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USA CODEN: JETRB4

Journal of Engineering And Technology Research, 2014, 2 (6):13-35

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EFFECT OF DIFFERENT PARAMETERS ON THE BEHAVIOR OF UNIFORMLY LOADED PILED RAFTS

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ABSTRACT

This paper presents a nonlinear computer program called PILEDRAFT to analyze piled rafts embedded in different soil profiles. The analysis method is based on the hybrid finite element-elastic continuum-load transfer method. The method of hybrid developed here extended to take into account the nonlinear behavior of the soil beneath the raft, nonlinear pile load-settlement behaviour, nonhomogeneous soil profile, multilayered soils and piles of different diameters, lengths and stiffness. Compared with results of the available published literatures, the developed program provides reasonable results. The program PILEDRAFT is used in a parametric study to investigate the effect of different parameters on the performance of a uniformly loaded piled raft. The study shows that the piles configuration beneath the raft has a profound effect on the overall and differential settlements and the bending moment of the raft. The reduction in the area occupied by the piles beneath the central area of the raft can reduce the overall and differential settlements and increase the induced bending moments of the raft. Moreover, the effects of the raft thickness, modulus of elasticity of the supporting soil and length of the piles on the behavior of piled raft are investigated. The results of this study may provide general guidelines for practical engineers to produce economical design of piled rafts.

Keywords: Piled rafts, piles configurations, nonhomogenous soil, multilayered soil, parametric study

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INTRODUCTION

Piled raft is a common foundation system to support high-rise buildings to be constructed on soils of low bearing capacity (i.e., soft clay, loose sand and sabkha soil) because of their efficiency in controlling the total and differential settlements. The conventional design of piled raft is based on the assumption that the piles, ignoring the bearing contribution of the raft, support the total load of the superstructure. This results in a conservative estimate of the foundation performance, and therefore an overdesign of the foundation. In reality, the loads of the superstructure are transferred to the soil not only by the interaction between the soil and the piles but also by the interaction between the soil and the raft. A different approach, involving the use of piles as settlement reducers, has been reported by Randolph (1994), Burland (1995), Poulos (2001), Sanctis et al. (2002), Fioravante et al. (2008), El-Garhy et al. (2013). The basic concept of this approach is that the foundation comprises only the number of piles that are necessary to reduce settlements to a tolerable amount and the loads from the superstructure are transmitted, via a raft, in part to the piles and in part to the supporting soil (load shared between the raft and the piles). This approach allows the piled raft design to be optimized and the number of piles to be significantly reduced.

The analysis of piled rafts is very challenging because of the complexity involved in the interaction between the soil, the piles and the raft. Randolph (1994) reported the different numerical techniques that can be used to analyze piled rafts. These are finite element method, boundary element method, hybrid load-transfer method, and finite or infinite layer method. Three-dimensional finite element analysis may be used for complex pile groups because of the high computational requirements.

Chow (1986) developed a hybrid model based on the load-transfer approach for homogeneous soil that developed by Randolph and Worth (1978) for a single pile and Mindlin's elastic continuum solution for interaction between piles. Clancy and Randolph (1996) and Horikoshi and Randolph (1999) used the hybrid method for analysis of pile groups and piled rafts embedded in Gibson soils. The finite layer method has been employed for analyzing pile groups and piled rafts in layered soil (Ta and Small, 1996; Zhang and Small, 2000; Chow and Small 2008).

Recently, a number of researchers developed analysis methods for piled rafts using different approaches (e.g., Huang et al. 2011, Nguyen et al. 2013, Lee et al. 2014 and Jeong and Cho 2014). Huang et al. (2011) proposed a nonlinear solution to analyze the response of a vertically loaded piled raft in layered soil. Based on the elastic-plastic analysis of a single pile in a layered soil, the shielding effect between a receiver pile and the soil is taken into account to modify the conventional interaction factor between two piles. An approximate approach with the concept of the interaction factor is employed to study the nonlinear behavior of pile groups with a rigid cap.

Nguyen et al. (2013) proposed a design method for a piled raft considering the interaction effects. In this method, the raft is considered as a plate supported by a group of piles and soil, the ultimate load capacity of the pile group is taken into account in calculating the settlement when the foundation is subjected to a large vertical external load. In addition, this method supports estimation of the nonlinear behaviour of the piled raft by considering the nonlinear behavior of the piles.

Lee et al. (2014) proposed a load-sharing model to analyze the load sharing behavior of piled rafts using a normalized load-settlement relationship that describes the combined load responses of raft and piles and takes into account the settlement-dependant variation of load sharing behavior. Lee et al. (2014) conducted centrifuge load tests for various model foundations to check the validity of the proposed load-sharing model.

Jeong and Cho (2014) proposed a nonlinear 3D analytical method for piled raft foundations by considering raft flexibility and soil nonlinearity. In this method the load transfer approach using $p-y$, $t-z$ and $q-z$ curves is used for the analysis of piles and an analytical method of the soil-structure interaction is developed by taking into account the soil spring coupling effects based on the Filnenko-Borodich model. The method of Jeong and Cho (2014) was verified by comparing its results with the results of other numerical methods and field case studies on piled raft.

There are numerous factors controlling the behaviour of the piled rafts such as raft thickness, modulus of elasticity of the supporting soil, length of the piles and piles configurations. It is necessary to consider these factors in the design of piled raft to achieve the objective of economic construction with satisfactory behavior.

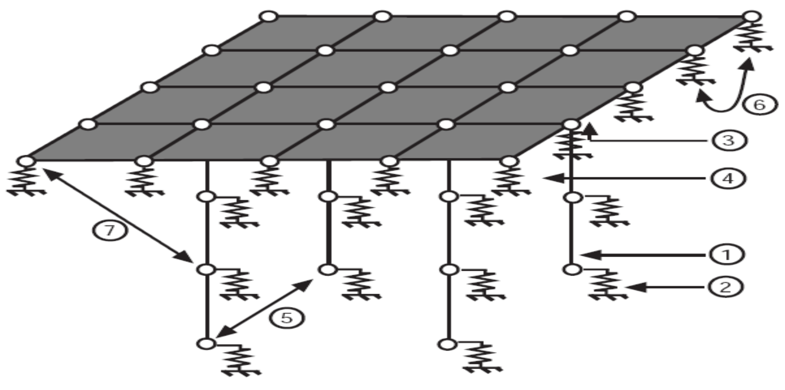
This paper consists of two main parts. The first part pertains to the development of a nonlinear computer program for the analysis of piled rafts based on the hybrid finite element-elastic continuum-load transfer method. The method employed and the program developed is validated by comparing its results with the results of other analysis methods available in the literature including more rigorous results of 3D finite element analysis. In the second part of this paper the developed program is used in a parametric study to investigate the effect of different parameters on the behavior of piled raft. These parameters include thickness of the raft, modulus of elasticity of the supporting soil, length of the piles and piles configuration.

MATERIALS AND METHOD

The numerical method of analysis described here is based on the hybrid finite element-elastic continuum-load transfer method, which has been developed specifically to minimize the amount of computation (Griffiths et al. 1991, Clancy and Randolph 1993, Clancy and Randolph 1996, El-Garhy 2002). Figure 1 shows the numerical representation of the problem. One-dimensional rod finite elements are used to model the piles, while the pile-soil contact is represented at node points by potentially non-linear load transfer springs (Chow 1986). Interaction between piles through the soil is calculated using Mindlin's elastic continuum solution.

