Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.18576/amis/180618

Load Sharing in Unconnected Piled Rafts of Different Spacings in Clayey Soils

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Received: 14 Mar. 2024, Revised: 20 May 2024, Accepted: 12 Aug. 2024.
Published online: 1 Nov. 2024.

Abstract: When piles are used to reduce raft settlement, significant shear stresses and bending moments can be created. Separate piles are utilized to alleviate concerns about high tensions in piles and rafts. A structural fill sand-gravel cushion in an unconnected piled raft foundation isolates the piles from the raft (UCPR). The cushion redistributes the load between the raft and the piles. This also prevents transferring moments from the raft to the piles. The effect of pile spacing in the foundation settlement and the load-sharing ratios of piles and raft were investigated by using the PLAXIS-3D finite element analysis software. The findings reveal that pile spacing is an important aspect in achieving a higher load ratio in the raft and a uniform load distribution among the piles. the settlement significantly decreases as the pile spacing increases from 2D to 3D, 4D, and 4.5D. The axial stress in the raft is affected by the pile spacing design. The decrease in pile spacing to 2D and 3D makes the raft carries a small ratio of the applied stresses, and with increase of pile spacing to 4D and 4.5D where the piles will cover all area under the raft, the stresses ratio in the raft increases by 25% and 65%, respectively, as compared with the connected piled raft. The pile load sharing ratio decreases by (90%, 90%, 56%, to 44 %) as the pile spacing varies from (2D to 3D to 4D and 4.5D), respectively.

Keywords: Piled raft; spacing; clay; finite elements; spacing.

1 Introduction

Long-short pile composite foundations bear both vertical and horizontal loads in many engineering applications (Lv, 2023). The piled raft foundation comprises three components: the raft, the piles, and the soil. The connected piled raft (CPR) principle is applied to produce a more economical design than pile foundations by utilizing the minimum number of piles needed to keep settlement within an acceptable range. A cushion layer is placed between the raft and the piles to avoid the connection reaction in which unconnected piles are used. In such circumstances, the piles will act as soil stiffeners rather than structural members. Wong et al. (2000) introduced a numerical investigation using plane strain finite element FE method to evaluate the behavior of unconnected piled raft, UCPR. The study showed that a much lower safety factor against structural failure of the piles could be used by disconnecting the piles from the raft. Because the piles can be considered soil reinforcement, members strengthened the subsoil rather than structural members carrying the applied load. Cao et al. (2004) reported that using unconnected piled rafts significantly reduces settlement and bending moments at the pile head. Tradigo et al. (2015) studied the soil-structure interaction mechanisms by using three-dimensional finite element analyses. The different pile configurations used a realistic range of raft-soil gaps under vertically applied loads. They concluded that the disconnected piles' system efficiently decreases the stress in pile, and bending moment in the raft. However, they also observed that increasing the raft-pile gap reduces overall settlement/stiffness efficiencies. Khalil (2000) carried out an experimental test in which a steel plate was used as a rigid raft on top of the soil. The effects of various factors, such as cushion thickness, the addition of geogrid layers and geocells, and stabilized soil material to increase cushion rigidity on a medium to stiff brown silty clay soil type, were also investigated. The results indicated that increasing the number of geogrid layers affects maximum settlement and load transfer to the pile group. Using soil additive materials such as cement and lime results in increased stiffness and load transmission to the pile group. Alhassani and aljorany (2019) studied the behavior of unconnected piled raft systems numerically using 3D finite element analysis via ABAQUS software. The numerical analysis was carried out to investigate the effect of thickness and stiffness of the cushion, pile length, stiffness of foundation soil, and stiffness of bearing soil on the performance of the unconnected piled raft. The results indicated that when unconnected piles are used, the axial stress along the pile is significantly reduced, e.g., the axial stress at the head of the unconnected pile is decreased by 37.8% compared with that related to the connected pile. Finally, Senoon et al. (2020) investigated the effect of cushion properties (thickness and material properties) and raft thickness on the distribution of load through piles lengths, raft settlement, and the portion

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of load carried by piles used the finite element software (plaxis 3D). The results showed that, the maximum settlement of raft increases as cushion thickness increases or raft thickness increases. While it decreases as cushion density increase. Zou et al. (2022) presented an extensive numerical analysis to investigate the lateral load and moment bearing performances of hybrid foundation, considering various potential influencing factors in sand-overlaying-clay soil deposits, with the complex lateral loads being simplified into a resultant lateral load acting at a certain height above the mudline. Finite element models were generated and validated against experimental data where very good agreements are obtained. The failure mechanisms of hybrid foundations under lateral loading are illustrated to demonstrate the effect of the friction wheel in the hybrid system. Parametric study showed that the load bearing performances of the hybrid foundation is significantly dependent of wheel diameter, pile embedment depth, internal friction angle of sand, loading eccentricity (distance from the load application point to the ground level), and the thickness of upper sandy layer.

Burland et al. (1977) first suggested the application of piles as only settlement reducers. The basic concept of this approach is to consider the foundation as several piles responsible for reducing the settlement to an acceptable level. These piles also carry a portion of the structural loads transferred from the foundation raft to piles. In other words, some portion of the load is taken by the foundation, and the piles tolerate the rest.

When the piles are used as settlement reducers, their total bearing capacity may be mobilized. A very little settlement in the soil is needed to mobilize the total bearing capacity of the shaft pile. In the presence of certain structural/geotechnical conditions, the use of a piled raft has been widely adopted as an effective foundation method for designing high-rise buildings because of the efficiency of piled rafts in:

- Increasing the global bearing capacity.
- Reducing the total and differential settlements.

2 Literature Review

The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) illustrated four kinds of interactions in piled raft foundation. These interactions are pile-pile, pile-raft, pile-soil, and raft-soil. In addition, the model has to simulate the increasing settlement of a single pile under increasing loads while taking into account the (Pile-Soil Interaction).

Therefore, it is necessary to calculate the ultimate skin friction of the pile as a function of depth, in-situ stresses, and the strength of soil layers. With increasing raft settlement, the vertical and the horizontal stress states change (Raft- soil Interaction).

Due to a higher stress-state of the soil, the ultimate shear strength of the soil and the bearing capacity of the pile increase (Pile-Raft-Interaction). When the pile spacing is small, the (Pile-Pile-Interaction) additionally has to be taken into account.

Randolph (1994) defined three design philosophies for piled rafts:

"Conventional approach" in which the piles are built as a group to take the majority of the load while at the same time making some allowance for the raft's contribution, primarily to the ultimate load capacity.

"Creep piling," in which the piles are configured to run at a working load at which major creeps begin to occur, is usually 70-80 percent of the ultimate load capacity. Sufficient piles are used to reduce the net contact pressure between the raft and the soil below the soil's pre-consolidation pressure.

"Differential settlement control," in which the piles are strategically located to minimize the differential settlement rather than essentially minimize the overall average settlement. Additionally, there is a more severe form of creep piling, in which the piles' maximum load capacity is used, i.e., some or all of the piles work at 100 percent of their ultimate load capacity. The theory is that piles are mainly used as settlement reducers while understanding that they also help increase the whole foundation system (Poulos, 2001).

Lee and Chung (2005) executed small-scale model tests on free-standing pile groups and piled footings in dense sand and analyzed the influence of the pile cap on the behavior of vertically loaded pile groups.

From the test results, the effect of the cap in contact with the underlying soil results in an increase in the skin friction, mainly after the pile yielding load has been reached, with dependency on the pile spacing. They also observed that a much lower load is carried by the raft in piled rafts than by the raft alone, at least at the initial loading stage.

Fioravante et al. (2008) performed centrifuge tests on rigid circular piled raft models in overconsolidated clay. They found that the load distribution within a pile group under a rigid raft, in the operating load range, is not uniform and is consistent with the prediction of linear–elastic analysis. They also observed that the load transfer mechanism within a group of settlement reducing piles is different from that observed for an isolated pile, and the difference can mainly be ascribed to the effect of the load that is transferred by the raft to the soil and the additional confinement between the neighboring piles.

El-Mossalamy et al. (2006) defined the behavior of piled raft foundation design as shown in Figure 1 so that, $\alpha_s = 1$ means conventional raft foundation while α_s gets closer to zero, conventional pile foundation is observed.

$0 < \alpha_s < 1$ is the region of piled raft foundation.

On the other hand, $\alpha_L = 0$ means conventional raft foundation while α_L gets closer to 1, conventional pile foundation is observed.

$0 < \alpha_L < 1$ is the region of piled raft foundation.

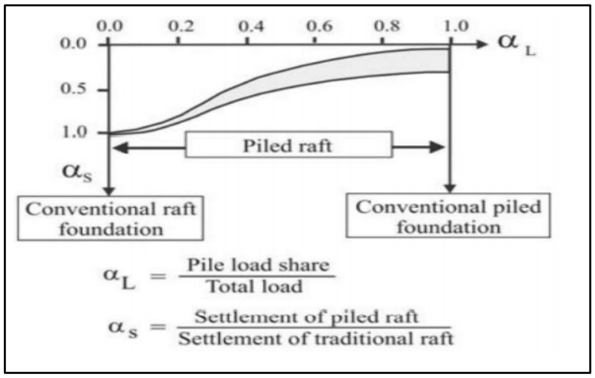


Fig. 1: αs and αL values for piled raft foundation design (El-Mossallamy et al., 2006).

