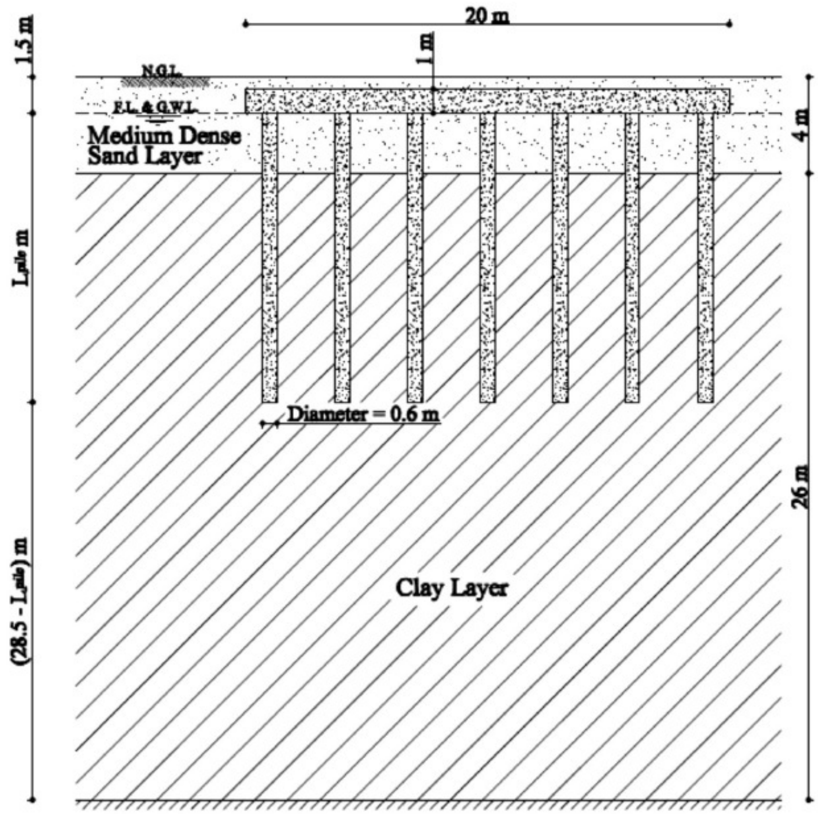


Figure 4. Elevation cross section for the foundation showing subsoil layering

5. COMPUTED RESULTS

5.1. Results of Unpiled Raft

The behaviour of unpiled raft was studied before studying the behaviour of piled raft in order to assess the percentage of enhancement in the behaviour of unpiled raft caused by inclusion of piles. The unpiled raft of thickness 1 m was modelled over the three soil profiles used in the parametric study.

Figure 6 shows the stress settlement relationship for the unpiled raft over the different soil profiles used in the study. From the latter relationship, we can get the stress that causes settlement of magnitude 15 cm over each soil profile. The ultimate bearing capacity of the raft could be obtained using criterion of De Beer [14] by plotting again its stress settlement relationship but in a log-log plot as shown in Figure 7. The stress at the point of break for each curve in Figure 7 is the ultimate bearing capacity of the raft over the soil profile corresponding to that curve.