The raft is subdivided into two-dimensional thin plate bending finite elements (Smith and Griffiths, 1988), and the raft-soil contact is lumped into an equivalent nonlinear soil spring at each node. An equivalent soil spring's response is calculated for each raft node using an analytical solution for the average settlement under a uniformly loaded rectangular area for different soil profiles. The elastic settlement, w, at the center of a uniformly loaded rectangular flexible area, bxl, can be calculated from the following equation.

$$w = \frac{bp(1-\nu_s^2)}{E_s} I_s \tag{1}$$



(1) One dimensional pile element (rod element)
(2) Soil resistance at each pile node represented by nonlinear t-z curve
(3) Two-dimensional plate-bending finite element raft mesh
(4) Soil resistance at each raft node represented by nonlinear spring
(5) Pile-soil-pile interaction effects calculated between pairs of nodes
(6) Raft-soil-raft interaction
(7) Pile-soil-raft interaction

Figure 1 Numerical representation of piled raft (Clancy and Randolph 1996)

Where E_s and ν_s are the elastic modulus and Poisson's ratio of the soil, p is the uniform load, b and l are the width and length of rectangular area and I_s is the influence factor (sometimes take symbol I_z in the literature). The nonlinear response of the soil at the raft soil interfaces is represented by the following hyperbolic relationship.

$$\Delta w = \frac{b \Delta p (1 - \nu_s^2)}{E_s \left(1 - \frac{p R_f}{q_{ult}} \right)^2} I_s \qquad (2)$$

Where Δw is the incremental soil settlement, Δp is the incremental load, p is the current uniform load, R_f is the hyperbolic curve fitting constant and q_{ult} is the ultimate bearing capacity of the soil. The value of the influence factor, I_s, is dependent on dimensions of rectangular area and soil profile. The present method of analysis considers four different cases of soil profiles. These are (1) semi-infinite soil medium (Giroud 1968, Hirai 2008), (2) finite soil layer (Hirai 2008), (3) semi-infinite multi-layered system (Hirai 2008) and multi-layered system resting on rigid base (Fraser and Wardle 1976).

The area of raft contributing to each node is calculated by summing the area of each raft element to which the node is attached, and by dividing this area by four (since each element has four nodes). The contributing area does not necessarily centre on the node itself and so the centre of this area is calculated for each node. These center points are then used to determine the interaction between raft nodes through the soil, which again makes use of Mindlin's equation.

The raft analysis and pile group analysis are combined by attaching piles to the raft via common nodes at the connecting points. The connection between the raft and the piles are assumed to be simple connections (i.e., only the vertical loads transmitted from the raft to the head of the piles). It is assumed that there is no raft-soil contact at the common nodes (i.e., pile nodes). Interaction between pile nodes and raft nodes is calculated using Mindlin's equation.

The method of hybrid developed here extended to take into account the following additional features: (1) nonlinear behavior of the soil beneath the raft, (2) nonlinear pile load-settlement behaviour, (3) nonhomogeneous soils where modulus increases with depth, (4) multilayered soils where each soil layer has a different soil modulus and (5) piles of different diameters, lengths and stiffness. The numerical method of analysis developed here is implemented into a nonlinear finite element computer code named PILEDRAFT for the analysis of unpiled rafts and piled rafts.

PROGRAM VALIDATION

Poulos (2001) solved and presented a piled raft problem for the purpose of comparisons between the different analysis methods of piled rafts. The dimensions of the rectangular raft are 6mx10m, its thickness is 0.5m and supported by a group of piles with a diameter of 0.5m. The raft has a bearing capacity of 0.3MPa and the pile has a load capacity of 0.873MN in compression. The piled raft is embedded in a homogeneous finite soil layer with a modulus of elasticity of 20MPa and Poisson’s ratio of 0.3. Figure 2 shows the properties of the piled raft and the supporting soil. Figures 3, 4 and 5 show the piles arrangements for the three cases of piled rafts that are considered in this example.

Loads are applied vertically as concentrated loads to the raft as shown in Figure 2. The present program is used to analyze the three cases of piled rafts (i.e., raft on 3 piles, raft on 9 piles and raft on 15 piles) and the results are compared with the published results from program GARP, the Poulos-Davis-Randolph (PDR) method (Poulos 2001), program FLAC3D (Poulos 2001), program APRILS (Chow 2007) and program ELPLA (Rabiei 2009).

In the present analysis, the limiting skin resistance along the pile length and the pile base resistance are back calculated to be 78kN/m^2 and 1170kN/m^2 from the ultimate capacity of the pile, pile dimensions, soil modulus of elasticity and the adhesion factor is taken 0.6 as recommended by Poulos (2001).

Figures 6, 7 and 8 show comparisons between the load-settlement curves obtained by the present program and those predicted by other methods for the three cases of piled rafts. Good agreement is obtained with the published results of the other methods as shown in Figures 6, 7 and 8.