The study carried out by Fattah et al. (2013a) was devoted to carrying out numerical analysis by the finite element method of the consolidation settlement of piled rafts over clayey soils and detecting the dissipation of excess pore water pressure and its effect on the bearing capacity of piled raft foundations. The ABAQUS computer program is used as a finite element tool. Five different configurations of pile groups are simulated in the finite element analysis. It was found that the settlement beneath the piled raft foundation resulted from the dissipation of excess pore water pressure considerably affects the final settlement of the foundation, and enough attention should be paid to settlement variation with time. The settlement behavior of the unpiled raft shows a bowl-shaped settlement profile with a maximum at the center. The degree of curvature of the raft under vertical load increases with the decrease of the raft thickness. For the same vertical load, the differential settlement of raft of (10x10 m) size decreases by more than 90% when the raft thickness increased from 0.75 m to 1.5 m. The average load carried by piles depends on the number of piles in the group. The groups of (2x1, 3x1, 2x2, 3x2, and 3x3) piles were found to carry about 24%, 32%, 42%, 58%, and 79% of the total vertical load. The distribution of load between piles becomes more uniform with the increase of raft thickness.

Fattah et al. (2013b, 2015) carried out an experimental study to investigate the behavior of piled raft systems in different types of sandy soil. A small-scale “prototype” model was tested in a sand box with load applied to the foundation through a compression jack and measured using a load cell. Nine configurations of a group (1×2, 1×3, 1×4, 2×2, 2×3, 2×4, 3×3, 3×4, and 4×4) were tested in the laboratory as a free-standing pile group (the raft not in contact with the soil) and as a piled raft (the raft in contact with the soil), in addition to tests for raft (unpiled) with different sizes. It is found that when the number of piles within the group is small (less than 4), there is no evident contribution of the raft to the load-carrying capacity. The failure load for a piled raft consisting of 9 piles is approximately 100% greater than a free-standing pile group containing the same number of piles. This difference increases to about four times for the 16-pile group. The piles work as settlement reducers effectively when the number of piles is greater than 6 than when the number of piles is less than 6. The settlement can be increased by about 8 times in (1×2) free-standing pile group compared to the piled raft of the same size. The effect of the piled raft in reducing the settlement vanishes when the number of piles exceeds 6.

Unconnected Piled Raft Foundation (UCPR)

Generally, the low number of piles in a pile raft system can cause significant bending moments and cracks and axial stress concentration at the tip of the piles. However, in the seismically active areas, in the pile's sections connected to the raft**,** massive shear forces, as well as failure moments, can develop at their tip due to the lateral dynamic load. In these cases, the possibility of foundation structural failure is more significant than soil failure.

Thus, to increase the bending moment of piles and prevent structural damage, the dimensions of piles have to be increased. In most design codes (ASTM 1969, British Standard 1986, Singapore Code 2002), substantial limitations have been imposed for the allowable stresses in the piles, which may lead to the uneconomical design of the foundation system.

The design concept of piled raft foundation has been proved to be an economical way to improve the foundation's performance by reducing settlements to acceptable levels. However, the piled raft foundation might not be applied in some circumstances.

Poulos (2001) outlined unfavorable situations involving soft clay layers or loose sand layers near the surface, soft compressible layers at relatively shallow depths, and others.

Therefore, Wong et al. (2000) suggested that to overcome the significant stresses between the foundation and piles, piles should be unconnected with the raft and considered the structural reinforcing elements in the soil underneath. For this purpose, a new type of piled raft foundation was developed in engineering practices**.**

Liang et al. (2003) proposed a type of foundation as shown schematically in Figure 2. It is named as "composite piled raft with cushion" (for short as "CPRC"). For this new type of foundation, short piles composed of relatively flexible materials such as mixed soil-cement or sand-gravel columns were applied to improve the bearing capacity of shallow natural subsoil.

Long and rigid piles were embedded in deep stiff clay or other supporting strata to reduce the settlement, while the gravel cushion placed on top of the piles plays an essential role in mobilizing the bearing capacity of subsoil and modifying the stresses transferred to piles.

Analysis of (UCPR)

Unconnected piled raft UCPR acts as a composite structure consisting of the raft, cushion, and non-uniform piles. In the new type of foundation, the cushion made of gravel on top of the piles plays an important role.

Firstly**,** gravel cushion between the raft and piles can adjust the load sharing ratios of piles and subsoil and enhance the strength of subsoil among piles. Notably, it could avoid the separation between raft and subsoil effectively, which occasionally occurred in the practices of coastal cities in China such as Shanghai (Zhao, 1998).

Secondly, the setting of gravel cushion assumes analysis closer to the actual boundary conditions of piled raft foundation. Thus, in the analysis of piled raft foundations, the interface between raft and soil is commonly assumed to be smooth and continuous. The connection between the raft and the pile is assumed to be a sliding ball joint for only the vertical forces transmitted from the raft to the head of piles, as shown in Figure 3 (Hain, 1975).

The two assumptions imply that only the vertical component of the contact stress is presented**.** The presence of gravel cushion makes only the vertical forces be transmitted.

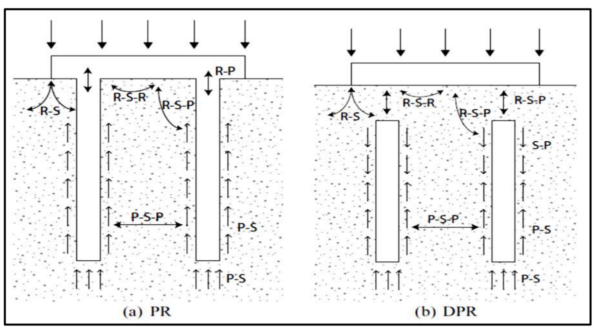


Fig. 2: Interactions between soil and structural members (R = raft; P = pile; S = soil), (Tradigo et al., 2016).

Many researchers in recent years have reported their research about connected and unconnected pile rafts. They examined the various parameters such as arrangement, length, and the number of piles, stiffness of the foundation, eccentricity of load, and relative density of sand, in addition to load transition mechanism.

The behavior of unconnected piled raft has been investigated using small-scale models. In the available literature, the main conclusions obtained from experimental investigations were reported by Cao et al. (2004), Fioravante and Giretti (2010), and Fioravante (2011).

Fioravante et al (2010) and Fioravante (2011) conducted an experimental investigation by centrifuge tests on rigid model rafts supported by one or more piles. Different thickness values of the interposed granular layer (cushion) between the raft and the piles were used. They concluded that, in unconnected piled rafts, the interposed of a granular layer between the raft and pile heads has an essential role in the downward relative displacement between the subsoil and pile, which appears along with a certain depth the pile heads. They also added that the piles are loaded through their heads and the negative skin friction acting on their upper shaft. Then, the pile will settle due to the head load and negative skin friction.

Consequently, the positive skin friction will be mobilized on the lower shaft and of the base resistance. It was found that the stiffness and thickness of the interposed cushion layer governed this mechanism. Also showed that the efficiency of the unconnected piled rafts could be lower than that of the analogous connected piled raft if the granular cushion layer is not stiff enough because the pile's bearing capacity is not fully mobilized. This study proved most of the results obtained by Cao et al. (2004), in particular, the axial force distribution along with the piles.

Wong et al. (2000) employed a parametric study based on the plane strain finite element method to evaluate the performance of unconnected piled raft. They showed that a much lower safety factor against structural failure of the piles could be used by disconnecting the piles from the raft. Thus, the piles can be considered soil reinforcement members were strengthening the subsoil rather than as structural members carrying the applied load.

Liang et al. (2003) studied numerically in the elastic regime the effect of stiffness of cushion and the gap thickness on load redistribution over long (located under the center of the raft) and short (distribute along the perimeter of the raft) piles. The long piles were used as settlement reducers, made from relatively rigid materials. While the short piles were used to strengthen the shallow soft subsoil made from flexible materials, the raft's cushion was found to redistribute and adjust the stress ratio of piles to the subsoil. The thickness and stiffness of the cushion, the pile length, and the elastic modulus of piles were investigated. The foundation settlement, as well as the pile load sharing ratio, were studied in detail. The study proposed optimizing the piling configuration to distribute the loads evenly and mitigate the stress concentration on the longer piles. It had been successfully applied the conclusions obtained from this study to practical buildings in the coastal cities of China.

Cao et al. (2004) performed an experimental investigation on small-scale models subjected to a vertical loading to assess the efficiency of the unconnected piles as settlement reducers. Many parameters were studied, as the raft stiffness, the pile's length, the spatial setup, and the number of piles to evaluate their influence on the average and differential settlements. Furthermore, to obtain the axial forces within the piles and the bending moments within the raft, strain gauge measurements and structural members were performed. The main conclusion drawn is that the maximum axial force located at a certain depth from the pile head is at variance with the connected piled raft in which the maximum axial force is located at the pile head. This finding explained the negative skin friction along the upper part of the piles, Figure 3.

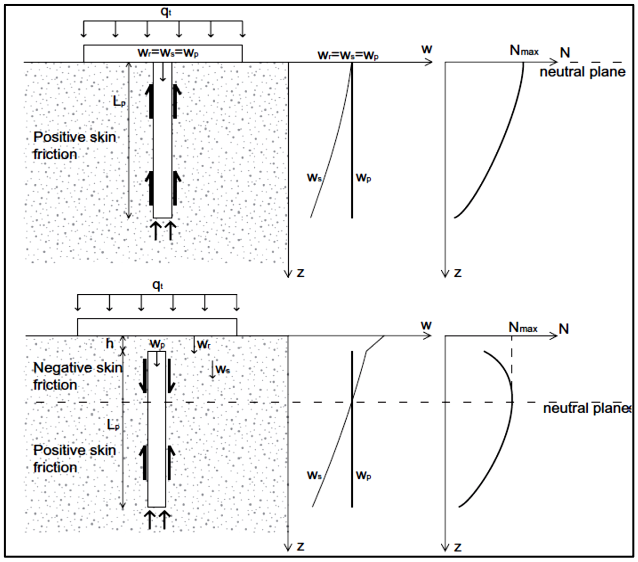


Fig. 3: Connected and unconnected piled raft settlements along with the pile depth (Gao et al., 2004).

