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Experimental investigation of circular piled raft foundation under vertical load in cohesionless soil

Anuj K. Chandiwala[1,*] and Sandip A. Vasanwala[1]

[1]Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, India
[*]Corresponding author: d16am004@amd.svnit.ac.in

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Abstract

A shallow foundation on cohesionless soil cannot withstand higher loads; a piled raft foundation is preferred because it combines the bearing capacities of piles and rafts. In this study, a series of experimental tests were conducted for various parameters such as pile length, raft thickness, soil density, and pile arrangement patterns to study the complexities of pile and pile group behavior under vertical loading. Piled and unpiled rafts were tested and compared using circular rafts under various soil conditions. The findings revealed that increases in the pile length, raft thickness, and soil density enhanced the bearing capacity and decreased settlement. A 35% increase in load-bearing capacity was obtained when the compaction level increased from loose to very dense, and a 75% increase in capacity was obtained when comparing the shortest piles to the longest ones. As a result of this model analysis, the pile raft system with an improved pile and raft design was found to be more efficient. Providing an alternative foundation option for large constructions may make this foundation system more affordable.

Keywords: Load-sharing ratio, Settlement reduction ratio, Relative density, Pile spacing, Pile arrangement pattern

1. Introduction

The burgeoning population requires extensive infrastructure. New buildings, bridges, and expressways are continually needed. High-rise skyscrapers, such as the Shanghai Tower and Kingdom Tower, change the public service and structure. The self-weight, gust loads, and geological forces of the structure add to the burden. In their view, foundations such as shallow rafts and piling alone are neither stable nor cost-effective, and construction projects require stable foundation structures. The right foundation system design makes the project safer, more efficient, and cheaper. Creating a foundation system is crucial in civil engineering planning. Previously, rafts and piles were used separately, whereas recently, founders have combined these two systems. The foundation engineer blends these two methods to meet the project demands. A traditional pile design involves piles that bear all the weights and are accepted as a group. The approach using a combination of rafts and piling foundations is becoming more frequent. The first piled raft foundation (PRF) approach was presented by Davis et al. [11]. Later, Burland et al. [12] proposed using a pile group to mitigate settlement. Researchers have measured the load-bearing capacities of piles and rafts numerous times to develop more effective design approaches for PRF systems. Simplified methods [13-15], semi-analytical methods [16-18], and numerical methods [19-27] can all be used to analyze the behavior and load-bearing capacity of PRFs. As an additional measure, centrifugal tests can be conducted to study the load-sharing ratio (LSR) of PRFs [28-33,24]. Although the literature provides a thorough understanding of the load transfer mechanism of the PRF system, the impact of design factors on the LSR of PRFs remains unclear. The primary objective of this experimental investigation was to determine how several factors (pile arrangement pattern, pile length, raft thickness, pile spacing, relative density of soil, and settlement) influence the LSR between the driven piles and raft in cohesionless soil. Differential settlement control, stacked rafts, and settlement reduction piles were used. The pile generally carries the aggregate weight. The raft is very cautious because it is on water and weighs a lot [1]. Piles carry 50-80% of the superstructure's weight [2]. A study using a clay piled raft system [3] reported that piles sustain the structural load, whereas the raft carries the remaining weight. Changing factors can easily affect the overall performance of PRFs. Equally weighted raft piles should be located at approximately 15-25% of the raft surface. Pile raft load settling and load sharing using static (vertical) sand models [4]. To test 1-g models on soft clay, a previous study [5] used 10-cm-square rafts with varying thicknesses on four (2×2), nine (3×3), and 16 (4×4) piles. A centrifugal model was used to study stiff piled circular rafts over loose silica sand beds. Unpiled rafts had one, three, seven, or 13 piles [6].

Within the central part of this piled raft, nine settlement-reducing piles were tested to determine how they affected their behavior. Pile-supported-raft foundations should be thoroughly studied to determine their settlement and bearing capabilities in various situations (such as pile length, pile pattern, pile spacing, and soil type). To assess PRFs, model tests should be used. PRFs have a significant impact on the overall performance.