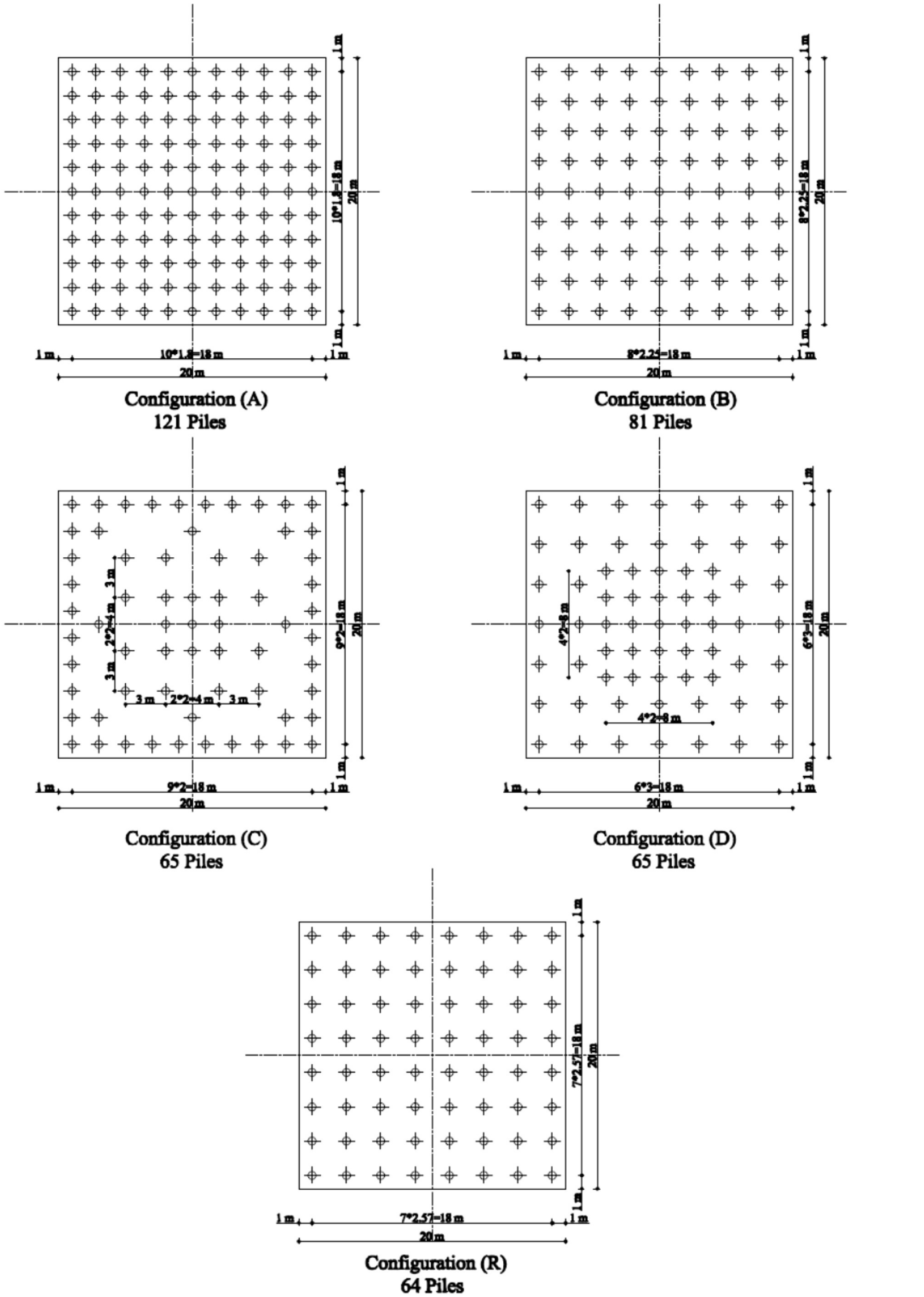


Figure 5. Geometry of pile configurations used in the study

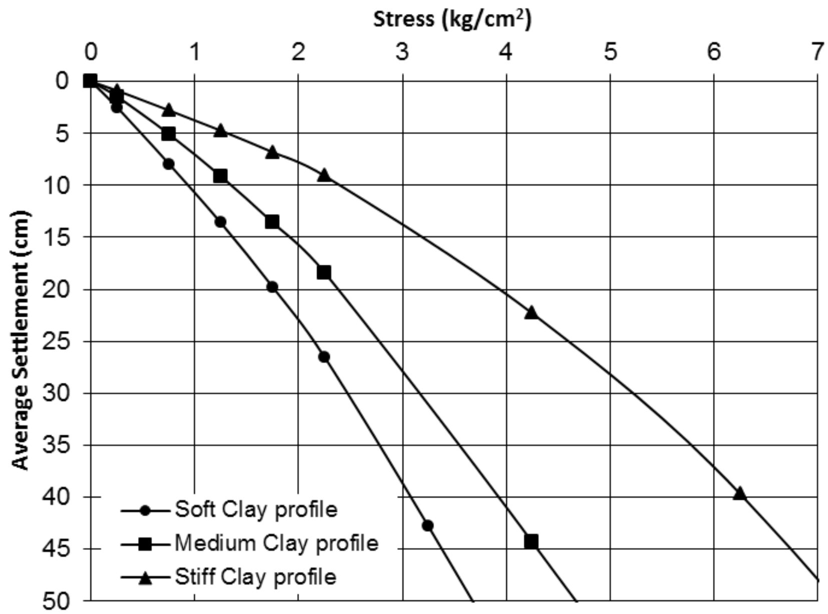


Figure 6. Stress settlement relationship of unpiled raft over different soil profiles

