



Research article

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Numerical modeling of unconnected piled raft system

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Abstract. In recent decades, increasing attention has been directed toward the behavior of unconnected piled raft foundations (UCPRFs) under various soil conditions. In this foundation system, a cushion layer is introduced between the pile heads and the raft, preventing direct structural contact between these components. The cushion provides an intermediate load-transfer medium and facilitates the redistribution of the applied load between the raft and the piles. Understanding this interaction is essential for evaluating the overall response of the foundation and the contribution of its individual components. This study numerically investigated the behavior of UCPRFs using the finite element method implemented in PLAXIS. The analysis considered bearing pressure, foundation settlement, axial stress distribution along the piles, and bending moment response. A parametric investigation was conducted to evaluate the effects of pile length, pile diameter, and raft stiffness on settlement reduction and foundation performance. The results showed that axial stresses in the piles increased with increasing pile length and diameter, demonstrating the influence of pile geometry on load transfer within the foundation system. Furthermore, the maximum axial load occurred at a certain depth below the pile head, indicating that load transfer continued along the upper portion of the pile rather than being concentrated at its head. Within the investigated range, changes in the raft's modulus of elasticity had no significant effect on settlement reduction. These findings improve the understanding of load-transfer mechanisms in UCPRFs and clarify the relative influence of pile geometry and raft stiffness on their numerical response.

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1. Introduction

The main concern associated with a piled raft foundation system is the connection between the piles and the raft. Although the full geotechnical capacity of the piles may not be mobilized, significant shear forces and bending moments can be transferred from the raft to the pile heads, potentially resulting in excessive structural stresses or failure [1]. To address these problems, several researchers have proposed the use of unconnected piled raft foundations (UCPRFs), in which the piles are separated from the raft by an intermediate cushion layer [1–5]. In this system, a compacted granular cushion is placed between the raft and the pile heads, allowing the piles to function primarily as subsoil reinforcement rather than as structural components directly connected to the raft [3, 6]. The cushion layer facilitates load redistribution between the raft and the piles and modifies the load-transfer mechanism within the foundation system [2, 7].

The use of a structural fill cushion can also reduce stress concentrations at the pile heads and protect both the pile heads and the underlying soil from localized structural damage [6–9]. A structural fill cushion can be used to maintain the separation between the raft and the unconnected piles [12, 13]. Typically, the cushion consists of a sand–gravel mixture compacted in layers between the underside of the raft and the pile heads. This cushion plays an important role in mobilizing the bearing capacity of the underlying soil

and modifying the load-transfer mechanism between the raft, piles, and surrounding soil. The granular cushion redistributes the applied stresses beneath the raft and reduces the stress concentration transferred directly to the pile heads.

Tradigo et al. [14] investigated the variation of skin friction along the pile and the location of the maximum axial force, $N_{\max}$, in unconnected piled raft foundations. The settlement of the raft center, pile, and soil at the pile–soil interface was represented by w_r , w_p and w_s , respectively. For the connected piled raft configuration, w_r and w_p were approximately equal because the raft and piles were directly connected, whereas w_s was lower than w_r and w_p . Under these conditions, positive skin friction developed along the pile, resulting in the maximum axial force occurring near the pile head.

In contrast, different settlement patterns were observed in the unconnected piled raft configuration. Because the pile and raft were separated by the cushion layer, relative displacement between the pile and the surrounding soil varied along the pile length, resulting in a transition between negative and positive skin friction. According to Tradigo et al. [14], $w_p > w_s$ in the lower portion of the pile, resulting in positive skin friction extending toward the pile base. The transition between negative and positive skin friction defines a neutral plane, where the relative displacement between the pile and surrounding soil is approximately zero and the axial force reaches its maximum value, $N_{\max}$. Therefore, the axial force distribution along the unconnected pile is governed by the combined effects of negative and positive skin friction, as illustrated in Fig. 1. The researchers concluded that the negative skin friction observed by Cao et al. [2] is attributed to the existence of $w_r \geq w_s > w_p$ at the upper part of the pile shaft. While, along the lower portion of the pile shaft; $w_p > w_s$, so that positive skin friction develops up to the pile base.