2. Materials and methods

2.1 Piled raft foundation mechanism

Design engineers should understand how loads are transferred from the raft to piles and earth media so that they can anticipate raft performance, such as settlement, bending moments, and borrowing capacity rate, as well as pile behavior, such as displacement and load sharing between piles. A crucial study of the interactions between piles, rafts, and soil. In a PRF, the entire load of the superstructure occurs partly through skin friction piles [7]. The raft carries the remaining weight via soil contact, as illustrated in (Figure 1). Q, Q_P, and Q_R are the weights of the piled raft, pile, and raft, respectively. When considering the safety aspect, the procedure for developing PRFs is far from superior to that of the raft or pile foundation design. The pile-soil-pile interaction results from the pile spacing and installation method and is similar to those of the free-standing pile group.

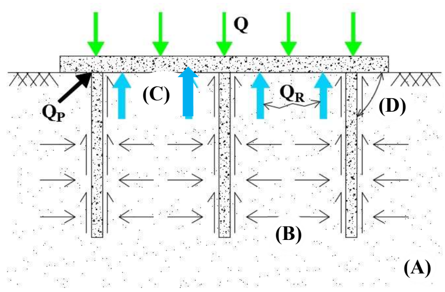


Figure 1 Schematic representation of different piled raft interactions: (A) soil pile interactions, (B) pile interactions, (C) soil raft interactions, (D) raft pile interactions.

2.2 Model piled raft and tank

The steel tank measures 1000 mm in length, 1000 mm in height, and 1000 mm in width. Each side has two 2.5-meter-tall columns and two 1.5-meter-tall horizontal beams, which form the loading frame shown in (Figure 2A), with a hand-operated hydraulic jack and a precalibrated load cell in the center. The loading platform was a 40×40×15-mm-square steel plate secured by four legs, two of which crossed the raft's center line, and the other two ran on each side of the center line with an equal spacing of 40 mm, as shown in (Figure 2B).

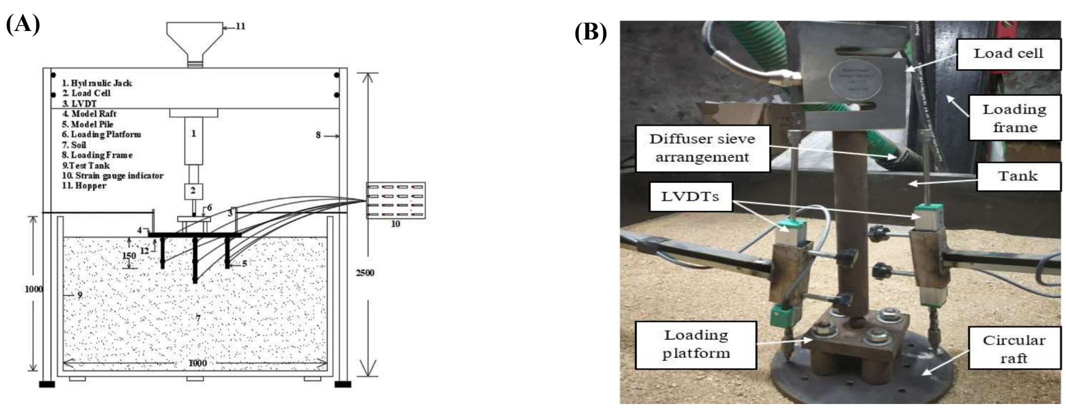


Figure 2 (A) Schematic view of the model test setup and (B) loading platform on a raft.

A circular mild steel raft model was built to replicate the raft of a narrow structure exposed to vertical loads. The model raft was 160 mm in diameter and 10 mm in thickness. The model raft had holes for pilings to be placed vertically at the desired pile spacing. To secure the pilings to the raft, each piling was equipped with a 6-mm-diameter and 20-mm-long bolt. Model piles made of 10-mm mild steel were used in the experiment. The model raft and piles had an elasticity of 1.8×10^5 MPa. The piles were 10-, 15-, and 20-cm long, with slenderness ratios of 10, 15, and 20, respectively.