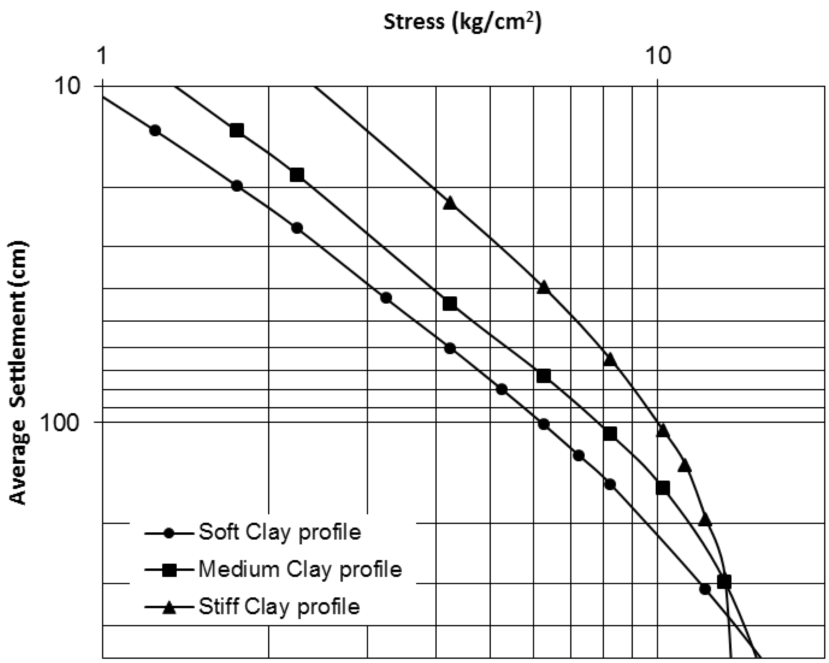


Figure 7. Log-log plot for stress settlement relationship of unpiled raft to estimate its ultimate bearing capacity

5.2. Results of Piled Raft

The effect of variation of piles number, configuration and length on the stress average settlement behavior and the stress differential settlement on pile raft was discussed in the following sections.

Figure 8 shows the patterns of the grid for the different pile configurations and the shell structural elements representing the raft and the pile structural elements.