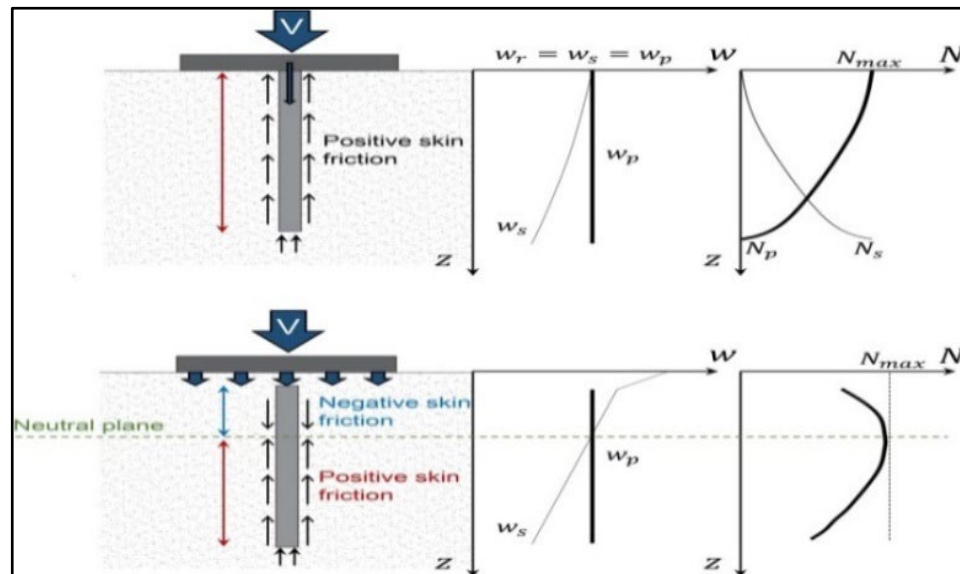


Figure 1. Settlement of the CPR and UPR [14].

The main advantages of unconnected piled raft (UPR) foundations can be summarized as follows:

1. A flexible cushion layer is placed beneath the relatively rigid raft to redistribute the applied external loads and modify the stress distribution between the piles and the surrounding soil [15].
2. Because the piles are not rigidly connected to the raft and cannot effectively transfer significant bending moments from the raft, they primarily function as subsoil reinforcement elements rather than conventional structural components [16].
3. The UPR system can provide an attractive alternative to conventional ground-improvement techniques, such as preloading, installation of vertical drains, electro-osmosis, grouting, and lightweight fills. The system can be implemented relatively quickly and generally does not require extensive soil replacement [17].
4. The UPR system uses vertical piles to improve the shear resistance and stiffness of the subsoil and reduce the potential for total and differential settlement. The granular cushion layer also limits the transfer of excessive shear forces and bending moments between the raft and the piles [18].

5. The cushion layer reduces stress concentrations at the pile heads and limits the direct transfer of excessive shear forces and bending moments between the raft and the piles, thereby improving the overall performance of the foundation system [19].

Despite these advantages, several limitations should be considered when using UPR foundations:

1. The UPR system may provide limited resistance to horizontal and lateral loads because the piles are not rigidly connected to the raft. Therefore, its application to structures subjected to significant lateral loads, such as structures located in areas with strong wind or seismic loading, requires careful assessment of lateral stability and deformation, as illustrated in Fig. 2 [2].
2. The stiffness and strength of the cushion layer should be carefully controlled to ensure adequate load transfer between the raft, piles, and surrounding soil. An improperly designed or poorly compacted cushion may result in excessive deformation and an inefficient distribution of load to the piles [15].

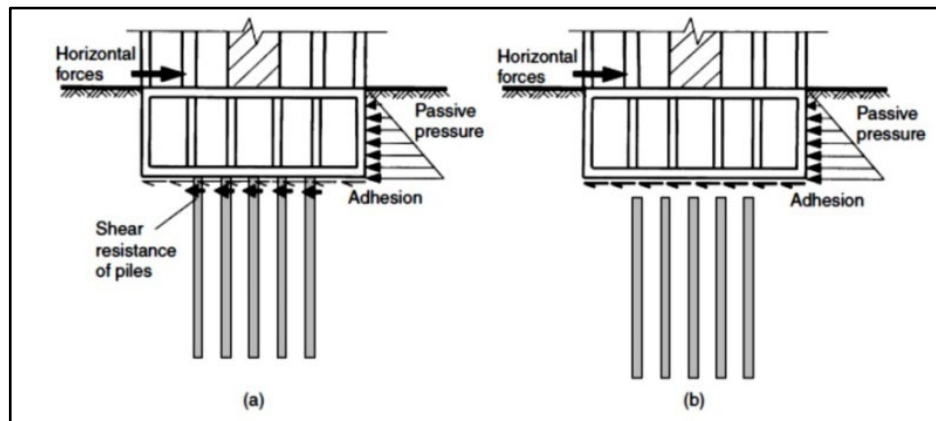


Figure 2. Transfer mechanisms for horizontal loads, (a) piles structurally connected to raft; (b) piles structurally unconnected from raft [2].