The model piled raft size was developed to prevent anxiety concentrations at the edge of the tank, and the PRFs considered bored piles. To prevent the influence of a stiff soil tank foundation on pile behavior [8,10], as shown in (Figure 2B), a ball bearing was used to provide vertical load to the loading platform, and two linear variable differential transformer (LVDTs) were used to measure the settling of the model raft.

2.3 Soil testing

The foundation soil used in this study was clean, dry sand. Table 1 lists the geotechnical parameters of the sand considered in the experiment. The grain size distribution of the sand was determined according to IS 2720 (Part 4): 1985.

Table 1 Geotechnical properties of sand.

Geotechnical property	Value	Unit	Method
Specific gravity (G)	2.631	-	IS: 2720 Part-3: (1980)
Maximum dry density	17.65	kN/m^3	IS 2720 Part 14: (1983)
Minimum dry density	14.80	kN/m^3	IS 2720 Part 14: (1983)
Loose sand Rd = 20%	15.49	kN/m^3	IS 2720 Part 14: (1983)
Medium sand Rd = 40%	15.98	kN/m^3	IS 2720 Part 14: (1983)
Dense sand Rd = 60%	16.57	kN/m^3	IS 2720 Part 14: (1983)
Very-dense sand Rd = 80%	17.16	kN/m^3	IS 2720 Part 14: (1983)
Angle of internal friction (Ø°) at Rd = 20%	37	Degree	IS 2720 Part 13: (1986)
Angle of internal friction (Ø°) at Rd = 40%	41	Degree	IS 2720 Part 13: (1986)
Angle of internal friction (Ø°) at Rd = 60%	42	Degree	IS 2720 Part 13: (1986)
Angle of internal friction (Ø°) at Rd = 80%	43	Degree	IS 2720 Part 13: (1986)

Rd: relative density.

Figure 3 shows the grain size distribution obtained by dry sieving. The soil was classified as poorly graded sand in India (SP). To prepare sand bed specimens for modeling research, a portable traveling pluviator (PTP) was constructed with a fixed 20-kg hopper and a 100-cm-long rigid tube. However, the stiff tube in the pluviator assembly allows the material to fall uniformly on the diffuser straps. The diagram of the diffuser is shown in (Figure 4A) in mm. An experimental constant height fall was achieved by plunging a reference rod into the sand bed. Uniform sand distribution is an essential requirement for pluviation and management of relative density (R_d). Ten diffuser sieves with 20% porosity were included to provide uniform material flow through the pluviator. (Figure 4B) shows the experimental diffuser arrangement.

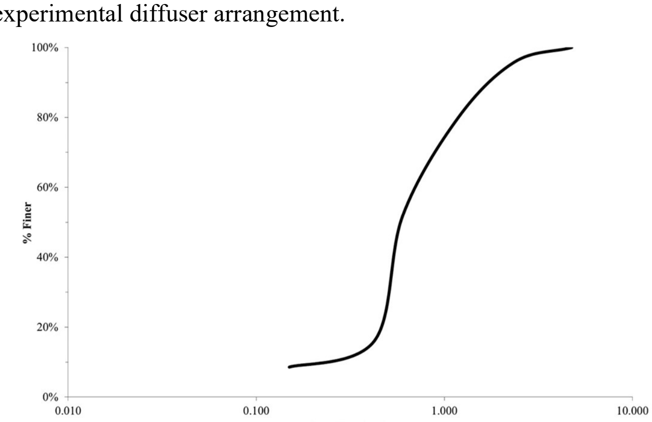


Figure 3 Particle size distribution curve for sand.

The diffuser sieves were oriented toward each other to break up the sand flow. The tube was vertically pluviated to ensure optimum sand dispersion. Diverter sieves were used to break sand flow. The sand was pluviated into thin horizontal layers using a rigid vertical tube for optimal sand dispersion. This created constant homogenous sand rain by regulating the flow. Flow management achieved consistent sand rain by avoiding sand gathering on diffuser sheets.