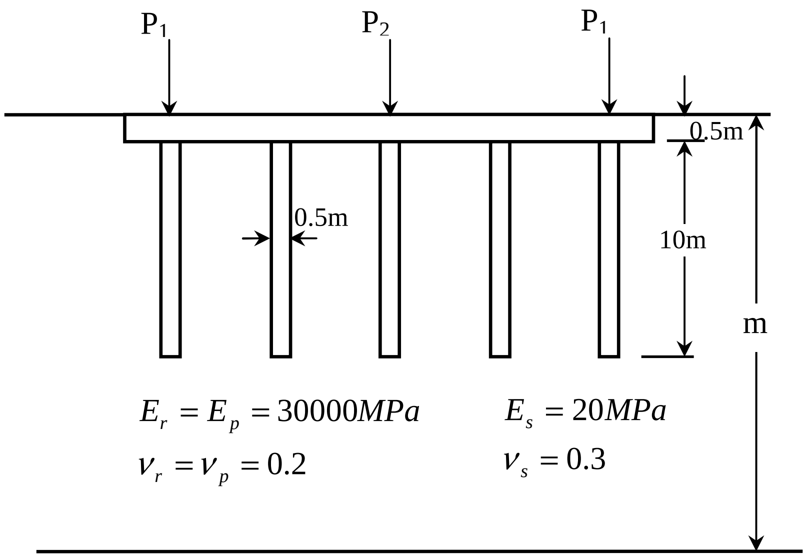


Figure 2 Properties of the piled raft and supporting soil

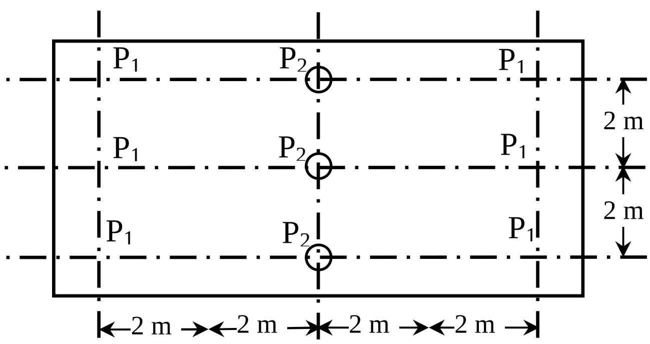


Figure 3 Case 1: raft on 3 piles

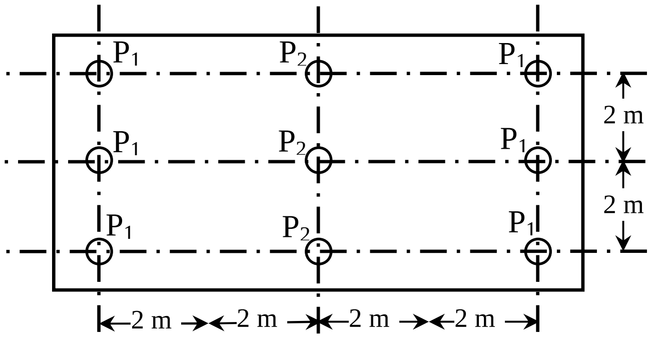


Figure 4 Case 2: raft on 9 piles

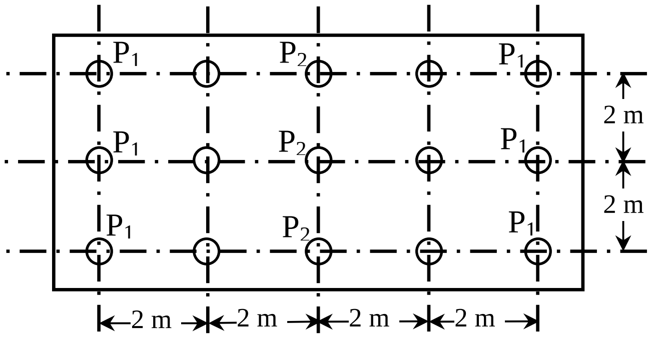


Figure 5 Case 3: raft on 15 piles

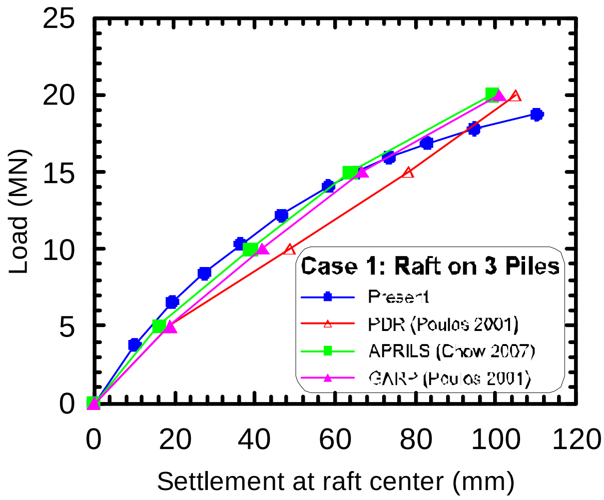


Figure 6 Comparison of load-settlement curves for Case 1: Raft on 3 piles

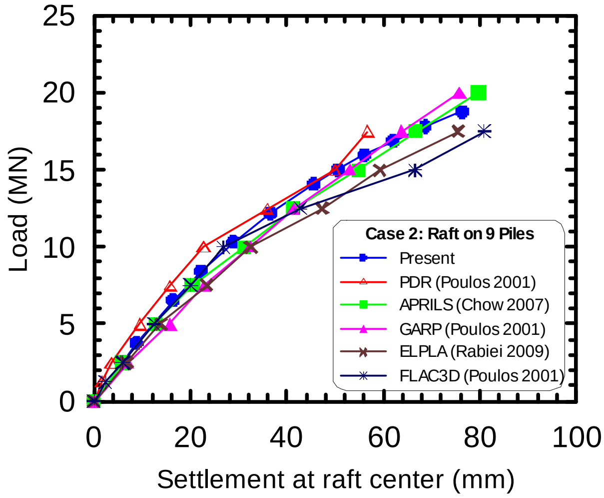


Figure 7 Comparison of load-settlement curves for Case 2: Raft on 9 piles

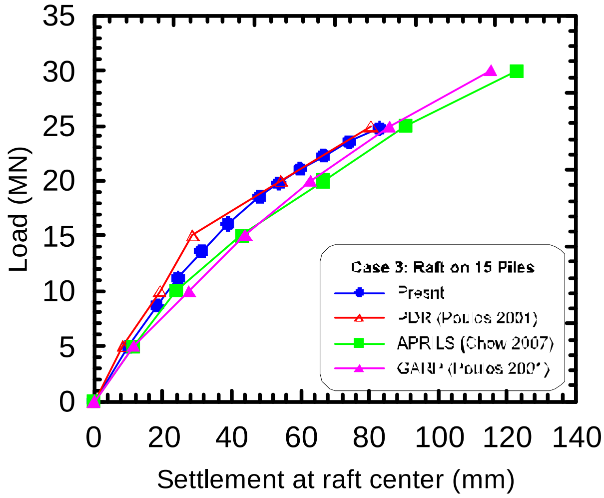


Figure 8 Comparison of load-settlement curves for Case 3: Raft on 15 piles

PARAMETRIC STUDY

The program PILEDRAFT is used in a parametric study to investigate the effect of different parameters on the performance of the piled raft. The dimensions of the raft used in the parametric study are 20mx20m and resting on 25 piles. The piled raft is subjected to a uniform load of 100kN/m^2. Figure 9 shows the properties of the piled raft and the supporting soil. Figure 10 shows the piles configuration beneath the raft.

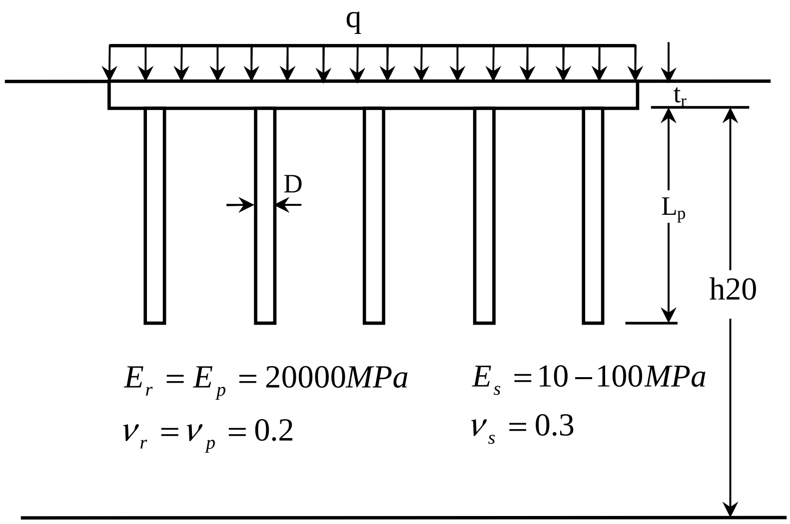


Figure 9 Properties of the piled raft and supporting soil

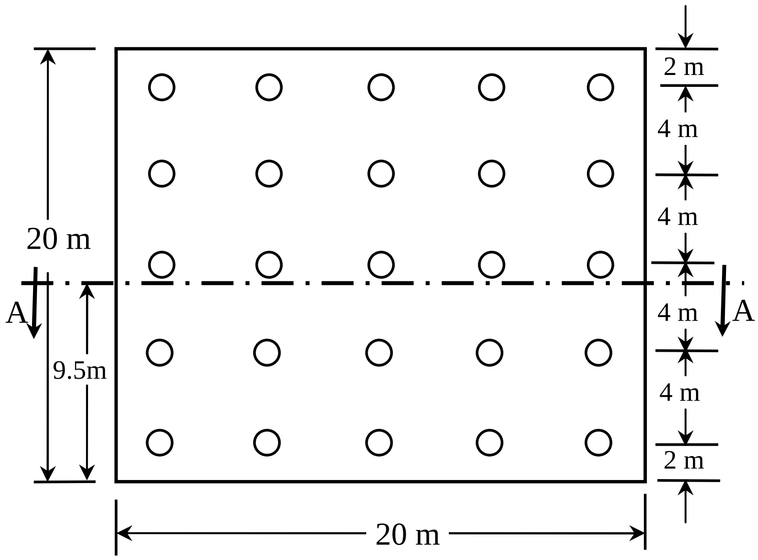


Figure 10 Configuration of the piles beneath the raft

In all the parametric study, the value of the ultimate bearing capacity of the raft, q_{ult}, is taken equal to $6c_u$ (Poulos 2001) and the undrained cohesion, c_u, is taken equal to $E_s/250$ (Bowles 2001, Das 2010). The value of the limiting shaft resistance, f_{sult}, is taken equal to αc_u (where α is the adhesion factor that can be calculated as a function of the undrained shear strength of the soil (Bowles 2001)) and the limiting pile base resistance is taken equal to $9c_u$ (Bowles 2001, Das 2010). In all the parametric study, the nonlinear analysis is considered and only one parameter is changed, and all of the other parameters are held constant at the basic values as presented in Table 3. The results of all the parametric study are presented in non-dimensional forms as follows:

$$I_{rw} = \frac{wE_sD}{qBL} \tag{3}$$

$$I_{dw} = \frac{w_d E_s D}{qBL} \tag{4}$$

$$I_{rm} = \frac{m}{qBL} \tag{5}$$

$$I_{pz} = \frac{A_z}{qBL} \tag{6}$$

Where I_{rw} is the normalized vertical settlement of the piled raft, I_{dw} is the normalized differential displacement of the piled raft, I_{rm} is the normalized bending moment per unit length of the raft, I_{pz} is the normalized axial force along the pile, w is the vertical settlement of the piled raft, w_d is the differential settlement of the piled raft, m is the bending moment per unit length in the raft, A_z is the axial load of the pile, B and L are the width and length of the raft, and q is the applied uniform load on the raft.

Table 3 Basic values of various parameters used in the parametric study

Parameter	Value
Uniform load over the raft	100kPa
Length of the raft	20m
Width of the raft	20m
Thickness of the raft	0.5m
Modulus of elasticity of the raft	20000MPa
Poisson’s ratio of the raft	0.2
Modulus of elasticity of the soil	20MPa
Poisson's ratio of the soil	0.3
Undrained cohesion of the soil	80kPa
Number of piles	25
Diameter of the pile	0.5m
Length of the pile	10m
Modulus of elasticity of the pile	20000MPa
Poisson's ratio of the pile	0.2

Effect of raft thickness

Figures 11 to 15 show the effect of the raft thickness on the behavior of the piled raft. The thickness of the raft is varied between 0.5m to 2.0m and the other parameters are kept constant at its basic values as presented in Table 3. Figure 11 shows comparisons of the normalized vertical settlements along the centerline of the piled raft at different values of raft thickness. As shown in Figure 11, the normalized vertical settlements of piled raft decrease as the raft thickness increases. As the raft thickness increases from 0.5m to 2.0m, the maximum settlement at the raft center decreases by 23% that shows the decrease in total settlement is not very significant. However, the decrease in differential settlement is more significant as shown in Figure 12. The differential settlements (i.e., center-edge and center-corner) decreased by 88.4% and 89.8%, respectively as the raft thickness increases from 0.5m to 2.0m.

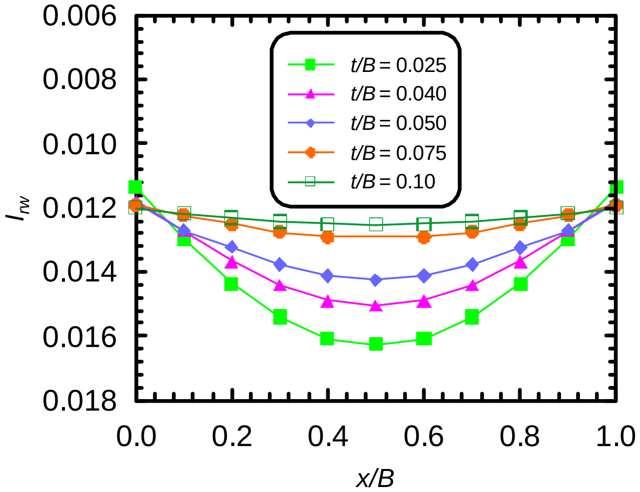


Figure 11 Effect of raft thickness on the vertical settlement along x-axis of the piled raft

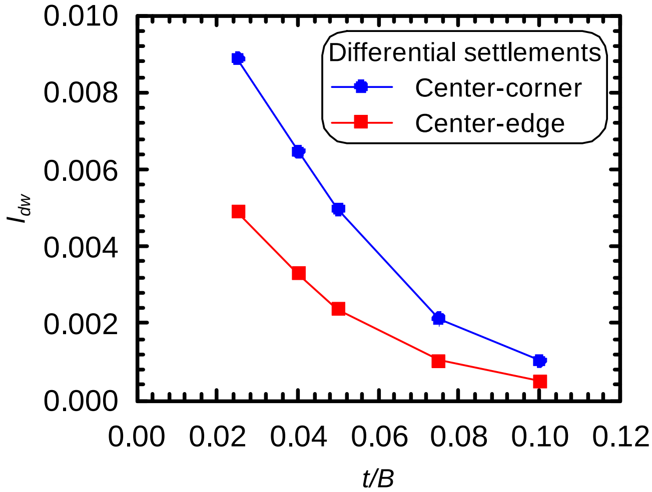


Figure 12 Effect of raft thickness on differential settlements of the piled raft

Figure 13 shows the effect of the raft thickness on the normalized bending moment in the raft along sec A-A (see Figure 10). The negative bending moment increases as the raft thickness increases. At the point located at 8.5m along sec A-A from raft edge, the bending moment increases by approximately 627.7% due to the increase of raft thickness from 0.5m to 2.0m. The rate of increase of this bending moment with the raft thickness is shown in Figure 14.

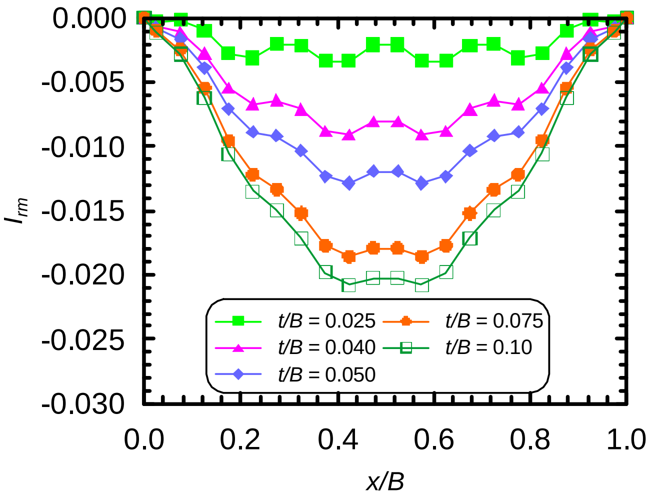


Figure 13 Effect of raft thickness on the bending moments along Sec A-A of the piled raft

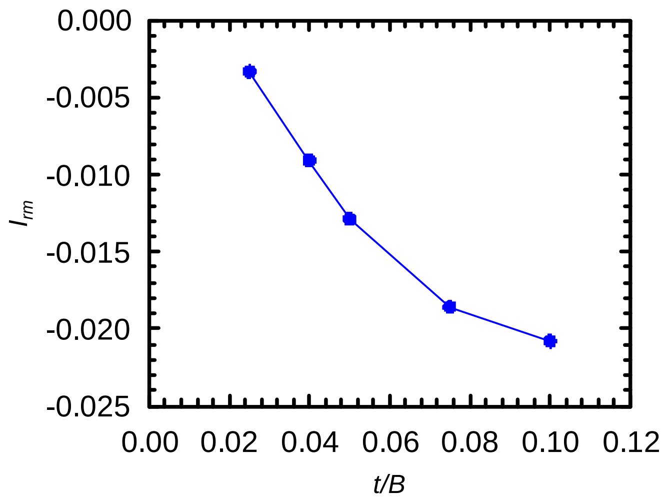


Figure 14 Effect of raft thickness on the bending moment at a point along sec A-A at a distance of 8.5m from raft edge

Figure 15 shows the effect of the raft thickness on the load distribution on the piles. The loads on three different piles are considered. These are pile No. 1 (i.e., corner pile), pile No. 3 (i.e., edge pile) and pile No. 13 (i.e., central pile). The effect of the raft thickness on the load carried by edge pile is too small and can be negligible. However, the load carried by corner pile increases as the raft thickness increases and inversely, the load carried by central pile decreases as the raft thickness increases. The increase in the load carried by corner pile is approximately 11.8% and the reduction in the load carried by center pile is 22.7% as the raft thickness increased from 0.5m to 2.0m.