2. Methods

Using PLAXIS 3D [20], a finite element analysis was conducted to investigate the behavior of an unconnected piled raft foundation (UPRF) resting on sand. The Mohr–Coulomb (MC) constitutive model was employed to simulate the mechanical behavior of the soil and cushion layer. The soil domain was modeled with dimensions of $700 \times 700 \times 700$ mm, with a single borehole located at the center of the model. The soil volume was discretized using 10-node tetrahedral elements. The UPRF was subsequently analyzed under static loading. The overall numerical model and its boundary conditions are illustrated in Figs. 3–5. The standard Mohr–Coulomb constitutive model available in the PLAXIS 3D material library was used to represent both the sand and cushion sand. Standard fixities were applied to the model boundaries; the lateral boundaries were restrained against horizontal movement, while the bottom boundary was fixed in all directions. The material properties of the soil were defined in the PLAXIS 3D material data sets based on the results of laboratory tests. The raft and piles were modeled as linear-elastic structural elements. The Mohr–Coulomb elastic–perfectly plastic constitutive model was used to simulate the soil layers and cushion material. Table 1 presents the experimentally determined soil properties, whereas Table 2 summarizes the material properties of the raft and piles. A relatively coarse mesh consisting of 57,960 nodes and 36,429 soil elements was initially generated. The mesh size was selected based on mesh-convergence considerations, while local mesh refinement was applied around the foundation components to obtain a more accurate estimation of the foundation response.

The unconnected piled raft foundation (UPRF) consists of four main components: the raft, piles, surrounding soil, and cushion layer. The raft was modeled as a solid volume with dimensions of 11.5×11.5 cm and a thickness of 0.03 cm. The pile group consisted of four piles, each with a diameter of 1.6 cm and a length of 50 cm. Each pile was represented as a solid volume element. The interaction between the piles and the surrounding soil was governed by both shaft and base resistance. Special interface elements were introduced to simulate the pile–soil interaction and to account for the shear behavior at the pile–soil contact. The cushion layer, which represents the fourth component of the UPRF system, had dimensions of $23 \times 23 \times 5.8$ cm. Interface elements were also employed to simulate the interaction between the cushion and the surrounding soil. These interface elements allow the thin zone of highly sheared material that develops at the contact between different materials to be represented in the finite element model. Table 2 presents the material properties of the raft, pile cap, pile shafts, foundation soil, and cushion layer used in the PLAXIS 3D finite element analysis.

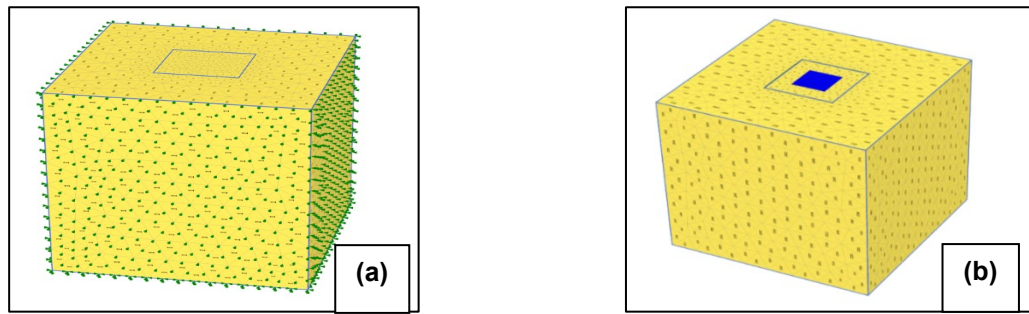


Figure 3. a): Boundary conditions of model and b) Finite element mesh of the model.

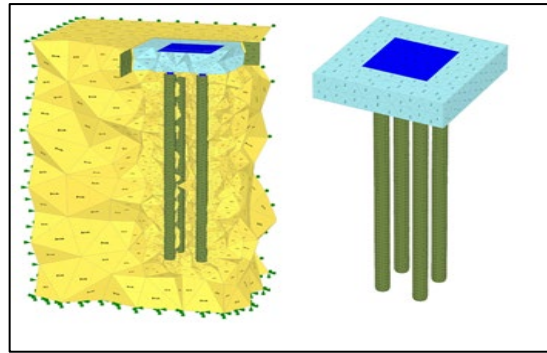


Figure 4. Finite element mesh of the unconnected piled raft foundation.

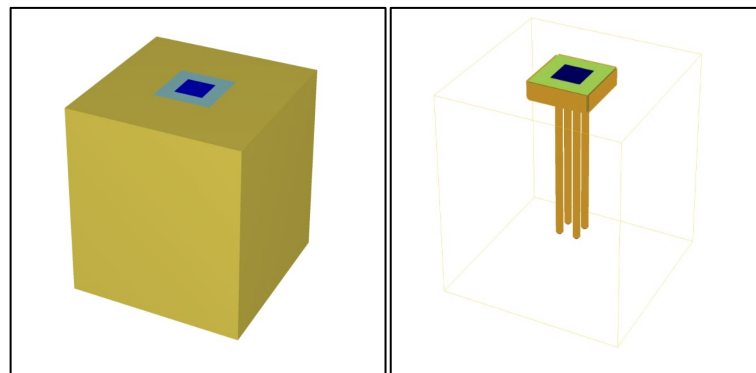


Figure 5. 3D modeling of unconnected pile raft model, $H/B=0.5$.