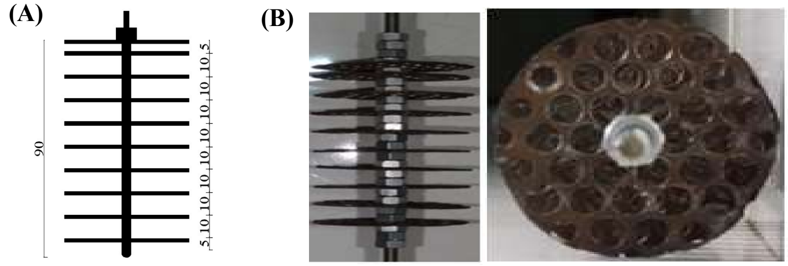


Figure 4 (A) Schematic view of the diffuser and (B) experimental diffuser arrangement.

2.4 Setup for experimental work

After reviewing the relevant literature, we found that the PRF model exhibited nonlinear load-settlement behavior. Practical methods were employed to define the ultimate load-bearing capacity under these circumstances; 0.1B, log-log, and tangential intercepts are examples. Only one of these approaches should be used to determine the load-bearing capacity of model PRFs because they produce similar but different findings. In model PRFs, the ultimate load-bearing capability is defined at 10% of the raft width [34-36]. PRFs have a difficult settlement. The rafts and piles were deployed at different load values. Depending on the size, the piles are mobilized before rafts at low loads. The raft's load-bearing capability improves with the applied load and settlement. The ultimate load-bearing capacity of the PRF model was experimentally determined using the 0.1B technique. Each experiment was repeated three times to obtain the load-settlement curves. After several experiments were compatible, the load-displacement curves were averaged [37].

Several model experiments were conducted to investigate the behavior of a vertically laden stacked raft on sand. Figure 5 depicts the model raft and pile geometry. Because the piles used were non-displacement piles, the installation testing technique was as follows:

1. PTP rainfall method placed sand.
2. The non-displacement piles required a sand height of up to 28 cm from the bottom of the tank. To guarantee good seating, 20-cm long piles were set vertically in sand, with 10-mm penetration. As long as the tank is incomplete, the piles remain in place.
3. Afterward, the model raft was installed on each pile using nuts.
4. The model raft was loaded using a loading platform.
5. 0.1 kN/min load was applied till failure.
6. Settlement equal to 10% of the raft width is often used to measure the maximum load capacity of the raft [34-36]. Therefore, the raft was loaded until it settled at least 10% of B, i.e., 16 mm.

2.5 Program for testing

For a PRF, the tests detailed in (Table 2) were conducted to determine the settlement of the raft, the settlement reduction ratio, and the percentage LSR by pile between the pile group and the raft. Figure 5 shows the five distinct piling designs used to explore the behavior of a model piled raft. The first design consisted of nine V-shaped piles, the second design consisted of nine ^-shaped piles, the third design consisted of nine 10-cm equal length piles, the fourth design consisted of nine 15-cm equal length piles, and the fifth design consisted of nine 20-cm equal length piles. All experiments employed the same number of piles (N_{total} = 9). Figure 6 shows the various configurations of the 160-mm circular piled raft system.

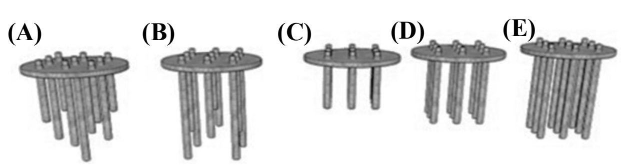


Figure 5 The pile arrangement pattern in 160-mm circular raft: (A) V-shape, (B) Nine ^-shaped, (C) 10-cm equal length piles, (D) 15-cm equal length piles, and (E) 20-cm equal length piles.

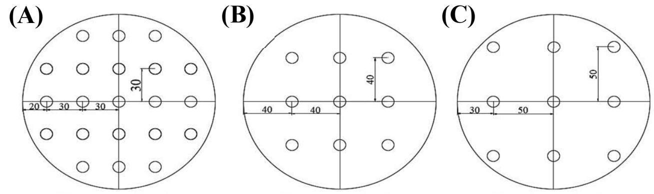


Figure 6 Various configurations of the 160-mm circular piled raft system: (A) 3d sapcing, (B) 4d sapcing, and (C) 5d sapcing.