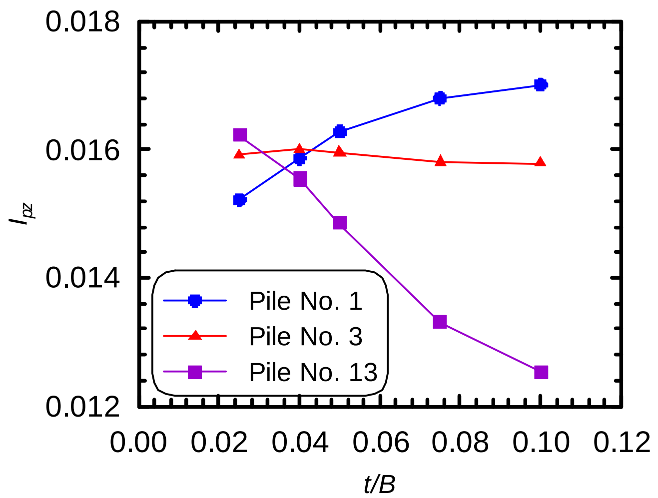


Figure 15 Effect of raft thickness on the loads carried by corner, edge and center piles

Effect of Soil Modulus of Elasticity

Figures 16 to 20 show the effect of the soil modulus of elasticity, E_s, on the behavior of the piled raft. The value of E_s is varied between 10MPa to 50MPa and the other parameters are kept constant at its basic values as presented in Table 3. Values of the different parameters dependant on the soil modulus of elasticity is calculated, as discussed in section 4, and presented in Table 4.

Figure 16 shows the effect of the soil modulus of elasticity on the normalized vertical settlement along the centerline of the raft. The vertical settlement along the x-axis decreases as the soil modulus of elasticity increases. The maximum settlement at the raft center decreases by 81.0% due to the increase in the soil modulus of elasticity from 10MPa to 50MPa.

Table 4 The value of different parameters used in the study of the effect of the soil modulus of elasticity

Parameter	Value				
Modulus of elasticity of the soil (kPa)	10000	20000	30000	40000	50000
Undrained cohesion (kPa)	40	80	120	160	200
Adhesion factor	0.94	0.788	0.692	0.596	0.5
Limiting shaft resistance (kPa)	37.6	63.0	83.04	95.36	100.0
Limiting pile base resistance (kPa)	360.0	720.0	1080.0	1440.0	1800.0
Ultimate bearing capacity of the raft (kPa)	240.0	480.0	720.0	960.0	1200.0

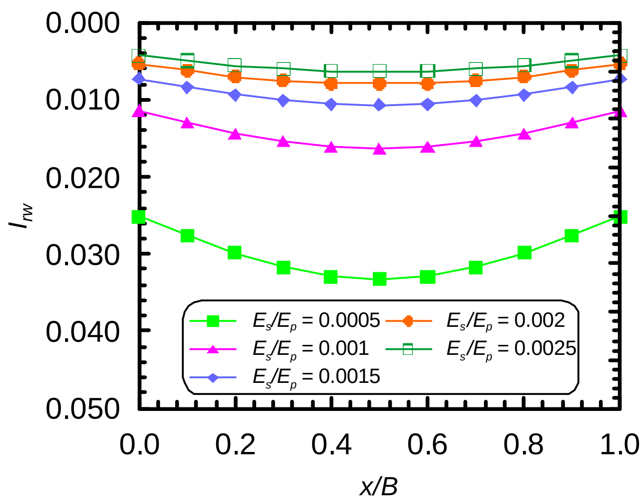


Figure 16 Effect of soil modulus of elasticity on settlement along x-axis of the piled raft

Figure 17 shows the effect of soil modulus of elasticity on the normalized differential settlements. The decreases in differential settlements (i.e., center-corner and center-edge) are 77.1% and 74.5%, respectively due to the increase in soil modulus of elasticity from 10MPa to 50MPa. The rate of decrease in differential settlements decreases as the soil modulus of elasticity increases as shown in Figure 17. This means that the effect of soil modulus of elasticity on total and differential settlements is significant.

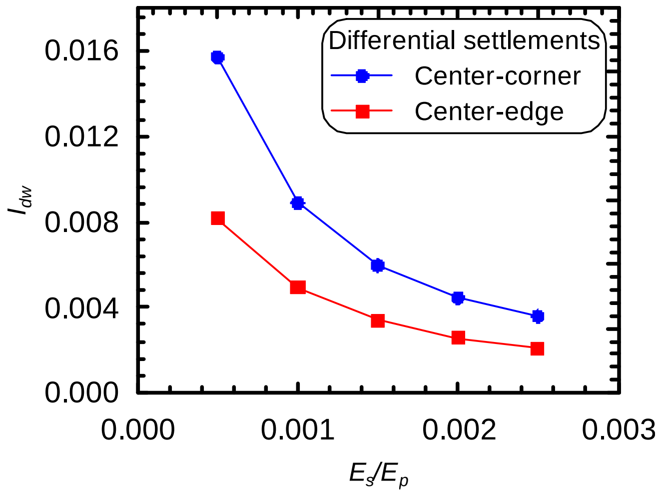


Figure 17 Effect of soil modulus of elasticity on differential settlements of the piled raft

Figure 18 shows the effect of soil modulus of elasticity on the normalized bending moment in the raft along section A-A (see Figure 10). The value of the negative bending moment decreases as the value of E_s increases. At the point located at a distance of 8.5m from the raft edge along sec A-A, the negative bending moment decreases as the value of E_s increases up to a certain value after which the value of the negative bending moment slightly increases as shown in Figure 19. Also from Figure 19, it is observed that the rate of decrease in the value of the negative bending moment decreases as the value of E_s increases.