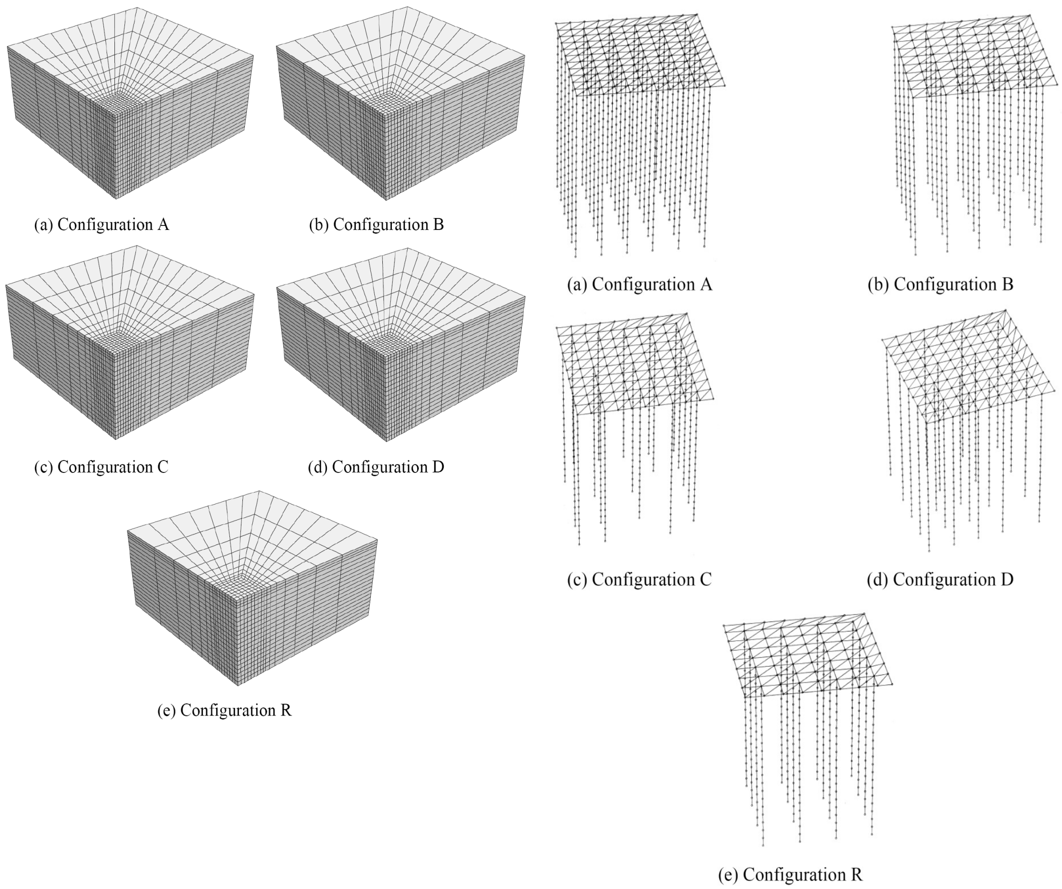


Figure 8. Finite difference grid for the different pile configurations

5.2.1. Stress – average settlement behaviour of piled raft

In order to study the effect of variation of piles' number, configuration and length on the stress – average settlement behaviour of piled raft for the different soil profiles, the average settlement was plotted versus the stress as shown in Figure 9 (the stress plotted in the figure is the vertical stress applied over the raft surface). The behaviour of unpiled raft was plotted for each case on the same figure for purpose of comparison with the corresponding behaviour of the piled raft. The stress causing 15 cm settlement will be referred to as the "piled raft working stress" as it is the stress corresponding to the allowable settlement for the foundation. Figures 10 through Figure 12 present the effect of piles' number, configuration and length on the piled raft working stress for the different soil profiles. Also, the unpiled raft working stress corresponding to 15 cm settlement was plotted to show the percentage of improvement in the working stress when piles are added to the unpiled raft. From the above mentioned figures we may notice the following:

- The increase in number of piles does not make a significant reduction in the average settlement of the piled raft. Consequently, the piled raft working stress is not significantly affected by the increase in number of piles. The ratio of the working stress of the pile configuration with maximum number of piles (configuration (A)) and that of the pile configuration with minimum number of piles (configuration (R)) ranged between 1.05 and 1.17 for the piles' lengths and soil profiles used in the study, while the maximum number of piles was about 1.89 times the minimum number of piles. The above mentioned ratio has its maximum values for the stiff clay soil profile and has its minimum values for the soft clay soil profile.

- The increase in pile length effectively reduces the piled raft average settlement and in turns significantly increases its working stress. The percentage of increase in the working stress due to the increase in pile length becomes higher when the stiffness of the clay layer in the soil profiles decreases, which means that soft clay soil profile has the largest percentage of increase in the working stress due to the increase in pile length.

Although the three pile configurations named (C), (D) and (R) have almost equal number of piles (65 for (C) and (D); 64 for (R)), but they have different stress-average settlement response. The percentage of difference in the value of working stress for the three configurations ranged between less than 1 % up to 14.5 %. The stiffness of configuration (R) is more than that of configurations (C) and (D) because the uniform distribution of piles in configuration (R) made the pile spacing kept constant at a value of 2.57 m, while in configurations (C) and (D) most of the piles (the piles at area of concentration) are spaced at a value closer than 2.57 m. The relatively narrow spacing for piles at the edges for configuration (C) and at the centre for configuration (D) increases the negative group action which reduces their stiffness compared to that of configuration (R). Also, the concentration of piles at the edges in configuration (C) causes a lesser negative group action than the concentration of piles at the centre in configuration (D) because piles at the edges are by nature stiffer than piles at the centre. This is attributed to the block deformation of the pile group which makes differential settlement relative to the surrounding soil for edge pile more than that for a centre pile. Hence, the pile shaft load for an edge pile will be greater than that for a centre pile while base loads are the same (Reul and Randolph [7]).