Table 2 Model configuration.

Particular Item	Size
Raft thickness (t)	5 mm, 10 mm, and 15 mm
Pile length (L)	100 mm, 150 mm, and 200 mm
Pile spacing (S)	3d, 4d, and 5d
Pile arrangement	V-shaped, ^-shaped, and all equal pile lengths (100 mm, 150 mm, 200 mm)

3. Results and discussion

This section evaluates and discusses the model test results from experimental testing. In this model test, the loading continued until raft settling reached 16 mm. The behavior of a raft exposed to vertical load with raft only and piled rafts was studied.

3.1 Relative density and raft thickness effect

The effects of relative density and thickness of the raft were studied by conducting several tests on a model raft immersed in a sand bed with four different unit weights, each indicating a distinct relative density. A raft subjected to vertical load with different relative densities was used in the first series of tests. The second series was conducted on rafts subjected to vertical loads with different raft thicknesses.

Figure 7 shows the typical changes in the bearing burdens vs. the extreme settlements under the raft. The load-carrying capacity of the raft increased dramatically as the soil density increased. When the thickness of the raft increased from 5 mm to 10 mm, the load-carrying capacity increased dramatically, whereas when the thickness increased from 10 mm to 15 mm, the load-carrying capacity of the raft increased marginally. This was because of the self-weight of the raft.

The graph depicts how the relative density of sand affects raft behavior. Compared with the improvements observed in medium-to-very-dense sand densities, a considerably lesser gain in bearing pressures was noted in loose sand conditions, as the surface friction increased owing to a surge in relative density. This behavior of increased.

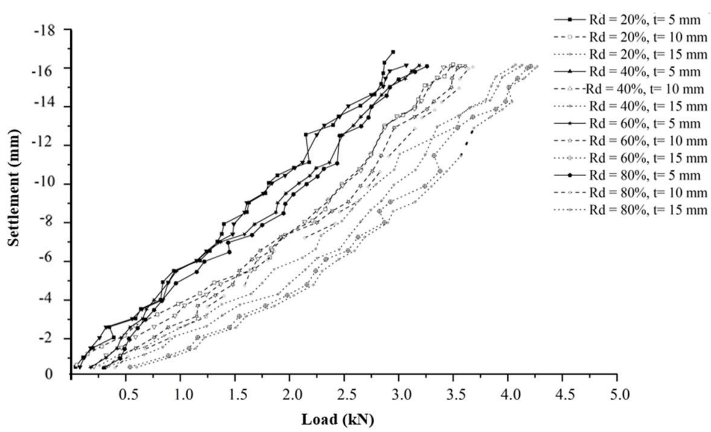


Figure 7 Relative density (R_d) and thickness (t) load-settlement curves for unpiled rafts.

3.2 Piled raft: variation in pile spacing and pattern

Tests were conducted using three pile slenderness ratios (L/d = 10, L/d = 15, and L/d = 20) and two pile arrangement patterns (V-shaped, ^-shaped) to investigate the influence of pile spacing on model raft footing performance supported on very-dense sand under longitudinal loading on the model piled raft footing. As shown in (Figures 5 and 6), the load-settlement behavior of the piled raft is shown in (Figure 8). The 5d spacing configuration provided a more significant proportion of the pile to the raft. Therefore, it represented a higher stiffness and load-carrying capacity than the 3d and 4d spacing configurations for longitudinal loading. Nine piles with 5d spacing showed better settlement resistance owing to increased stiffness. This configuration also indicated minimum differential settlement owing to a higher group of pile areas to raft. The pile arrangement patterns for the 3d and 4d configurations were concentrated more in the central region of the raft, and they represented lower stiffness. A similar observation has been reported by other researchers [9] that piles are concentrated in the central region of the plate, and settlement is decreased in the center but may increase toward the edge.