Table 1. Soil properties considered in MC model analysis.

Parameter	Unit	Soil bed	Cushion
Type of drainage	–	drain	drain
Dry unit weight, γ_d	kN/m ³	14.8	17
Angle of internal friction, ϕ	degree	30°	40°
Dilatancy angle, ψ	degree	0	10.2
Cohesion, c	kPa	0.2	0.2
Young's modulus, E_s	MPa	10	60
Poisson's ratio, μ	–	0.3	0.35

Table 2. Material properties of (raft and pile cap, and pile shaft, bed soil, cushion) used in PLAXIS 3D.

Model Parameters	Unit	Steel square plate	Aluminum pile shaft
Model type	Linear Elastic	Linear Elastic	Linear Elastic
Diameter, D	m	----	0.016
Wall thickness, t	m	0.003	0.001
Unit weight, γ_p	kN/m ³	70	27
Young's modulus	MPa	7.5×10^4	60×10^3
Poisson ratio, μ	–	0.29	0.30

3. Results and Discussion

4.1. Effect of Pile Length

To evaluate the effect of pile length on the performance of the unconnected piled raft foundation (UPRF), five different pile lengths 10, 20, 30, 40, and 50 cm were considered in the numerical analysis. According to Eq. (1), the piles with lengths of 10, 20, 30, and 40 cm were classified as rigid piles, whereas the 50-cm-long piles were classified as flexible piles, based on the criterion proposed by Fleming et al. [21], as expressed in Eq. (1).

$$\text{If } 0.25\sqrt{\frac{E_p}{G_l}} < \frac{L}{d} < 1.5\sqrt{\frac{E_p}{G_l}}, \quad (1)$$

where E_p and G_l are modulus of elasticity of pile and shear modulus of bearing soil layer.

Based on the results presented in Fig. 6, increasing the pile length resulted in a reduction in foundation settlement, which is consistent with the findings reported by [17]. The maximum settlement decreased, while the bearing capacity of the unconnected piled raft foundation (UPRF) increased as the pile length increased. The beneficial effect of increasing pile length on reducing foundation settlement was particularly evident in the results reported by [12]. The longer piles transferred a greater proportion of the applied load to the pile group, thereby reducing the settlement and bending moments of the model raft. This observation is also consistent with the findings of Cao et al. [2]. The variation in axial stress distribution along the piles is presented in Fig. 7. The results indicate that the axial stress generally increased with increasing pile length. However, the axial stress near the lower end of the pile decreased as the pile shaft became longer. In addition, the location of the neutral plane shifted to a greater depth as the pile length increased, which agrees with the observations reported in [12]. Furthermore, in the unconnected piled raft system, increasing the pile length caused the location of the maximum axial stress to shift downward from the pile head to a specific point along the pile shaft, consistent with the findings reported in [22,23]. Fig. 8 presents the bending moment distribution along the centerline of the model raft under loading for the different pile lengths. The results indicate that increasing the pile length did not produce a significant reduction in the bending moment within the raft foundation. A similar observation was reported by Cao et al. [2]. The total displacement distributions obtained from the finite element analyses for all investigated pile lengths are presented in Fig. 9.

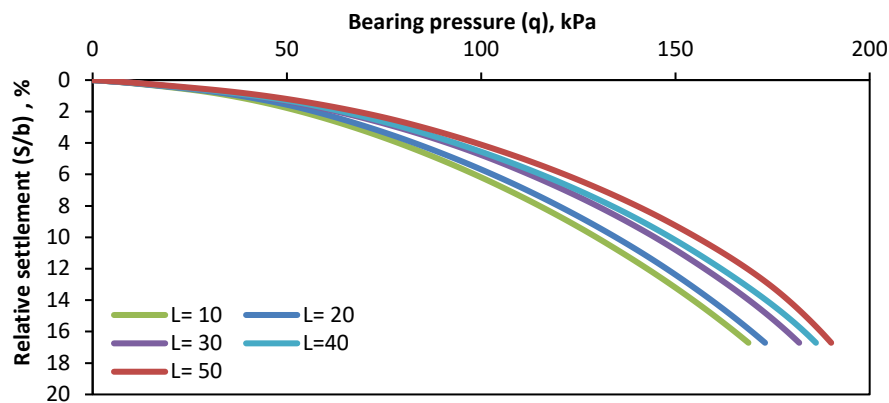


Figure 6. Variations of bearing pressures with relative settlements for different pile length of unconnected piled raft.