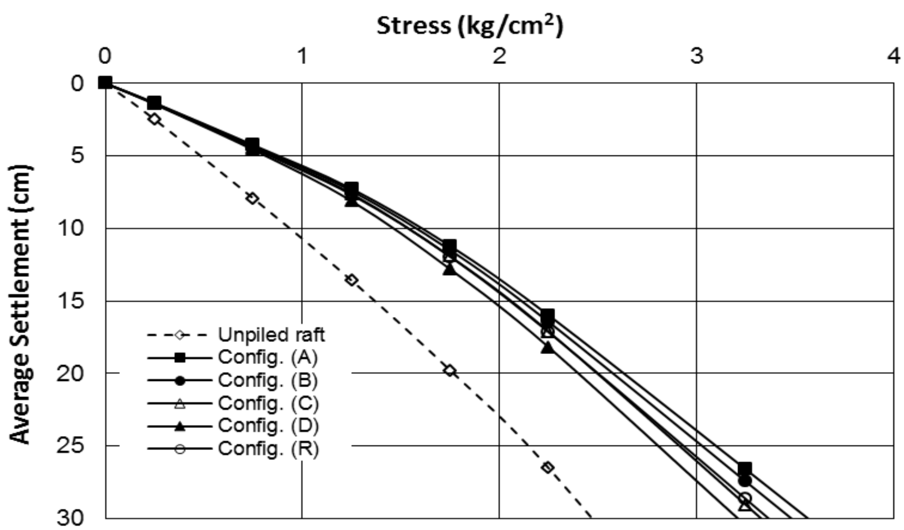


Figure 9. Stress-average settlement relationship for piled raft over soft clay soil profile (pile length = 12 m)

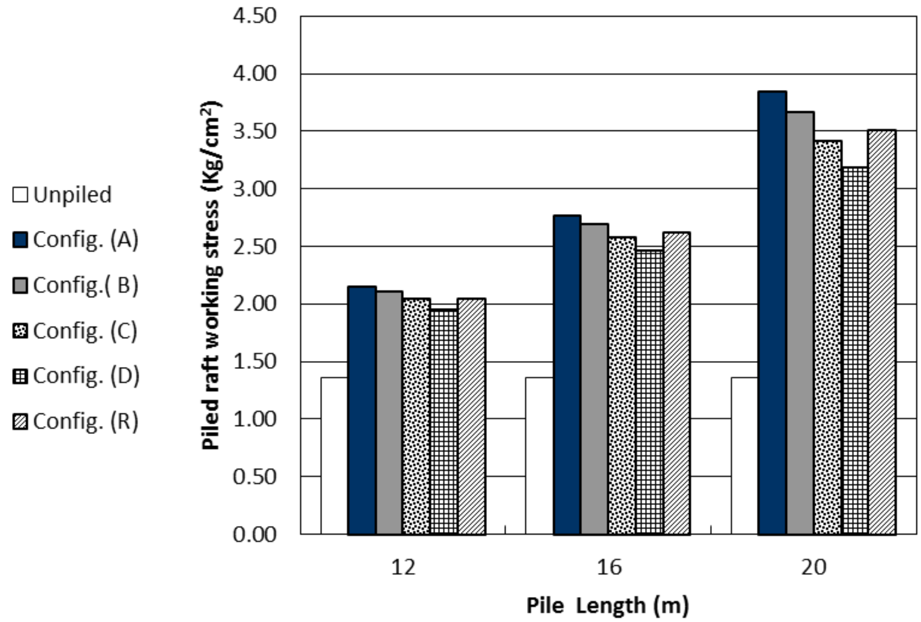


Figure 10. Effect of piles' number, configuration and length on piled raft working stress for soft clay soil profile

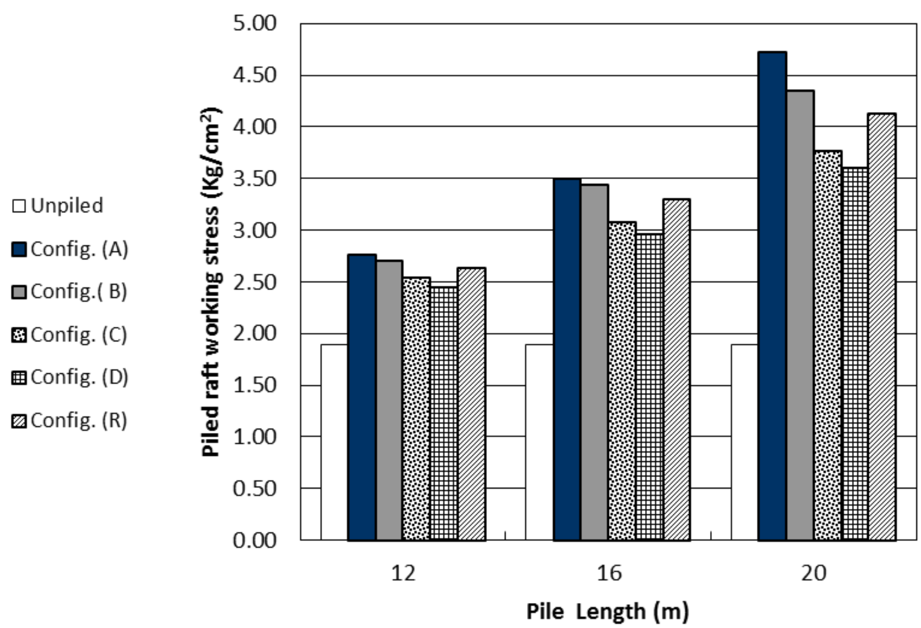


Figure 11. Effect of piles' number, configuration and length on piled raft working stress for medium clay soil profile