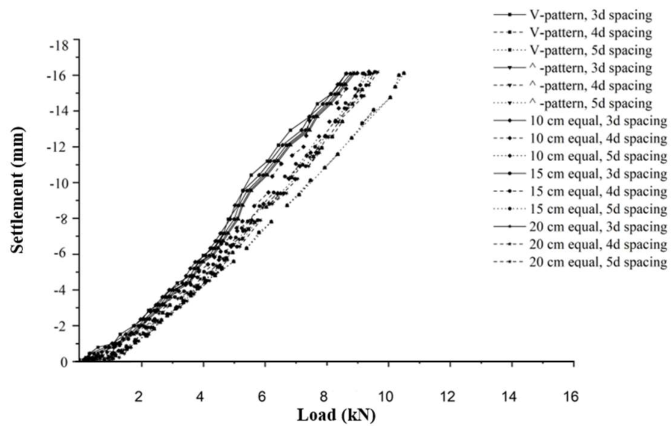


Figure 8 Load-settlement curves for piled rafts at 80% relative density (R_d) and 10-mm raft thickness (t) for various pile patterns and pile spacing.

3.3 Influence of pile spacing, raft thickness, and relative density on the settlement reduction ratio

The settlement reduction ratio (SRR) is a dimensionless quantity representing decreased settlement.

$$\mathrm{SRR} = \frac{S_p}{S_r} \tag{1}$$

where S_p = pile raft settlement at a given load, S_r = raft settlement at a given load

Figure 9 shows SSRs for raft thicknesses of 5, 10, and 15 mm with varying relative densities. Figure 9 shows that decreases in the average ratio of settlement of raft for ^-type, 10-cm equal length, 15-cm equal length, and 20-cm equal length patterns are 1.76%, 3.81%, 7.15%, and 10.58% for 3d pile spacing; 3.81%, 6.30%, 9.82%, and 13.63% for 4d pile spacing; and 3.01%, 5.92%, 8.56%, and 12.13% for 5d pile spacing with respect to the V-type pile arrangement pattern. As shown in the results, pile spacing, raft thickness, and relative density of sand greatly influenced SSR, as it is evident that L/d = 20, 5d spacing pile arrangement with 80% relative density and 15-mm raft thickness pattern increases the pile group area with respect to the raft area. For this reason, the settlement of rafts is drastically reduced compared with all other pile arrangement patterns and thickness of rafts.