Liang et al. (2005) presented a numerical analysis by simulating the cushion layer with Winkler springs. The study's main aim was to optimize piled raft foundation by varying the cushion rigidity. The study showed that a cushion made with sand-gravel materials plays an essential role in mobilizing the subsoil's bearing capacity and modifying the load transfer mechanism of piles. The load sharing ratio of subsoil increased obviously after optimization, and then the bearing capacity of subsoil could be better used with the appropriate cushion technique

El Sawwaf (2010) investigated the connected and unconnected piled raft models system. The effect of the connected or unconnected short piles on the performance of the foundation system under asymmetrical loading was explored. Many parameters were studied, including the number and length of piles, the configuration of piles, the relative density, and the eccentricity of the load. The results showed that short piles have a considerable influence on improving the performance of the piled raft foundation model under eccentric loads. Furthermore, the results indicated that to overcome the eccentricity of loads, the best locations for installing the piles are the edges of the foundation. In addition, insertion of a granular layer between the raft and piles similar to the tested soil (without gradation and compaction) and causes an improvement in the foundation's performance with unconnected short piles is better than that of a connected case.

Sharma et al. (2011) claimed that they modified the concept of the piled raft to a new type of foundation named composite piled raft. The modified system used short and long piles, the flexible short piles to strengthen the shallow soft soil, and the long rigid piles to reduce the settlements. The cushion underlines the raft was used to redistribute and adjust the stress ratio of piles to the subsoil. They studied the behavior of the modified type of foundation subjected to vertical load using the finite element method. They investigated the effect of the cushion layer on some properties of composite piled raft foundation systems, such as the axial stresses in piles, superimposed stress on subsoil, and settlements of piles and subsoil. They showed that using the cushion will adjust the load-sharing ratios evenly among the piles. Furthermore, they reported that the bearing capacities of shallow subsoil could be better used through appropriately applied cushion technique, especially for ground containing hard crust in shallow layers. Compared with the connected piled raft, the maximum axial stress shifts lower from the piles' head to a certain depth.

Eslami et al. (2012) performed a numerical analysis for the unconnected piled raft to present a design optimization by investigating different parameters such as piles spacing, embedment length, the configuration of the piles, and raft thickness. They showed that an optimum design with the minimum total length of piles is achieved by located the piles under the central area of the raft foundation. They also concluded that the unconnected piled raft foundation could considerably minimize the settlements and raft bending moments by increasing the stiffness of the subsoil stratum.

Tradigo et al. (2015) studied the soil-structure interaction mechanisms by using three-dimensional finite element analyses. The different pile configurations used a realistic range of raft-soil gaps under vertically applied loads. They concluded that the disconnected piles' system efficiently decreases the stress in pile, and bending moment in the raft. However, they also observed that increasing the raft-pile gap reduces overall settlement/stiffness efficiencies.

Rasouli et al. (2015) conducted 17 centrifuge tests to study various parameters such as the number of piles, the distance between piles, gradation, and thickness of the granular layer on the load-settlement behavior of a pile raft system. The results showed the importance of a granular layer to reduce the settlement of unconnected pile raft systems when the roles of piles are to reduce the settlement. In other words, when the piles have a significant contribution to the bearing capacity of the pile raft system, a granular layer may decrease the settlement.

Zhu (2017) performed experimental tests on piled raft models to explore the influence of a gravel cushion interposed between a raft and piles. The insertion of a deformable cushion between a raft and pile heads allows downward soil-pile relative displacement, which produces negative skin friction on the upper part of the shaft. The study's main conclusions were the settlements of the raft increased with the cushion thickness and decreased with the pile diameter. In addition, the pile-soil stress concentration ratio decreased with the Hc/D ratio and with the particle size of the gravel cushion.

Azizkandi et al. (2019) presented an experimental test of a square foundation on the effects of parameters such as S/D, L/D, etc. where (S: distance between piles, D: pile diameter, and L: length of the pile) in two cases of connected or unconnected piled raft system under the eccentrically loaded raft. The results showed that for square raft with S/D = 3 and L/D = 8, the bearing capacity of the unconnected piles is more than that of the connected piles. However, by decreasing the pile spacing, the bearing capacity is increased in unconnected pile raft.

An experimental investigation to examine the behavior of piled-raft foundations in loose sand was introduced by Fattah et al. (2024). A small-scale model was tested in a sandy soil container.

Three sensors were fabricated on the pile heads to record the axial load induced by any pile in the group, and the foundation's settlement was also measured. In addition to experiments for an unpiled raft, model groups for 1 pile, 1 × 2, 1 × 3, 2 × 2, 2 × 3, 3 × 3, 3 × 3 triangle heaps, 4 diamond piles, 5 piles, and 9 circle piles were tested in the lab. The loading test was carried out until a relative pile displacement of 10 % of the length of the raft was passed. It was found that the piled-raft models with piles placed in uniform configurations (2 × 2 and 3 × 3) showed an increase in bearing capacity higher than that of piled rafts with the circle and diamond configurations, but not higher than that of triangular configuration. Also, it was found that when the value of loading was 1,000 N and the pile spacing increased from 2.5d to 3d, the settlement increased from 11 to 13 mm, 9.5 to 11 mm, 8.5 to 10 mm, and 7 to 9 mm for models PR2, PR3, PR4, and PR5 (referring to 2-, 3-, 4-, and 5-piled-raft models), respectively.

The goal of this research is to see how a compacted granular cushion placed directly above the pile group affects load transmission and stress distribution in disconnected piled raft foundations in clayey soil. Emphasis is made on the spacing between piles and the effect on interaction on the unconnected piled raft. models such as GARP5, GASP, FLAC 2D, and FLAC 3D. The soil material model is chosen to be the Mohr-Coulomb model, and the other soil parameters used in the Plaxis-3D model are listed in Table 1.

3 Research Methodology

Verification Problem

A pre-solved problem is reanalyzed in order to validate the numerical modelling of piled raft systems in finite element analysis. The case of piled-raft foundation, which was introduced in the 2001 "(ASCE) Technical Committee-18 (TC-18) report," is also used to validate the developed PLAXIS-3D model, Figure 4. Poulos (2001) reported the load-settlement relationship for this piled-raft model using various approaches, including the simple method, the PDR-Method (Poulos-Davis-Randolph method), and software numerical

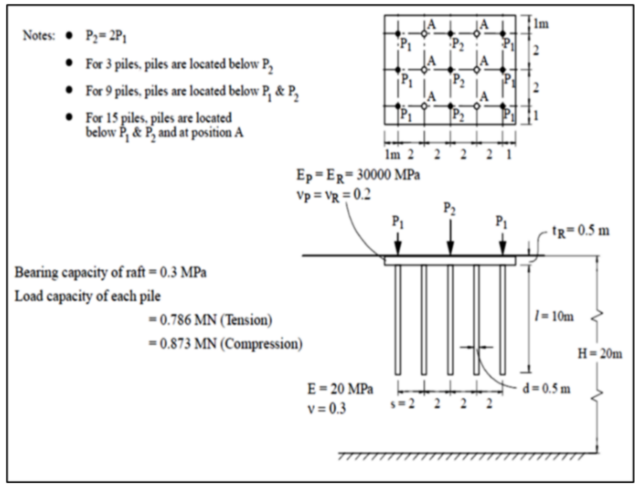


Fig. 4: Layout of piled raft example.

Table 1: Soil properties and concrete parameters [7].

Property Name	***Soil***	***Pile***	***Raft***
Material model	Linear elastic	Linear elastic	Linear elastic
Size (m)	50*50*20	D = 0.5 L = 10	10*6*0.5
Unit weight (kN/m3)	17	25	25
Young's modulus (MPa)	20	30000	30000
Poisson's ratio	0.3	0.2	0.2

Figure 5 illustrates the results obtained from the developed PLAXIS-3D model compared with other methods. The PLAXIS-3D analysis resulted in excellent agreement with Poulos-Davis-Randolph (PDR), Geotechnical Analysis of Raft with Piles (GARP5), and Geotechnical Analysis of Strip on Piles (GASP), but was significantly different from the FLAC 2D and FLAC 3D output. This could be because FLAC software is based on the finite difference method rather than the finite element method, where the result's accuracy is higher than the last method.

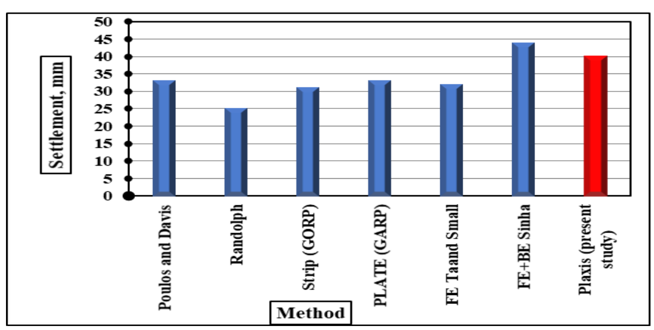


Figure 5. Maximum-settlement relationship for different approaches for the example reported by Poulos [7].