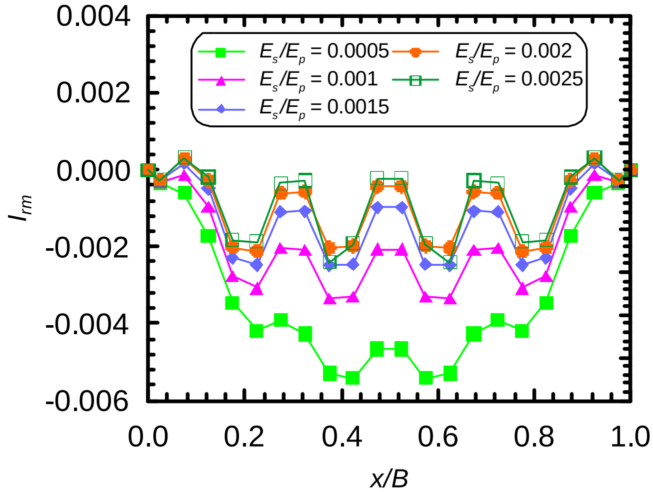


Figure 18 Effect of soil modulus of elasticity on bending moment along Sec A-A of the piled raft

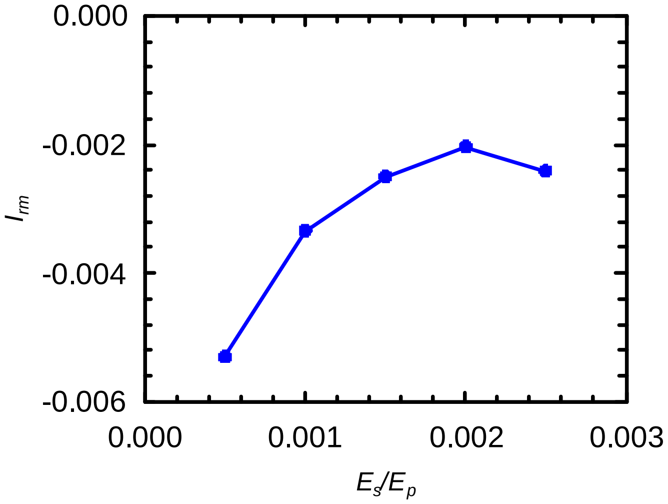


Figure 19 Effect of soil modulus of elasticity on the bending moment at a point on sec A-A at a distance of 8.5m from raft edge

Figure 20 shows the effect of soil modulus of elasticity on the load carried by the corner, edge and center piles (i.e., piles No. 1, 3 and 13). At the smaller value of E_s, the load carried by the piles are approximately equal as shown in Figure 20. As the value of E_s increases the loads carried by the piles (i.e., corner, edge and center piles) increase up to a certain value after which the loads on the piles are approximately constant. The difference between the loads carried by the three piles increases as the value of E_s increases (i.e., the central pile carry the maximum load and the corner pile carry the minimum load).

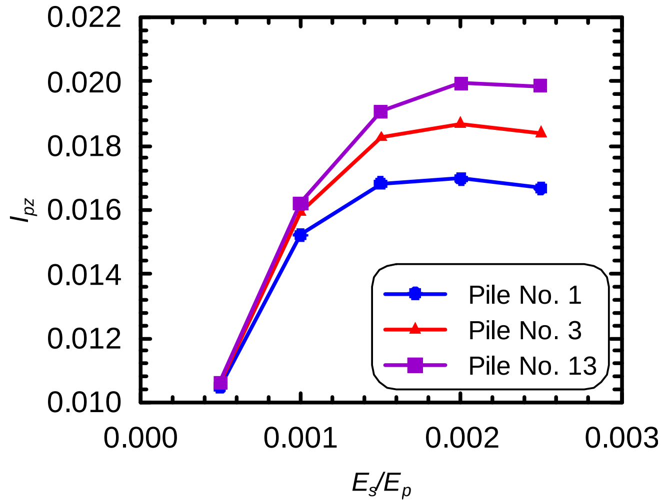


Figure 20 Effect of soil modulus of elasticity on the loads carried by corner, edge and center piles

Effect of Pile Length

Figures 21 to 25 show the effect of the pile length on the behavior of the piled raft. Figure 21 shows the effect of the pile length on the normalized vertical settlement along x-axis of the piled raft. Generally, the normalized vertical settlement decreases as the length of the pile increases. As the length of the pile increases from 10m (i.e., $L_p / D = 20$) to 30m (i.e., $L_p / D = 60$), the maximum vertical settlement at the raft center decreases by 26.2%.

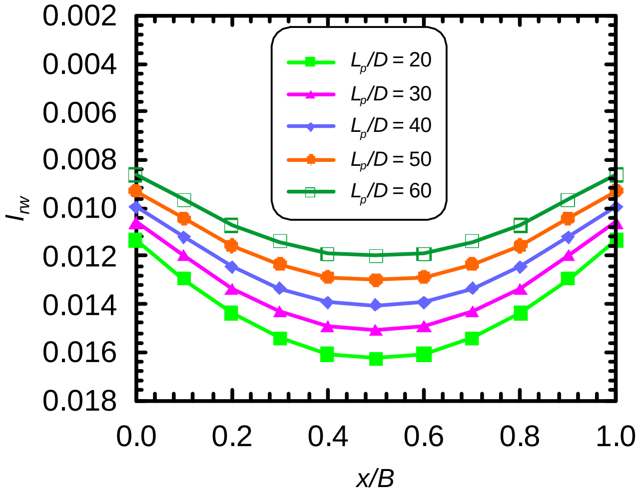


Figure 21 Effect of pile length on the vertical settlement along x-axis of the raft

Figure 22 shows the effect of the pile length on the differential settlements of the piled raft. As the length of the pile increases, the differential settlements (i.e., center-corner and center-edge) decreases. As the length of the pile increases from 10m (i.e., $L_p / D = 20$) to 30m (i.e., $L_p / D = 60$), the differential settlements (i.e., center-corner and center-edge) decreases by approximately 30.3% and 31.3%, respectively. From the above discussion, it is obvious that the effect of the pile length on both total and differential settlements is significant.

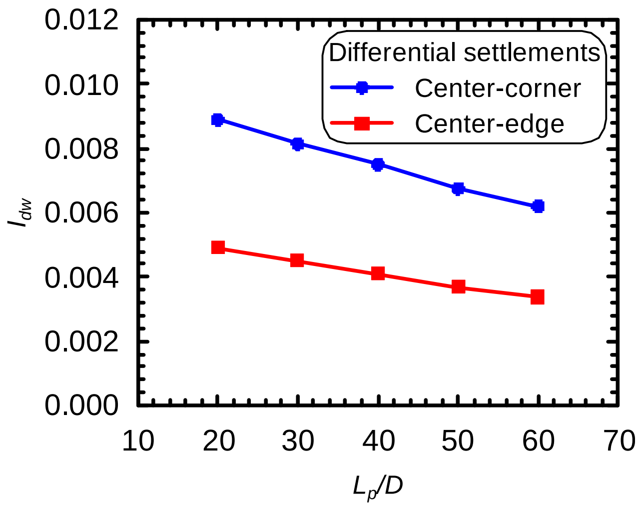


Figure 22 Effect of pile length on the differential settlements of the piled raft

Figure 23 shows the effect of the pile length on the normalized bending moment along sec A-A (see Figure 10) of the piled raft. The value of the negative bending moments along sec A-A decreases as the length of the pile increases. At the point located at a distance of 8.5m from the raft edge along sec A-A, the negative bending moment decreases as the value of the pile length increases as shown in Figure 24.