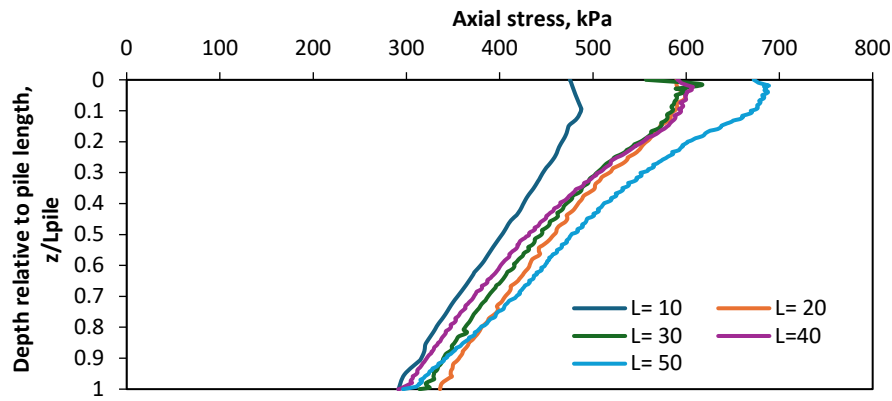


Figure 7. Distribution of axial stress along the center pile for unconnected pile raft for different pile length.

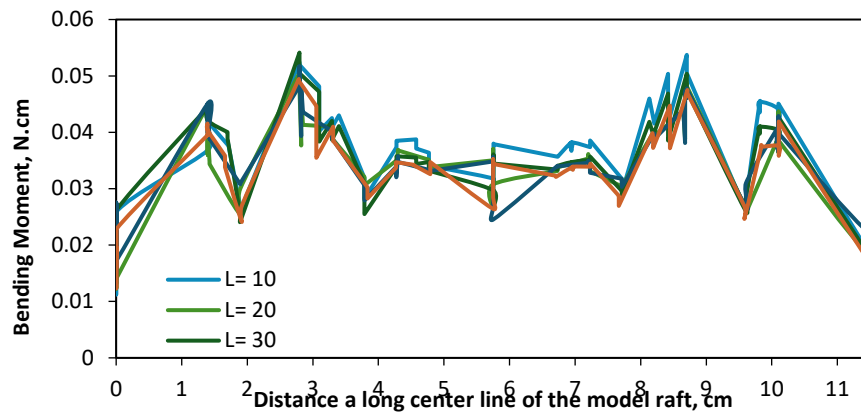


Figure 8. Bending moment diagrams along center line of the raft for unconnected pile raft for different pile length.

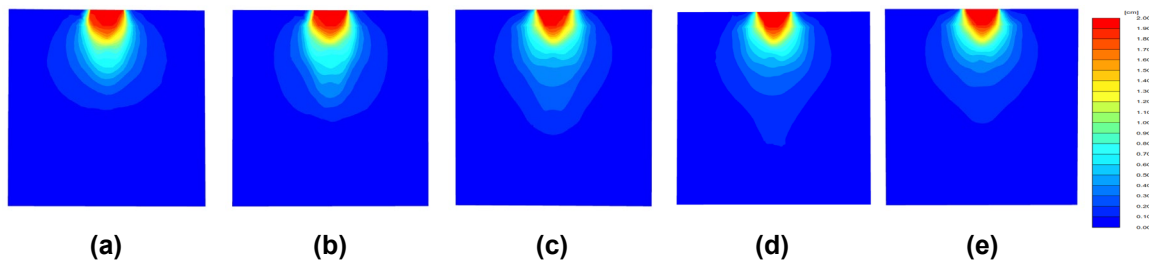


Figure 9. The total displacement finite element (scale up to 5 times) of a) L = 10 cm, b) L = 20 cm, c) L = 30 cm, d) L = 40 cm, and d) L = 50 cm.

4.2. Effect of Pile Diameter

To investigate the effect of pile diameter on the behavior of the unconnected piled raft foundation (UPRF), numerical analyses were conducted using pile diameters of 12, 16, 20, and 24 mm, while maintaining a constant pile length of 50 cm. The corresponding slenderness ratios (length-to-diameter ratio, L/D) were 41.67, 31.25, 25, and 20.83, respectively. According to the criterion given by Eq. (1), the piles were classified as rigid or flexible based on their slenderness ratios. Fig. 10 presents the relationship between the relative settlement (S/B) (%), and bearing pressure (q) for the different pile diameters. The results indicate that increasing the pile diameter while maintaining a constant pile length resulted in a reduction in the overall foundation settlement. This behavior can be attributed to the increase in pile stiffness associated with the larger diameter, which improves the load-transfer capacity of the pile group. In addition, increasing the pile diameter reduces the clear spacing between the piles for a constant raft configuration, thereby influencing the interaction between the piles and the surrounding soil [24, 25].