Main Problem

A raft (12 x 12) m and 0.8 m in depth, a pile group of (6 x 6) piles with 0.5 m in diameter and 12 m in length, spaced at 2 m (4D), and a cushion layer (1) m depth were chosen as the reference model for this parametric analysis. On the raft, a uniform pressure of (100) kPa is applied. The geometry of the disconnected piled raft used in finite element analysis is shown in Figure 6. PLAXIS-3D has the advantage of assessing a quarter of the piled raft foundation that is not connected. This benefit was evaluated, and just one-fourth of the geometry was used to replicate the unconnected piled raft foundation in question. The domain of the soil continuum used in this research is stretched to a substantial distance to mitigate this effect. The soil mass is 20 meters long (in x-direction), 20 meters wide (in y-direction), and 20 meters tall (in the z-direction). Clay and granular subbase characteristics are listed in Table 2. They are picked based on results from laboratory tests or traditional relationships. Hameedi et al. (2019), who tested soft clay from Al-Amarh city in the Missan governorate in southern Iraq, provided the clay properties. It is presumed that the cushion and sand components constitute granular subbase. Their properties are based on the work of Hassan et al. (2018). Primary compression of Cam-clay-type soil is performed using the "soft soil" model. It can nevertheless simulate the compression behavior of very soft soils and simulate soil behavior under various stress levels. Following the Mohr-Coulomb model, the cushion material is supposed to be subbase material, while the piles and their cap are assumed to behave elastically. The fundamental soil elements in the three-dimensional finite element mesh are tetrahedral elements with 10 nodes, as shown in Figure 7.

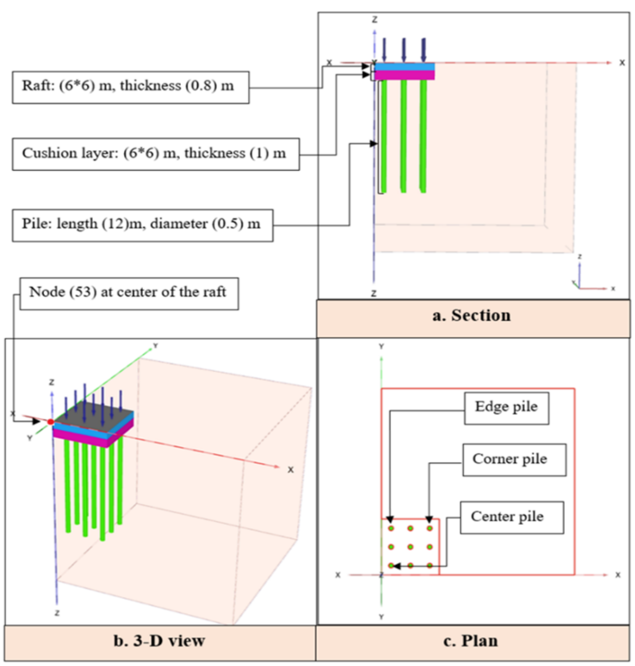


Figure 6. One-fourth of the reference unconnected piled raft system.

The analysis is performed on a 0.8 m thick square raft with a surface area of 144 m^2. It is supported by 36 unconnected piles with a diameter of 0.5 m and a length of 12 m. Cushion with a thickness of 1 m and a modulus of elasticity is 120 MPa were adopted. The pile spacing (S) was ranged to (2D, 3D, 4D, and 4.5D) as illustrated in Figure 8.

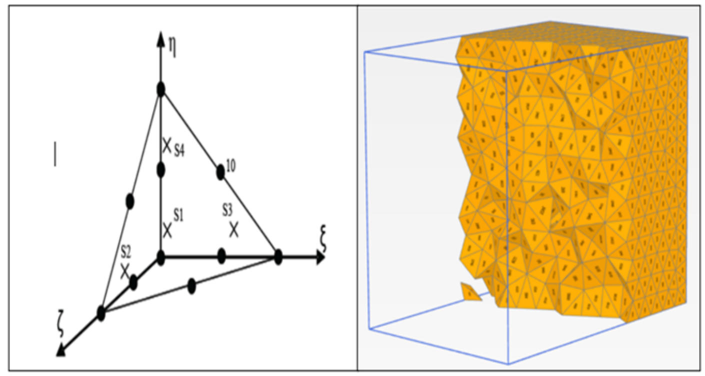


Figure 7. 3-D soil element (10-Node Tetrahedron).

Table 2: The parameters of the soil and piled raft.

	Clay	Subbase	Concrete for Raft, Pile
Model	Soft soil	Mohr-Coulomb	Linear elastic
Unit weight γ (kN/m^3)	17.1	22.06	24
Modulus of elasticity E' (kN/m^2)	----	120000	37000000
Angle of friction ϕ' (°)	1	40	-
Dilatancy angle ψ (°)	-----	10	-
Poisson's ratio		0.35	0.2
λ*	0.135	-	-
κ*	0.0123	-	-
c' (kPa)	15	-	-

4 Results and Discussions

This study's major steps are to determine the total and differential settlement of a disconnected pile raft, the relative settlement of the pile group, axial force via the length of a pile, and the ratio of pile loads. A parameter used in the design of the piled raft base is the load sharing between the pile and the raft. The pile load ratio (αPR) is defined in Equation (1):

$$\alpha_{PR} = \frac{\sum P_{pile}}{P_{total}} \tag{1}$$

Where ∑P pile is the sum of loads at pile head, and Ptotal is the total applied loads. This parameter defines the load distribution between the piles and the raft.

Effect of Pile Spacing

Figures 9 illustrates the effect of increasing the pile spacing on the total and differential settlement in the raft. The vertical settlement in Figure 5 is computed at the node (53) shown in Figure 6. The figure demonstrate that the settlement significantly decreases as the pile spacing increases from (2D) to (4.5D). The settlements are (0.55, 0.3, 0.22, and 0.18) m, respectively, while the connected piled raft settles about 0.24 m. Settlement decreases as the pile spacing increases due to the soil's support in all areas beneath the foundation, especially at the foundation's edges, which bear the most stress. This finding establishes that the unconnected piled raft system exhibits increased rigidity as the pile spacing increases. As a result, it is cost-effective to use a larger spacing to achieve the best performance of a piled raft. Hadi et al. (2021) results indicated that the piles act efficiently as a settlement reducer when the piles are higher than (6), the influence of the P-R foundation in decreasing the settlement disappears when the number of piles more than (6), this indicates that as the pile number increases further, the decrease in the settlement becomes smaller and no economic advantage is achieved.

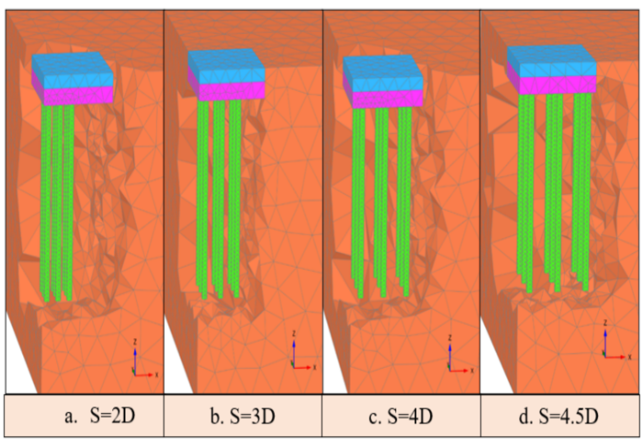
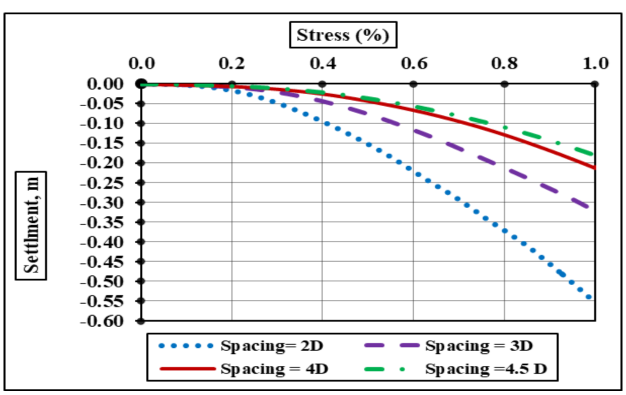
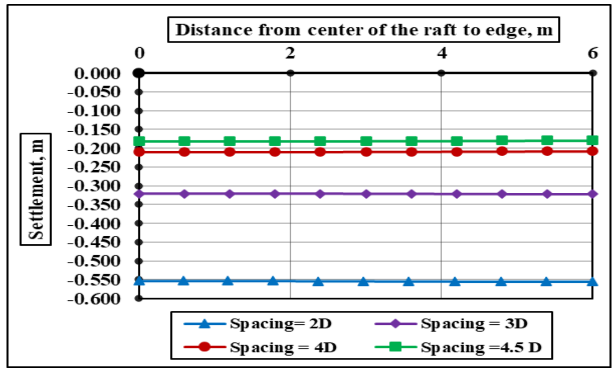


Fig. 8: Finite elements mesh of unconnected piled raft foundation with different pile spacing (S).



(a)



(b)

Fig. 9: Settlement variation as a function of the pile spacing: (a) in the centre of the raft, (b) along the raft's centreline.

Figures 10 and 11 illustrate the effect of increasing the pile spacing on the total and differential settlement in the raft. The vertical settlement in Figures 10 is computed at the node (53) shown in Figure 6.