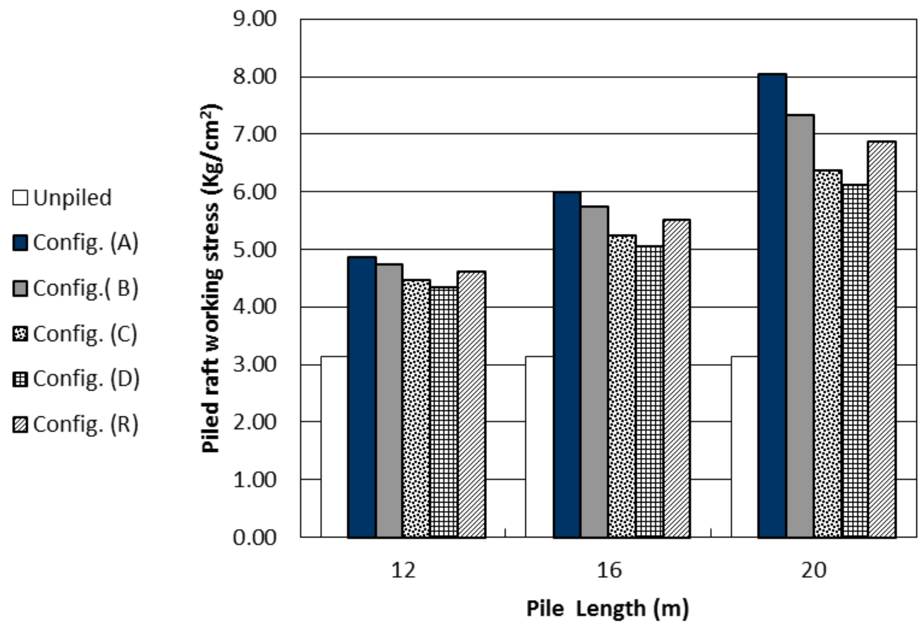


Figure 12. Effect of piles' number, configuration and length on piled raft working stress for stiff clay soil profile

5.2.2. Stress – differential settlement behaviour of piled raft

The differential settlement is an important issue in studying the behaviour of piled raft foundation as it has a great effect on the safety and serviceability of the superstructure. In the present study, the differential settlement is considered to be the difference between the settlement of the raft centre and that of the raft corner. The differential settlement of the piled raft was plotted versus the stress as shown in Figure 13. Also the differential settlement of the unpiled raft was plotted for each case on the same figure. From the plotted stress-differential settlement curves we may notice the following:

- The increase in number of piles has a very small effect on the differential settlement. This can be proved by comparing the stress-differential settlement curves of the three uniformly distributed pile configurations ((A), (B) and (R)), which are almost identical or very near to each other.

- The change of the distribution of piles upon the raft area has the maximum effect on the stress-differential settlement response of the piled raft. The pile configurations with uniform distribution of piles named (A), (B) and (R) take the same trend and their curves are near to the unpiled raft curve especially at the zone of positive differential settlement. It is noted that as the stiffness of the clay layer in the soil profile increases, the behaviour of uniformly distributed pile configurations diverges away from the behaviour of the unpiled raft. The response of configuration (C) with piles concentrated at the edges shows that it always has positive values of differential settlement even at higher stress levels and its differential settlement tends to increase by increasing the stress level. This behaviour of configuration (C) is due to the concentration of piles at edges which makes the settlement of the raft centre always greater than that of the raft corner. On the contrary, we notice that the behaviour of configuration (D) with piles concentrated at the centre shows small values of positive differential settlement and a quick transition to the zone of negative differential settlement. The negative values of differential settlement in configuration (D) should be taken into account in the structural design of the raft as they yield different deformed shape than the ordinary dish shape of the other configurations at working stress level. This in turn changes the values and signs of the bending moments in the raft.