Fig. 11 presents the variation of axial stress along the pile shafts with depth for the different pile diameters. The results show that the axial stress distribution along the pile shafts generally increased with increasing pile diameter, indicating enhanced load transfer through the larger-diameter piles. Fig. 12 illustrates the bending moment distribution along the centerline of the model raft for the different pile diameters. The results indicate that increasing the pile diameter had no significant effect on reducing the

bending moment in the raft; however, a slight variation in the bending moment was observed as the pile diameter increased. Finally, the total displacement distributions obtained from the finite element analyses for all investigated pile diameters are presented in Fig. 13.

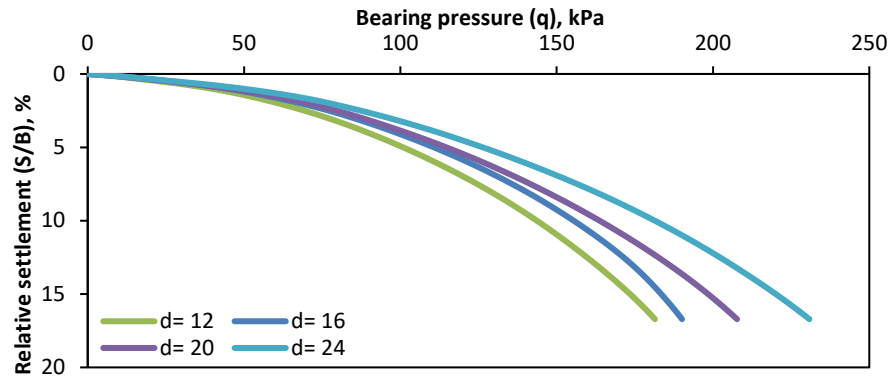


Figure 10. Variations of bearing pressures with relative settlements for different pile diameter of UPR.

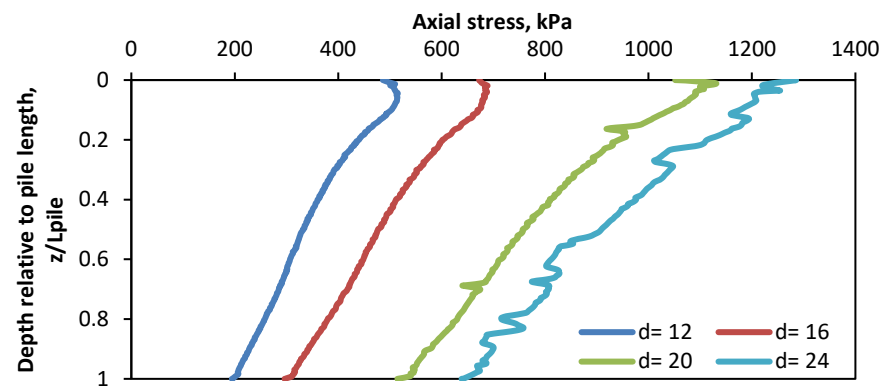


Figure 11. Distribution of axial stress along the center pile for UPR for different pile diameter.

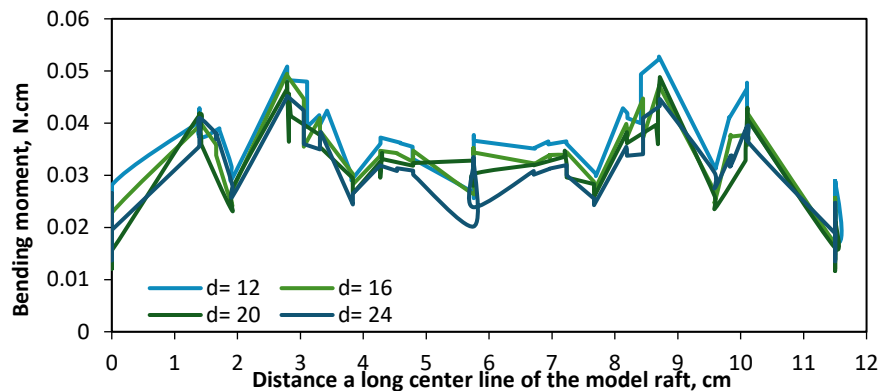


Figure 12. Bending moment diagrams along center line of the raft for UPR for different pile diameter.