These figures demonstrate that the settlement significantly decreases as the pile spacing increases from (2D) to (4.5D). The settlements are (0.55, 0.3, 0.22, and 0.18) m, respectively, while the connected piled raft settles about 0.24 m. Settlement decreases as the pile spacing increases due to the soil's support in all areas beneath the foundation, especially at the foundation's edges, which bear the most stress. This finding establishes that the unconnected piled raft system exhibits increased rigidity as the pile spacing increases. As a result, it is cost-effective to use a larger spacing to achieve the best performance of a piled raft.

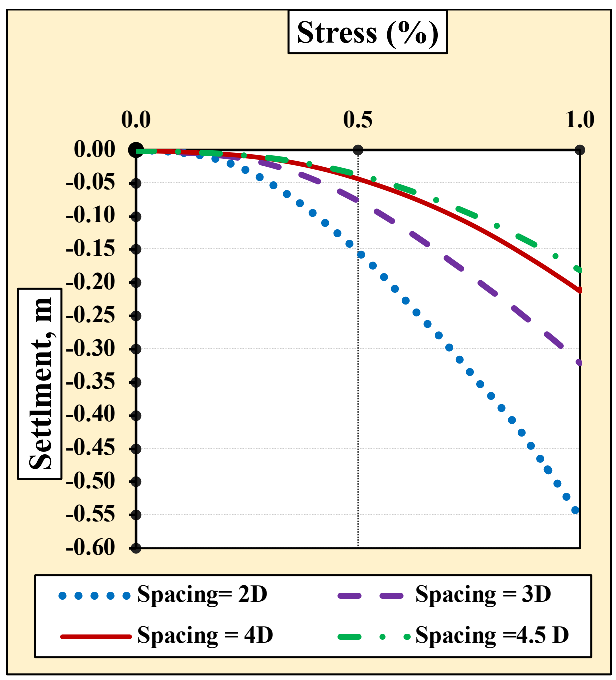


Fig. 10: Variation of settlement in the center of the raft with the pile spacing (S).

The spacing between the piles has a direct effect on how the piles interact. For example, a pile group with a small spacing between the piles may exhibit block behavior, necessitating the proper application of the pile raft concept. On the other hand, the spacing between piles should be sufficient to allow the raft to carry some of the load and strategically use the pile as a settlement reducer, as argued (Karim et al., 2013).

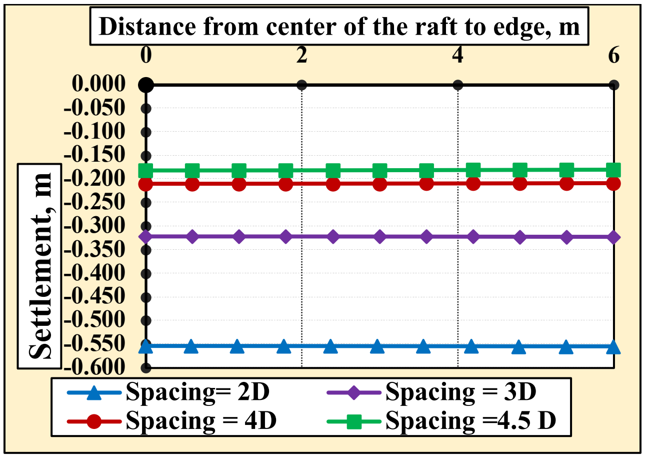


Fig. 11: Variation settlement along the centerline of a raft with the pile spacing (S).

Figure 12 illustrates the effect of pile spacing on the axial stress along the raft's centerline. The stress that the raft bears increase to (138, 681, 1585, and 2026) kPa as the distance between the pile's increases from 2D to 3D, 4D, and 4.5D. And this is because the soil is soft clay, and the distribution of the piles along with the distance beneath the raft stiffens and strengthens it, allowing the raft to withstand more significant stress.

It is noticed in Figure 12 that increasing the pile spacing to 4D and 4.5D results in low percentage of load transferred to the piles. This may be encased by interaction among piles which decreases with spacing that weakens the layer below the cushion. This ascertains that piles behave as soil improvement and their spacing is an important factor.

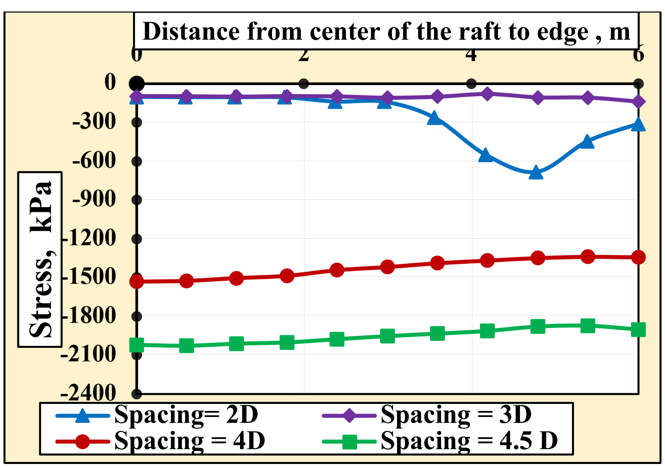
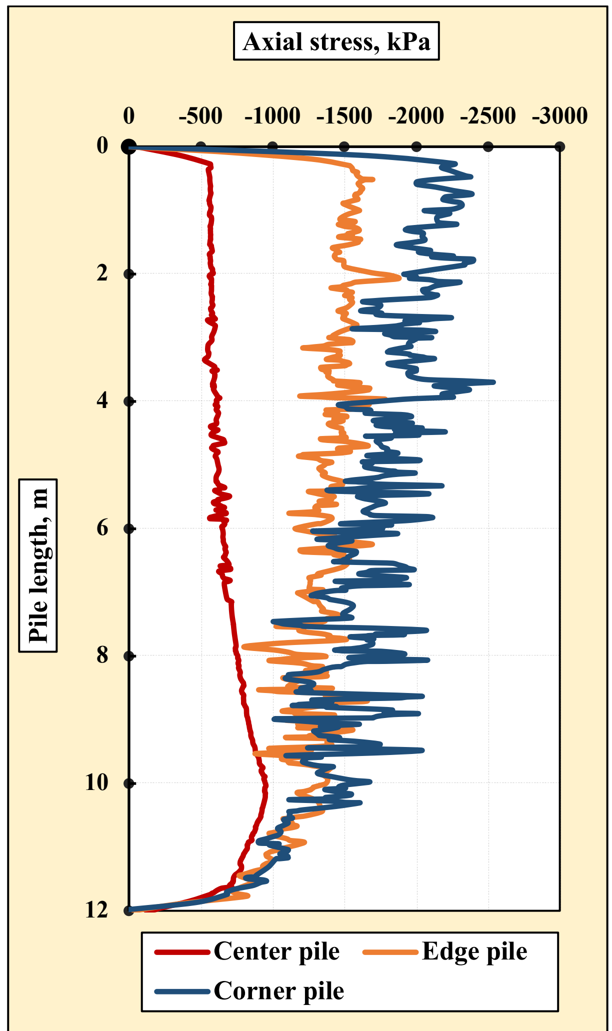


Fig. 12: Effect of the pile spacing on the axial stress along the centerline of the raft.

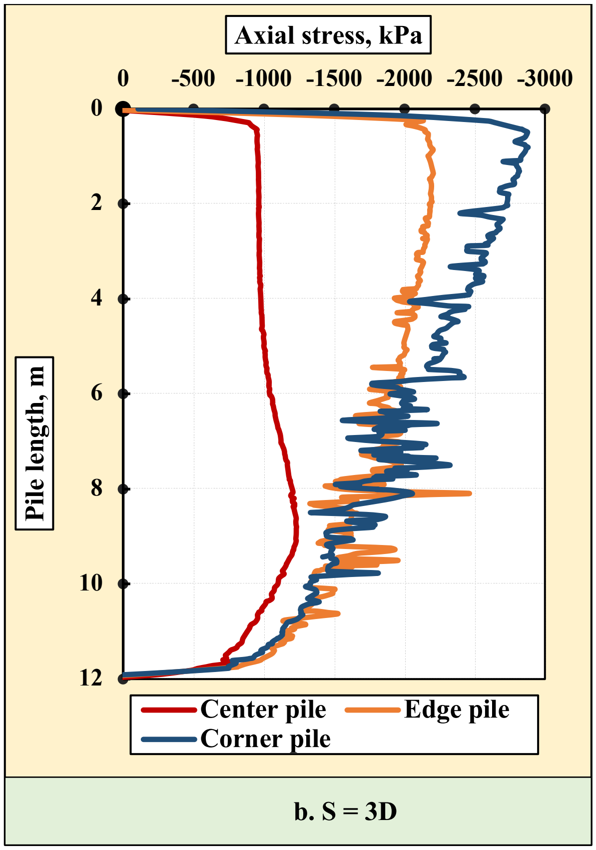
The axial stress distribution along the length of a pile (center pile, edge pile, and corner pile) is depicted in Figure 13 for four different spacings (2D, 3D, 4D, and 4.5D). As can be seen, there is a difference in the stress values that occur, with the highest value occurring at the corner pile, because the distribution of stresses beneath the raft in the clayey soil is high at the edges.