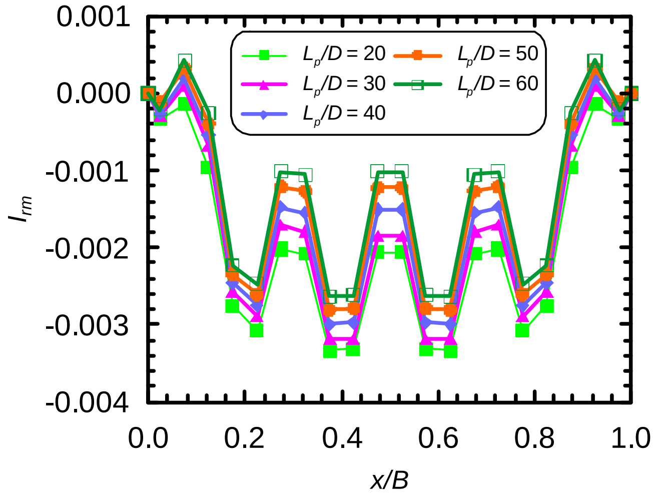


Figure 23 Effect of pile length on the bending moment along sec A-A of the piled raft

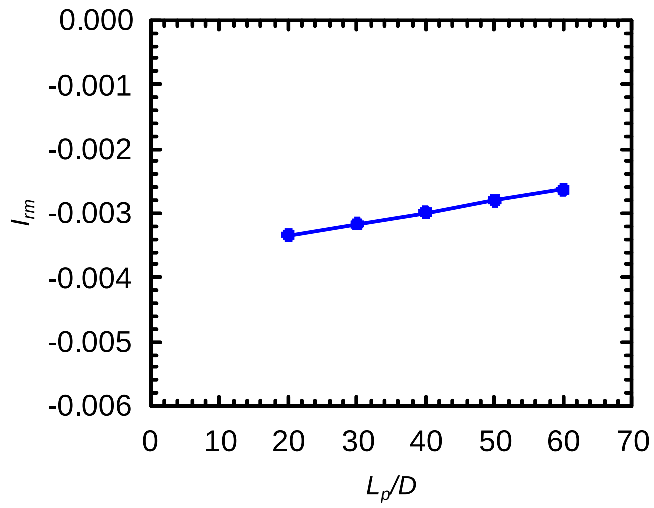


Figure 24 Effect of pile length on bending moment at the point located at 8.5m along sec A-A from the raft edge

Figure 25 shows the effect of the pile length on the load carried by pile No. 1 (i.e., corner pile), pile No. 3 (i.e., edge pile) and pile No. 13 (i.e., central pile). As the pile length increases, the load carried by the piles (i.e., pile No. 1, pile No. 3 and pile No. 13) increases. The rate of load increase for the three piles is approximately equal as shown in Figure 25.

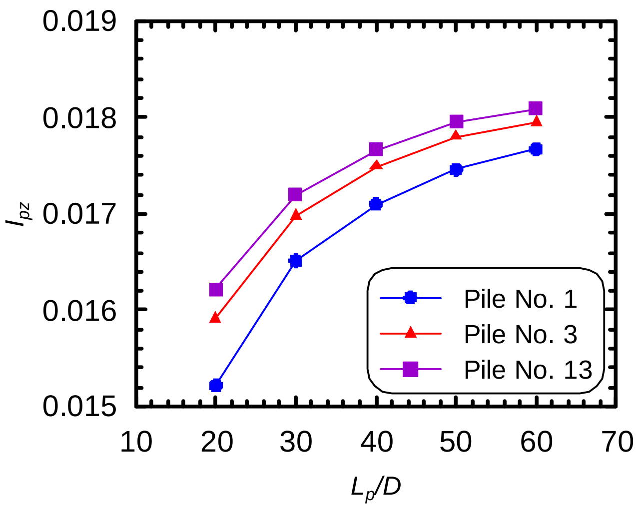


Figure 25 Effect of pile length on the load carried by corner, edge and center piles

Effect of Piles Configurations

To study the effect of piles configurations on the performance of piled raft, three pile configurations below the raft with three different S/D ratios are considered as shown in Figures 26, 27 and 28. These configurations will be referred hereafter as PC1, PC2 and PC3 for simplicity. For piles configurations PC1, PC2 and PC3, the S/D ratios are 8, 4 and 2 respectively.

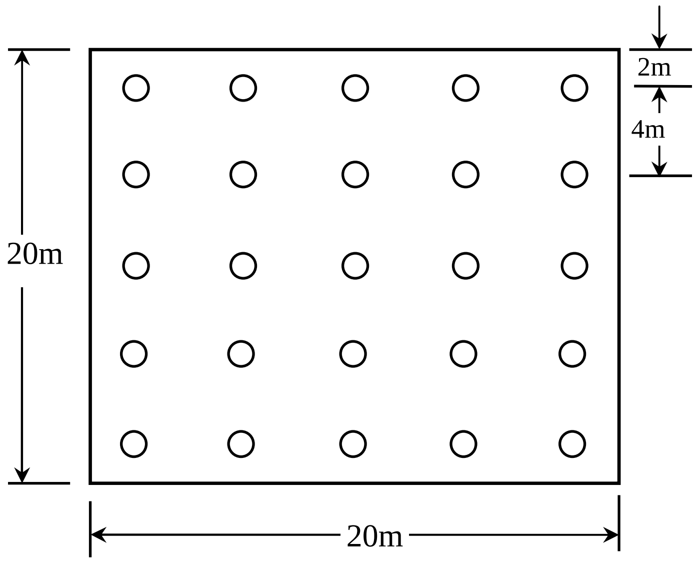


Figure 26 Pile configuration, PC1, with S/D = 8

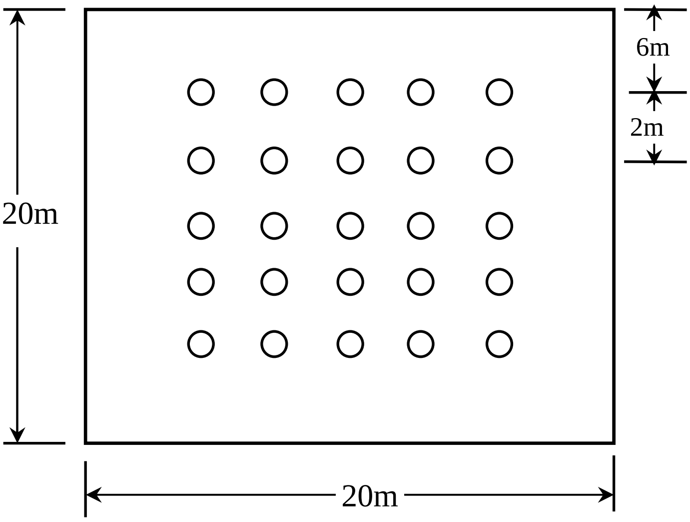


Figure 27 Pile configuration, PC2, with *S/D* = 4

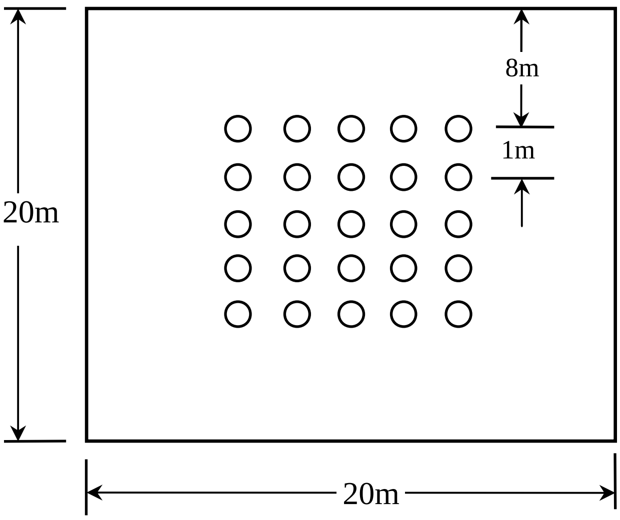


Figure 28 Pile configuration, PC1, with *S/D* = 2

Figure 29 shows the effect of the piles configurations on the normalized vertical settlements along the x-axis of the piled raft. Generally, the vertical settlements along the x-axis of the piled raft decrease as the area occupied by the piles beneath the central area of the raft decreases (i.e., the S/D ratio decreases). There are two differential settlements along x-axis for piles configuration, PC3, while, there is one differential settlement along x-axis for piles configurations PC1 and PC2 as shown in Figure 29.