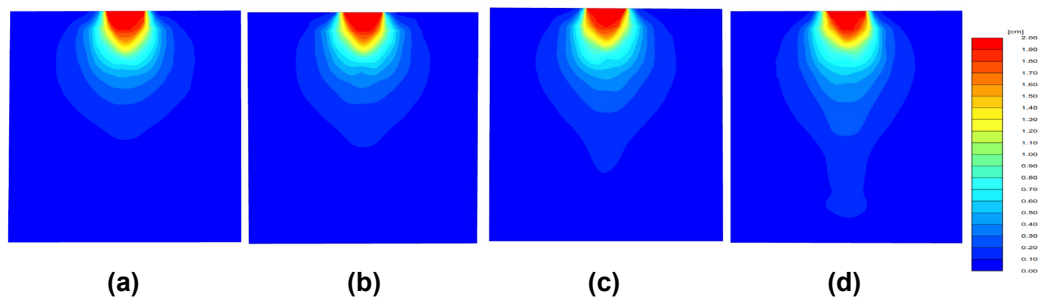


Figure 13. The total displacement finite element (scale up to 5 times) for a) d=12, b) d=16, c) d=20, and d) d=24.

4.3. Effect of Modulus of Elasticity of Raft

To investigate the effect of raft rigidity on the behavior of the unconnected piled raft foundation (UPRF), particularly the relationship between relative settlement (S/B) and bearing pressure, five different values of the raft elastic modulus (E_r) were considered: 5, 7.5, 10, 60, 75, and 180 GPa. The raft–soil relative stiffness, k_{rs} , was used to quantify the relative rigidity of the raft with respect to the supporting soil. According to [26], an expression for determining the raft–subsoil stiffness ratio (k_{rs}) was proposed, as given in Eq. (2).

$$k_{rs} = 5.57 \frac{E_r (1 - \mu_s^2)}{E_s (1 - \mu_r^2)} \left(\frac{B_r}{L_r} \right)^{0.5} \left(\frac{t_r}{L_r} \right)^3, \quad (2)$$

where B_r – width of the raft, t_r – thickness of the raft, L_r – length of the raft, μ – Poisson's ratio of the soil.

According to the above equation, the model raft with a thickness of 3 mm can be classified as a flexible raft when the raft–soil stiffness ratio, k_{rs} , is relatively low, with values of 0.486, 0.727, and 0.970. In contrast, the raft can be considered rigid when k_{rs} is sufficiently high, with values of 5.82, 8.10, and 17.46. Fig. 14 illustrates the relationship between bearing pressure and relative settlement (S/B) for the different values of raft elastic modulus. The results indicate that increasing the elastic modulus of the raft had no significant effect on the overall settlement of the unconnected piled raft foundation. The results clearly indicate that raft rigidity had a negligible effect on the overall foundation behavior, and no significant improvement in bearing capacity was observed with increasing raft stiffness. Furthermore, as shown in Fig. 15, increasing the elastic modulus of the raft did not result in a significant increase in the axial stress distribution along the pile depth. These results suggest that, within the range of raft stiffnesses investigated, increasing raft rigidity has a limited influence on load transfer to the piles and the overall response of the unconnected piled raft foundation. Fig. 16 illustrates the bending moment distribution along the centerline of the model raft for the different modulus of elasticity of pile. The results indicate that increasing the modulus of elasticity of pile foundation had significant effect on reducing the bending moment in the raft. The total displacement distributions obtained from the finite element analyses for all investigated pile diameters are presented in Fig. 17.

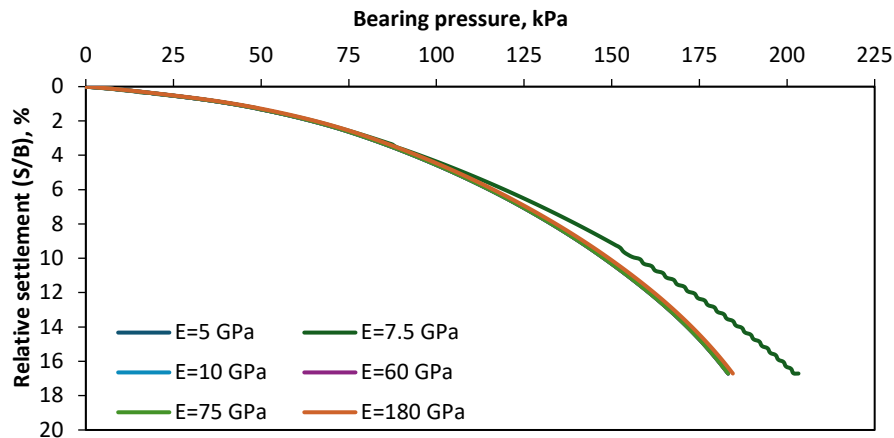


Figure 14. Variations of bearing pressures with relative settlements for different the modulus of elasticity of the raft of UPR.