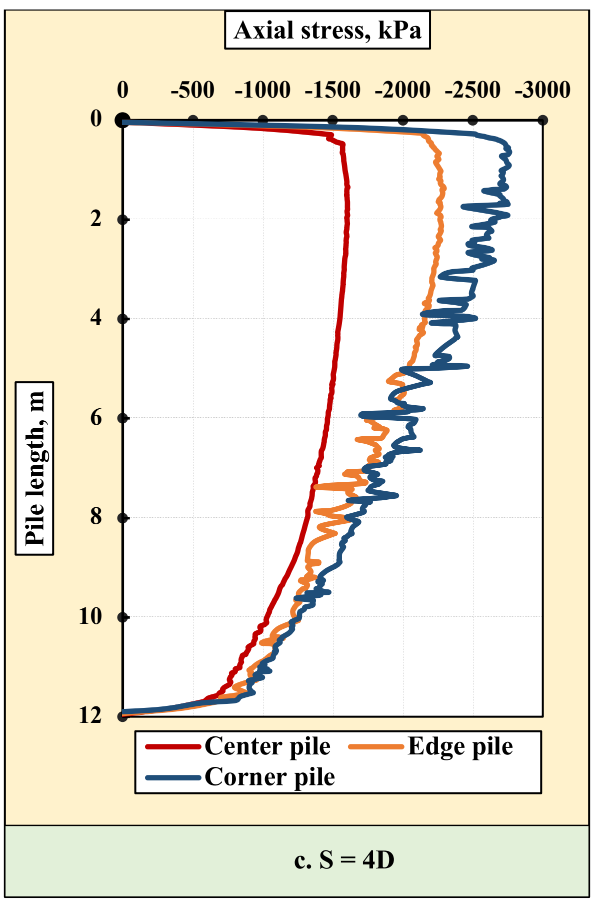
As the distance between the piles increases, the value of stress in the piles decreases. In the case of (S= 4.5D), where the piles are almost parallel to the raft's edge, the stress value between the piles was nearly equal. The more uniform the pile, the greater the coverage will be, particularly in the edge areas of the raft. The increased distance between the piles has reduced the amount of work overlapped by a single pile and the impact of pile blocks.

Waheed (2016) showed that the outermost piles in the piled raft foundation bear a more significant axial load than the inner piles; this highlights an important point for designers to consider when designing the piled raft foundation.



a. S = 2D





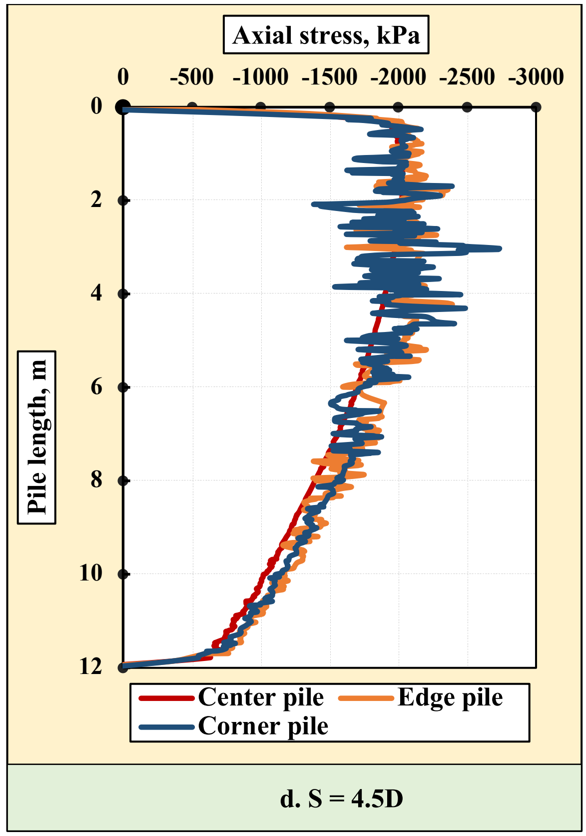


Fig. 13: Axial stress along the pile length for different pile spacings (S).

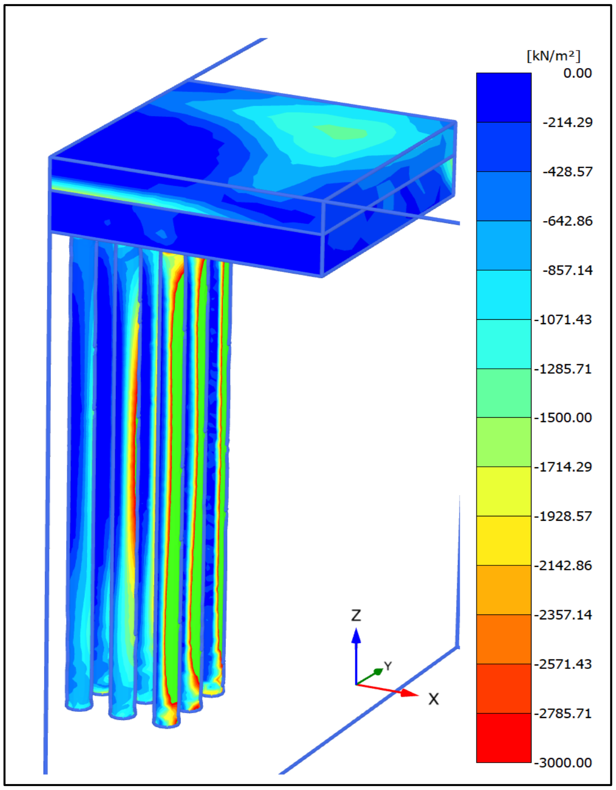
Table 3: Variation of the load sharing ratio of the unconnected piled raft with the pile spacing (S).

Description of foundation		Load sharing ratio	
		Pile	Raft
Connected piled raft	S = 4D	0.66	0.34
Unconnected piled raft (Spacing between piles) (c/c) m	S = 2D	0.9	0.1
	S = 3D	0.9	0.1
	S = 4D	0.58	0.42
	S = 4.5D	0.44	0.56

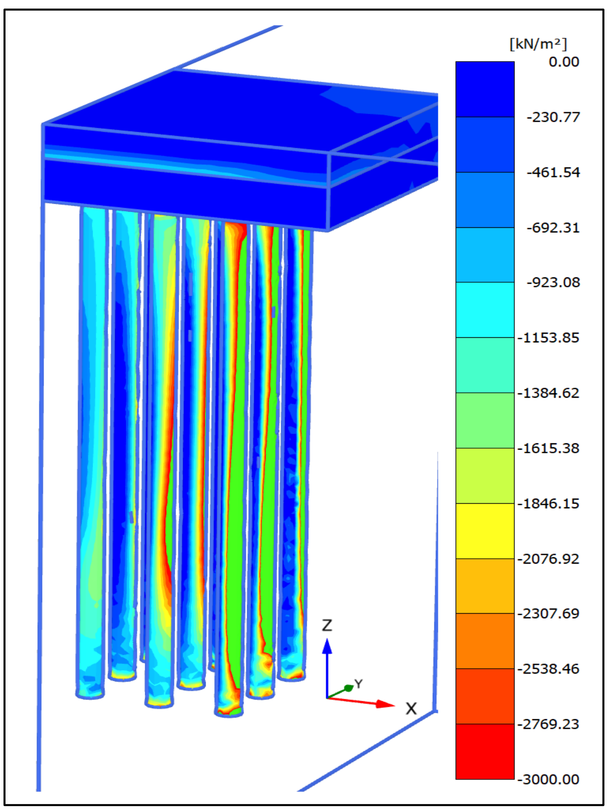
D = pile diameter (0.5) m

It is concluded that the spacing among piles of 4.5D cases uniform destribution of load among piles. In addition, this spacing provides the lower settlement and increase in raft sharing of load. Therefore, it can be deduced that a wider spacing of piles (4D) to (4.5D) will be the optimum spacing for the performance of the unconnected piled raft system with regards to the load distribution among the components of the unconnected piled raft system. Still, the total system load is lower when compared to that of closely spacing piles (2D, 3D).

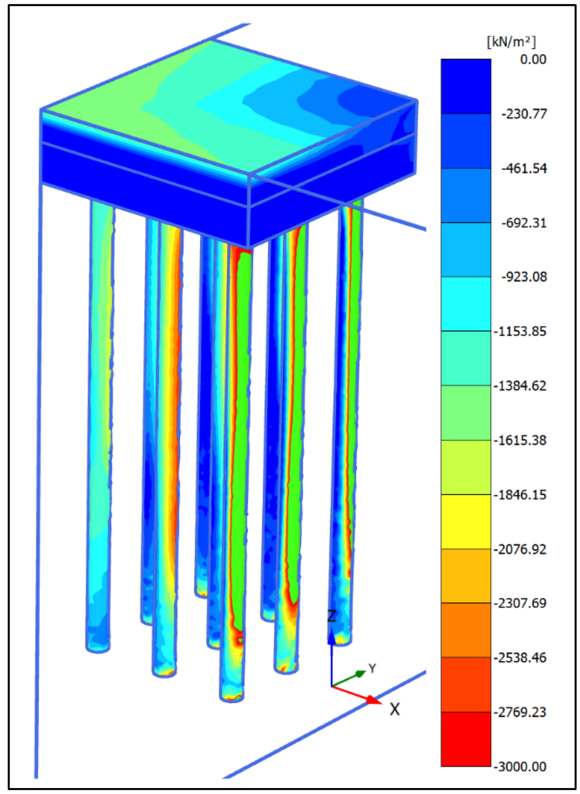
Figure 14 presents the shadow shapes of axial stress distribution along the piles and the raft in unconnected group of different spacings. The figure reveals that the spacing 4.5D allows larger stresses in the raft and maintains uniform distribution of stress among the piles.