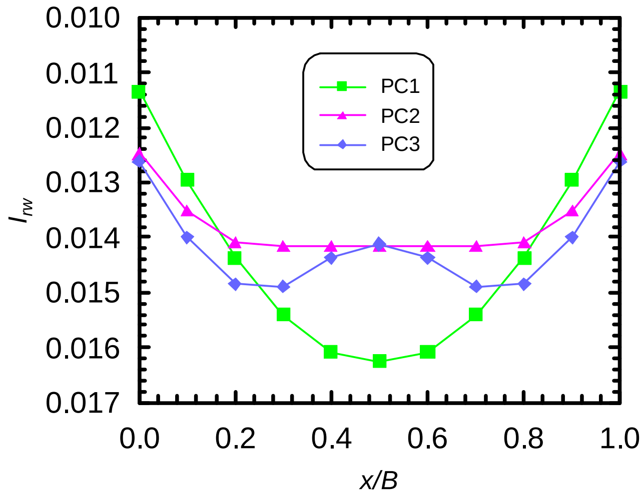


Figure 29 Effect of piles configurations on the vertical settlement along x-axis of the piled raft

Figure 30 shows the bar charts for differential settlements (i.e., center-corner and center-edge) for piles configurations PC1, PC2 and PC3. The minimum differential settlements (i.e., center-corner and center-edge) obtained with the piles configurations PC2 and PC3.

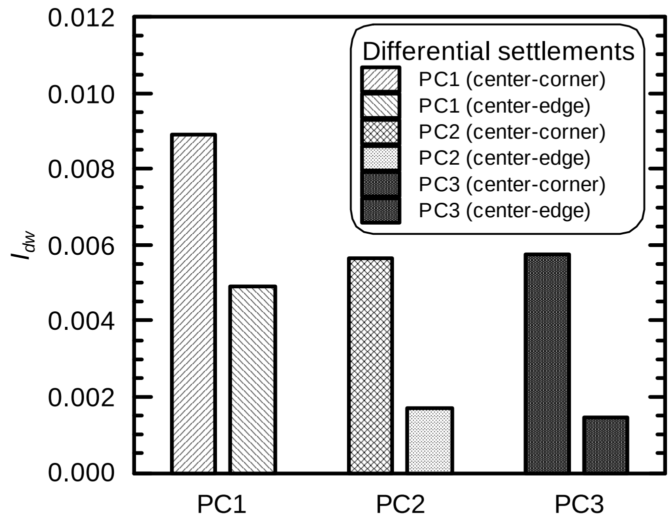


Figure 30 Effect of piles configurations on the differential settlements of the piled raft

Figure 31 shows the effect of piles configurations on the normalized bending moment along sec A-A of the piled raft. The values of the maximum positive and negative bending moments in the raft increases as the area occupied by the piles beneath the central area of the raft decreases (i.e., the S/D ratio decreases).

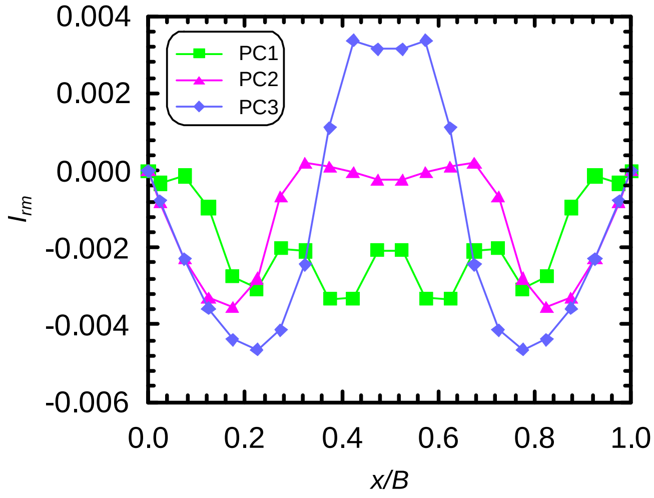


Figure 31 Effect of piles configurations on the bending moment along sec A-A of the piled raft

Figure 32 shows the effect of piles configurations on the load carried by pile No. 1 (i.e., corner pile), Pile No. 3 (i.e., edge pile) and pile No. 13 (i.e., central pile). As shown in Figure 50, the load carried by the three piles (i.e., corner pile, edge pile and central pile) decreases as the area occupied by the piles beneath the central area of the raft decreases (or as the S/D ratio decreases).

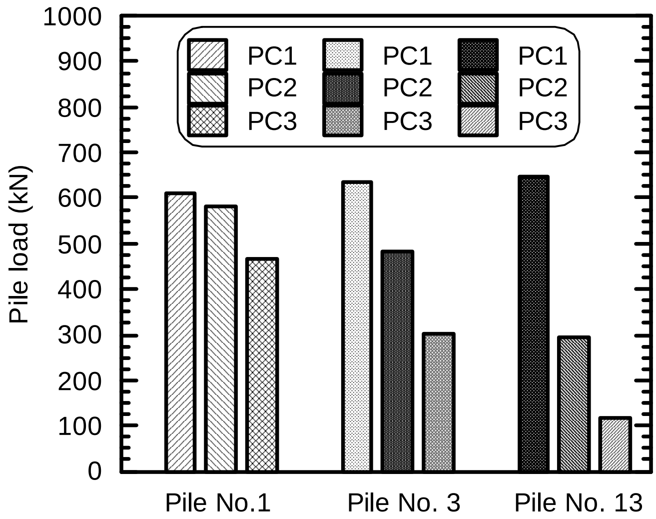


Figure 32 Effect of piles configurations on the load carried by corner, edge and center piles

CONCLUSION

Based on the results presented in this paper, the following conclusions may be drawn:

1. The method employed and the program developed produced good comparisons with the results of other analysis methods published in the literatures for piled rafts.

2. Increasing the raft thickness leads to a reduction in the overall settlement and a significant decrease in the differential settlement. Conversely, the bending moment in the raft increases with increasing the raft thickness. The proportion of load carried by the raft and piles is insensitive to the raft thickness whereas, the distribution of the loads on the piles is significantly affected by increasing the raft thickness. Increasing the raft thickness causes an increase in the load on the central pile, and a decrease in the load on the corner pile. However, the load on the edge pile is approximately not affected by increasing the raft thickness. For the case considered here, there is little or no benefit in increasing the raft thickness above about t/B = 0.075
3. The overall settlement, differential settlement and bending moment of the raft reduced significantly by increasing the soil modulus of elasticity. Increasing the soil modulus of elasticity leads also to an increase in the proportion of load carried by the piles and a decrease in the proportion of load carried by the raft. The distribution of the loads on the supporting piles (i.e., corner pile, edge pile and central pile) is approximately equal at low values of the soil modulus of elasticity. However, the loads on these piles increase as the soil modulus of elasticity increases. Generally, for the case considered here, there is little or no benefit in increasing the soil modulus of elasticity above about $E_S / E_p = 0.002$.
4. The overall settlement, differential settlement and bending moment of the raft reduced due to the increase of the pile length. Increasing the length of the piles leads also to an increase in the proportion of load carried by the piles and a decrease in the proportion of load carried by the raft. For the case considered here, the effect of the pile length on the distribution of the loads on the piles is insignificant.
5. The piles configuration beneath the raft has a profound effect on the overall and differential settlements and the bending moment of the raft. The reduction in the area occupied by the piles beneath the central area of the raft can reduce the overall and differential settlements, increase the bending moments of the raft and increase the percentage of the load carried by the raft. The loads on the corner pile, edge pile and central pile decrease as the area occupied by the piles beneath the central area of the raft decreases.

ACKNOWLEDGEMENT

This research is supported by the University of Tabuk (UT), Deanship of Scientific Research, under Grant No. S-1435H-0090. The author is gratefully acknowledges this financial support.

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