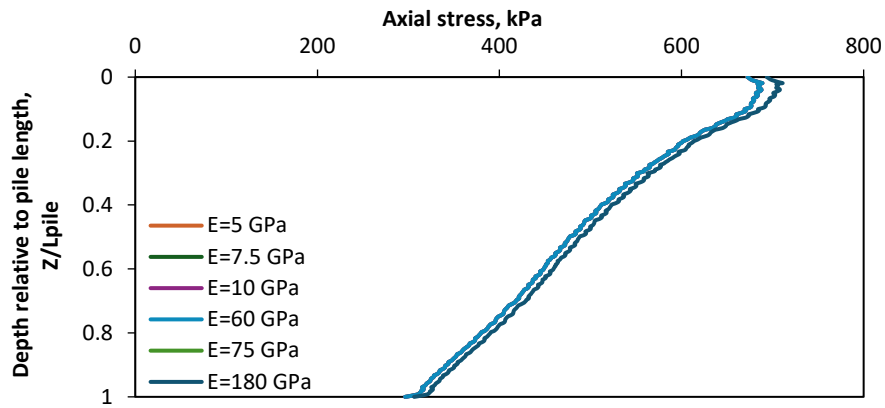


Figure 15. Distribution of axial stress along the center pile for different the modulus of elasticity of the raft of UPR.

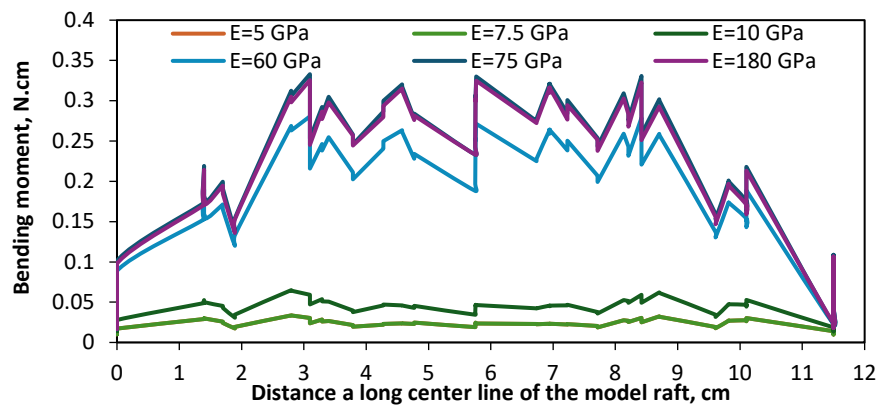


Figure 16. Bending moment diagrams along center line of the raft for different the modulus of elasticity of the raft of UPR.

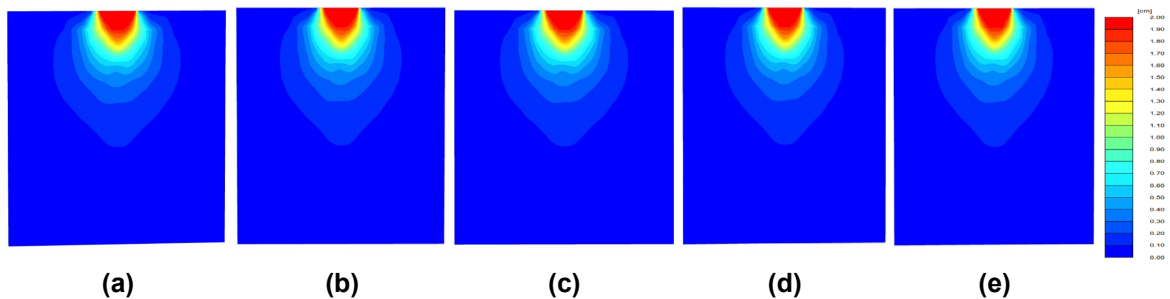


Figure 17. The total displacement finite element (scale up to 5 times) of a) E = 5 GPa, b) E = 7.5 GPa, c) E = 10 GPa, d) E = 60 GPa, and e) E = 180 GPa.

4. Conclusions

1. The maximum settlement is reduced and the bearing capacity of an unconnected pile raft foundation is increased as the pile length is increased, As the pile length increases, the settlement reduces.
2. The pile length increases in the unconnected system, the position of the maximum axial stress shifts lower to a specific location below the pile head.
3. An increased pile length did not lead to a significant reduction in the bending moment in center line of raft foundation.
4. The axial stress along pile shaft was increases as the pile diameter increased.
5. The effectiveness of increase the diameter of piles for bending moment reduction along the center line of the model raft is not significantly changed.
6. It is clear that the raft elastic modulus has no effect on the behavior of unconnected piled raft, the bearing capacity has been not improved.

7. The bending moment reduction along the center line of the model raft is significantly changed, increase with increase raft modulus of elasticity.

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