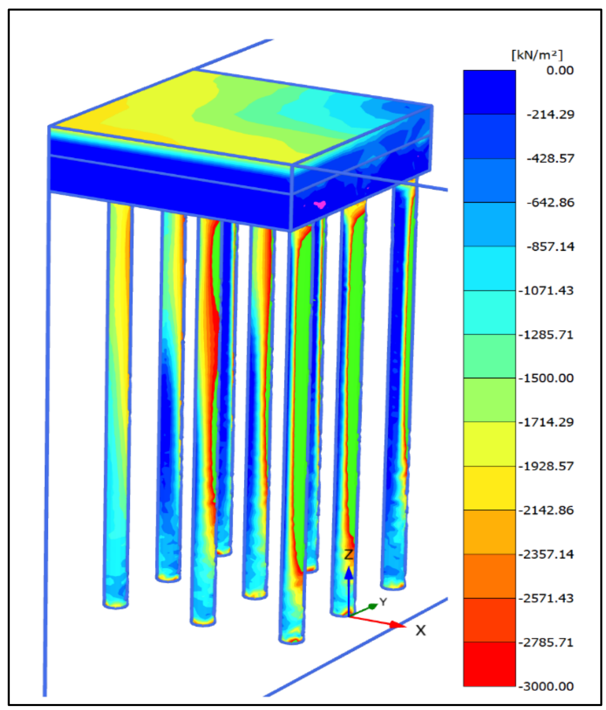
a. S = 2D



b. S = 3D



c. S = 4D



d. S = 4.5D

Fig. 14: The shadow of UCPR showing the distribution of the axial stress along the pile length and the raft in different pile spacing (S).

Fattah et al. (2013a) found that for the case of (2×1) piled raft in clayey soil, each of the two piles carry the same amount of load since the load is concentrated and applied at the center. It can be noticed that the force taken by the piles reduces as moving from the head to the base of the pile and this is normal since the skin friction is of maximum value near the pile head. Figures 15 and 16 illustrate the effect of the pile spacing on the axial stress along with the pile and raft. From the figures, the stress that the raft bears increase to (138, 681, 1585, and 2026) kPa as the distance between the piles increases from 2D to 3D, 4D, and 4.5D. This is because the soil is soft clay, and the distribution of the piles along with the distance beneath the raft stiffens and strengthens it, allowing the raft to withstand more significant stress. The axial stress distribution along the length of a pile (center pile, edge pile, and corner pile) is depicted in Figure 7 for four different spacings (2D, 3D, 4D, and 4.5D).

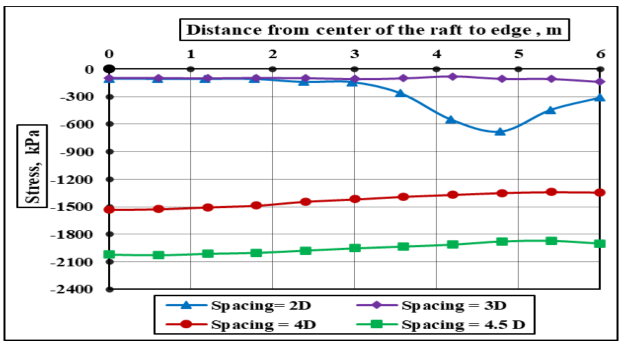


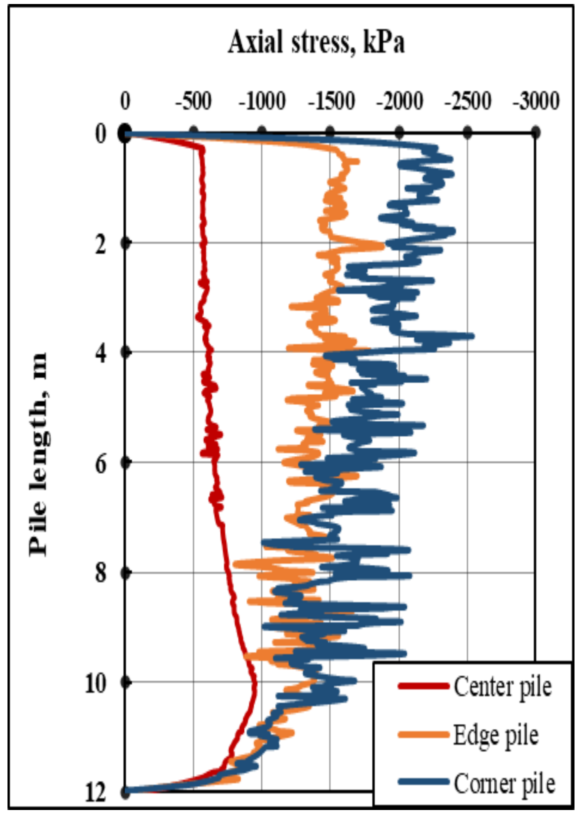
Fig. 15: The pile spacing (S) effect on the axial stress parallel to the raft's centerline.

As can be seen, there is a difference in the stress values that occur, with the highest value occurring at the corner pile, because the distribution of stresses beneath the raft in the clayey soil is high at the edges.

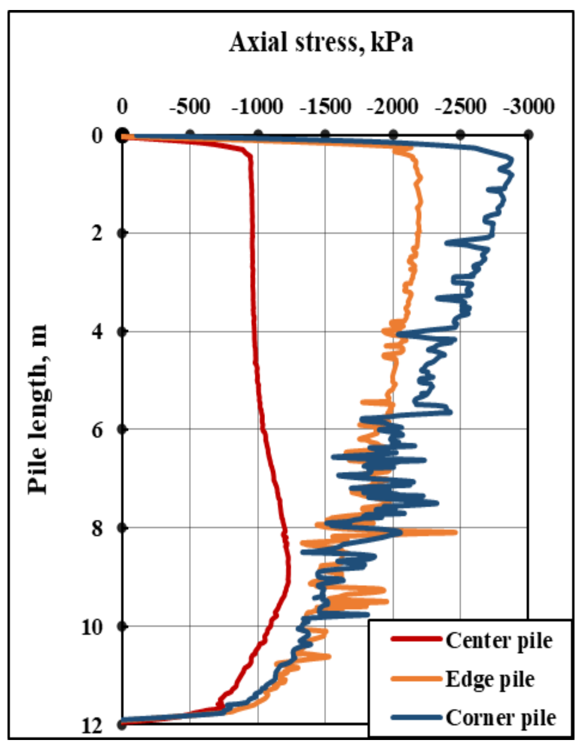
As the distance between the piles increases, the value of stress in the piles decreases. In the case of (S= 4.5D), where the piles are almost parallel to the raft's edge, the stress value between the piles was nearly equal. The more uniform the pile, the greater the coverage will be, particularly in the edge areas of the raft. The increased distance between the piles has reduced the amount of work overlapped by a single pile and the impact of pile blocks.

The load sharing ratio has been calculated. The values of this parameter for the various cases studied are listed in Table 3. As a result of Table 3, it is concluded that selecting an appropriate pile spacing is paramount (4.5D). While in models with 2D and 3D pile spacing, the piles bear the entire load, with no effect on the raft, these cases are unsuitable for piled raft systems.

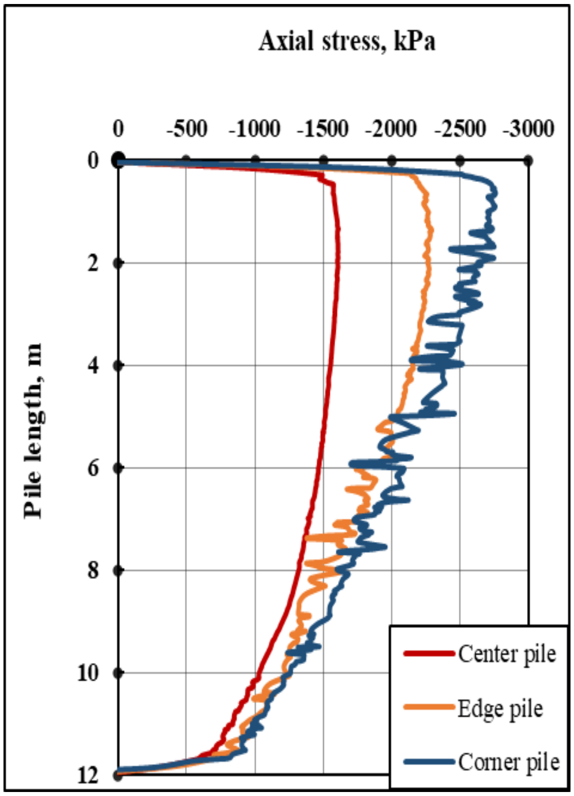
Figure 17 presents the shadow shapes of axial stress distribution along the piles and the raft in unconnected group of different spacings. It is noticed that increasing the pile spacing to 4D and 4.5D results in low percentage of load transferred to the piles. This may be caused by interaction among piles which decreases with spacing that weakens the layer below the cushion. This ascertains those piles behave as soil improvement and their spacing is an important factor.