In order to assess the differential settlement behaviour of the piled raft at the working stress level, the differential settlement values corresponding to 15 cm average settlement were plotted for both the piled and unpiled rafts on Figures 14 through 16. In the latter figures, the effect of changing piles' number, configuration and length for the different soil profiles may be summarized as follows:

- For the three uniformly distributed pile configurations ((A), (B) and (R)), the change in number of piles has a small effect on the differential settlement at working stress level. This effect causes a small increase in differential settlement at working stress level with increasing number of piles for soft clay soil profile while it has a negligible effect for medium and stiff clay soil profiles.

- The increase in pile length has an effect of increasing the differential settlement at working stress level for the pile configurations with uniform distribution of piles and piles concentrated at edges. The latter effect becomes more significant as the stiffness of the clay layer in the soil profile decreases. For pile configuration (D) with piles concentrated at centre, increasing pile length reduces the algebraic value of differential settlement at working stress level but its absolute value may increase as in the case of medium clay soil profile.

The pile configurations with uniform distribution of piles and piles concentrated at edges ((A), (B), (R) and (C)) always have positive values of differential settlement at working stress level. Configuration (C) in all the cases has the highest value of differential settlement while uniformly distributed pile configurations ((A), (B) and (R)) have values close to each other as mentioned before. Configuration (D) always has the least absolute value of differential settlement at working stress level compared to the other pile configurations. Also its absolute value of differential settlement at working stress level does not exceed its corresponding value for the unpiled raft in the majority of the cases on the contrary to the other pile configurations.

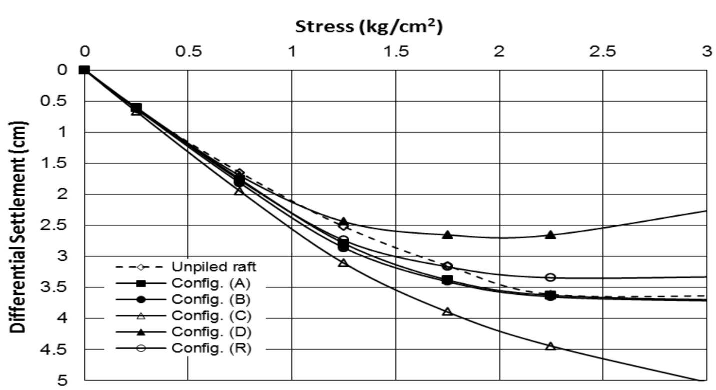


Figure 13. Stress-differential settlement relationship for piled raft over soft clay soil profile (pile length = 12 m)

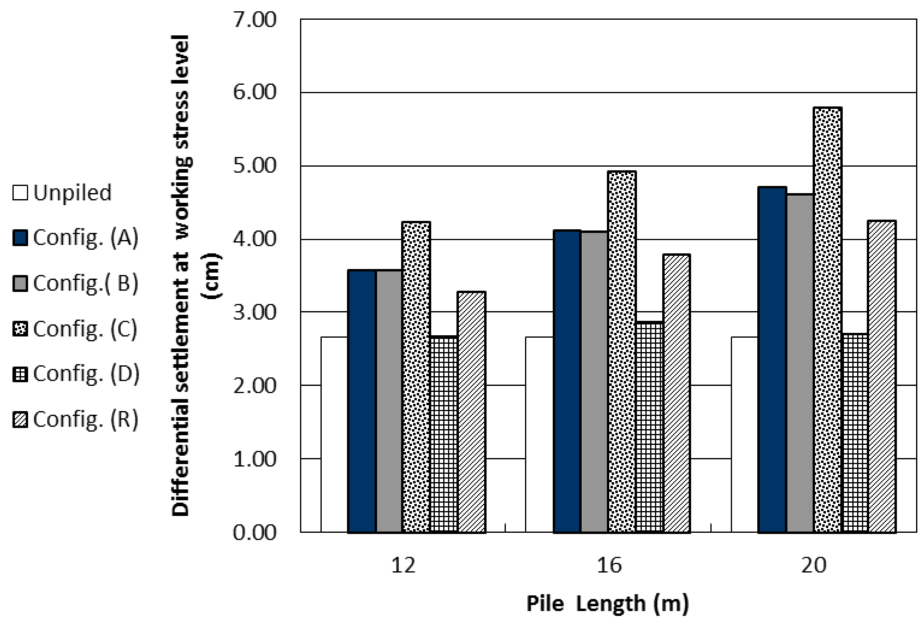


Figure 14. Effect of piles' number, configuration and length on piled raft differential settlement at working stress level for soft clay soil profile

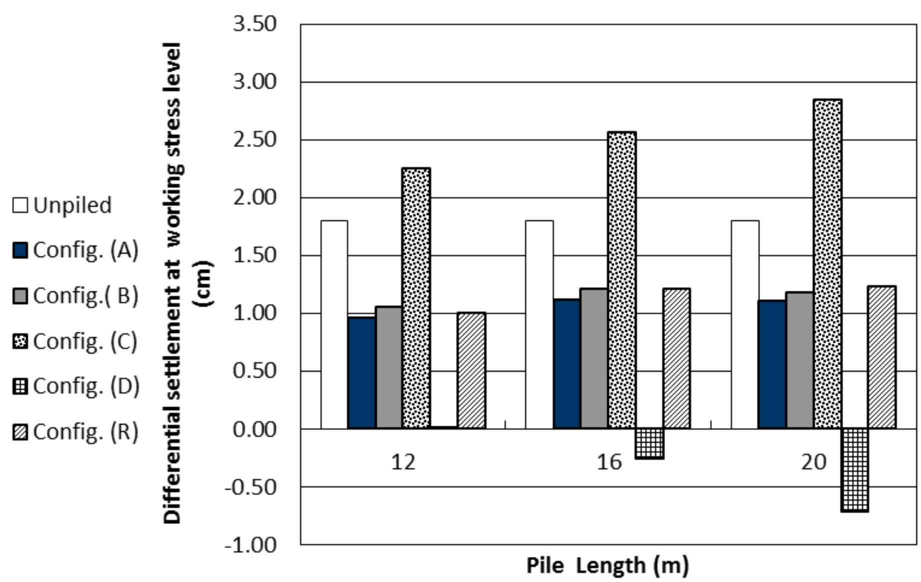


Figure 15. Effect of piles' number, configuration and length on piled raft differential settlement at working stress level for medium clay soil profile

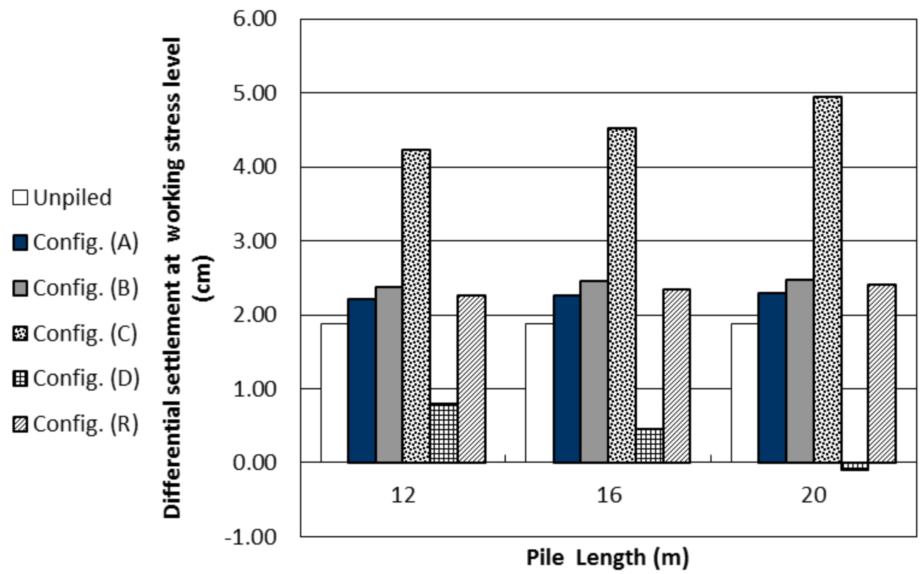


Figure 16. Effect of piles' number, configuration and length on piled raft differential settlement at working stress level for stiff clay soil profile

6. CONCLUSIONS

A series of 3D elasto-plastic finite difference analyses were conducted to investigate the behaviour of a square piled raft in clay soil subjected to vertical loading. From the results of the numerical analyses performed throughout the present study, the following conclusions may be obtained:

- The three dimensional finite difference modelling of piled raft foundation proved to be an efficient tool for analyzing real piled raft systems.
- Increasing number of piles has a small effect on the piled raft average settlement and differential settlement (provided that the piles' structural capacity is adequate).
- The effect of increasing number of piles becomes less significant for softer soil profiles.
- Increasing length of piles has a significant effect on the piled raft average settlement and differential settlement between raft and piles.
- The effect of increasing length of piles becomes more significant for softer soil profiles.
- For the same number of piles, the change in piles' distribution over the raft area has a slight effect on the piled raft average settlement while it has a considerable effect on the piled raft differential settlement.

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