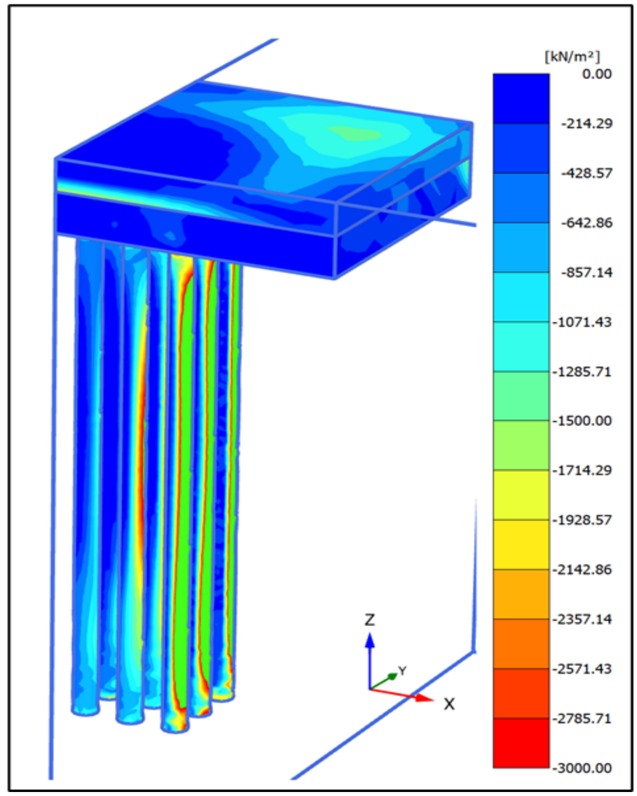
(a). S = 2D



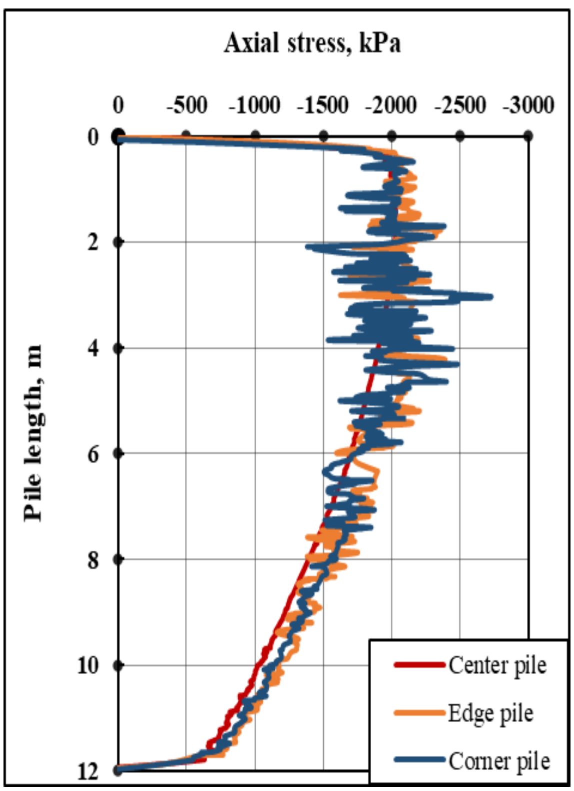
(b). S = 3D



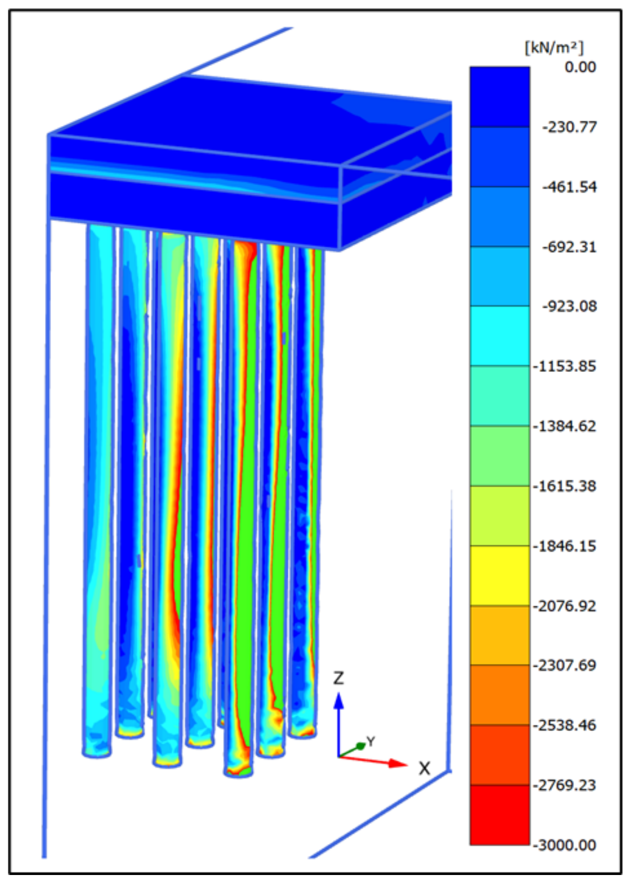
(c). S = 4D



(a). S = 2D

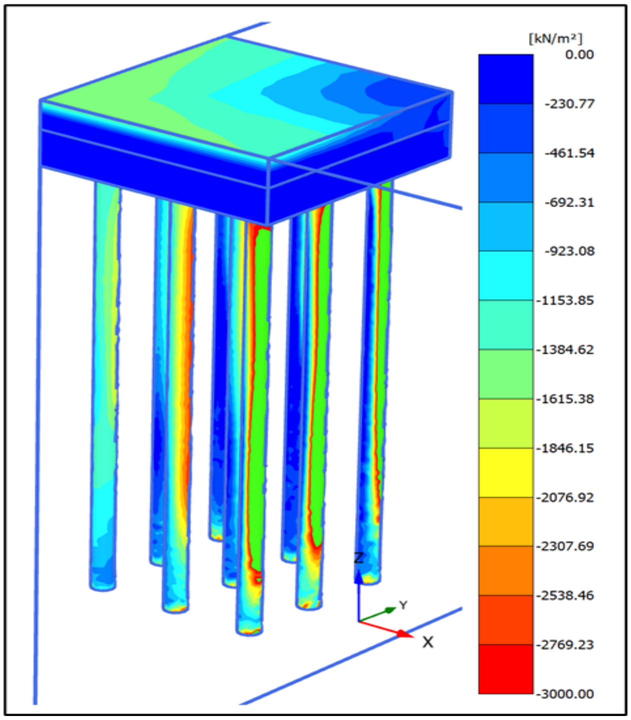


(d). S = 4.5D

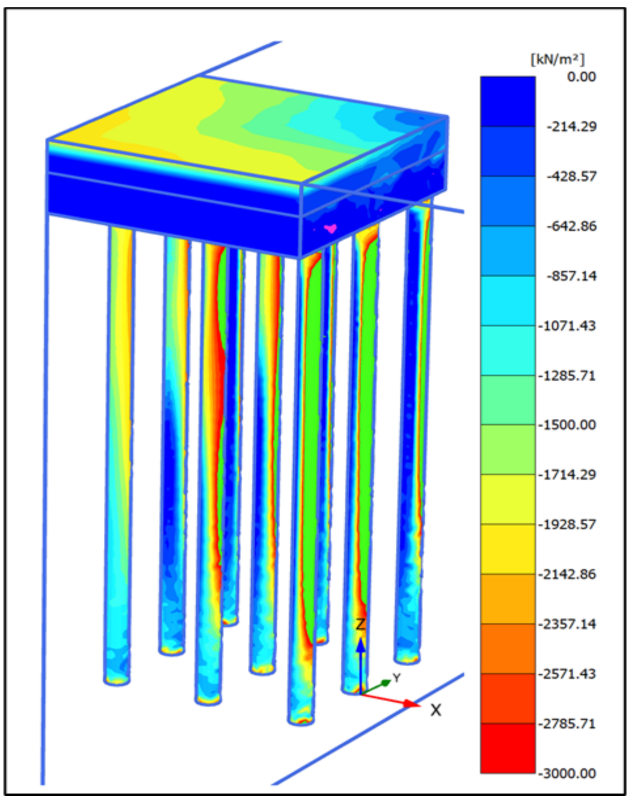


(b). S = 3D

Fig. 16: Axial stress along pile length in different piled spacing (S), a. S = 2D, b. S = 3D, c. S = 4D, d. S = 4.5D.



(c). S = 4D



(d). S = 4.5D

Fig. 17: The shadow of UCPR showing the distribution of the axial stress along the pile length and the raft in different pile spacing (S)., a. S = 2D, b. S = 3D, c. S = 4D, d. S = 4.5D.

5 Conclusion

The effect of pile spacing in the foundation settlement and the load-sharing ratios of piles and raft were investigated by using the PLAXIS-3D finite element analysis software. The following conclusions were obtained:

1. In clayey soil, the outermost piles in the piled raft carry higher axial loads than the inner piles; this points out the proper design of the outermost piles in the unconnected piled raft foundation.

2. To optimize the design of an unconnected piled raft system, the raft must be allowed to share some portion of the superstructural load so that the ratio of load sharing of raft increases by using cushion layer between the piles and the raft.

3. The pile spacing is the controlling factor in getting higher load ratio in raft, and uniform distribution of load among the piles.

4. The settlement decreases as the pile spacing increases, and no impact on the differential settlement occurs. The settlement increases by (129% and 25%) for 2D and 3D pile spacing and decreases by (8.4% and 25%) for 4D and 4.5D pile spacing, compared with the connected piled raft having pile spacing = 4D.

The axial stress in the raft is affected by the pile spacing design. The decrease in pile spacing to 2D and 3D makes the raft carries a small ratio of the applied stresses, and with increase of pile spacing to 4D and 4.5D where the piles will cover all area under the raft, the stresses ratio in the raft increases by 25% and 65%, respectively, as compared with the connected piled raft. The pile load sharing ratio decreases by (90%, 90%, 56%, to 44 %) as the pile spacing varies from (2D to 3D to 4D and 4.5D), respectively.

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