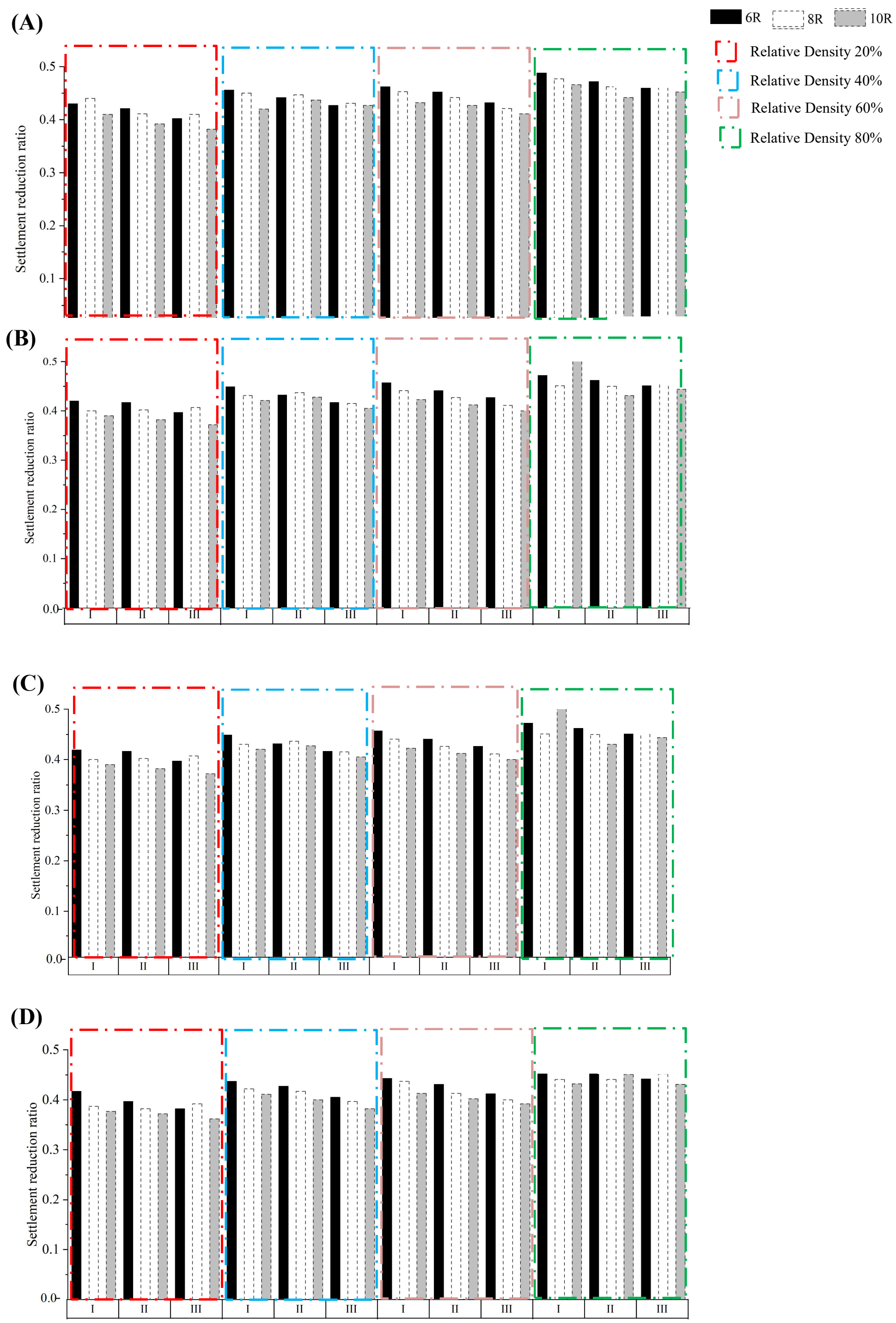


Figure 9 Settlement reduction ratio (A) V-type, (B) ^-type, (C) 10-cm equal length, (D) 15-cm equal length. I 0.5 cm thick raft, II 1.0 cm thick raft, and III 1.5 cm thick raft.

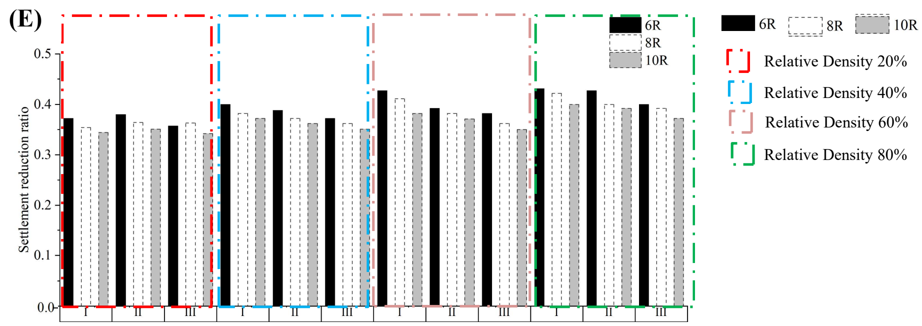


Figure 9 (continued) Settlement reduction ratio (E) 20-cm equal length pile arrangement pattern. I 0.5 cm thick raft, II 1.0 cm thick raft, and III 1.5 cm thick raft.

3.4 Influence of pile spacing, raft thickness, and relative density on percentage of load-sharing ratio by a pile

LSR is a nondimensional quantity representing the total load shared.

$LSR = L_P/L$

where L_P = Total load shared by the pile

L = Applied load on the pile raft system

The 5-mm, 10-mm, and 15-mm raft thicknesses with varying relative densities demonstrate LSR variances with the pile arrangement pattern and spacing, as shown in (Figure 10).

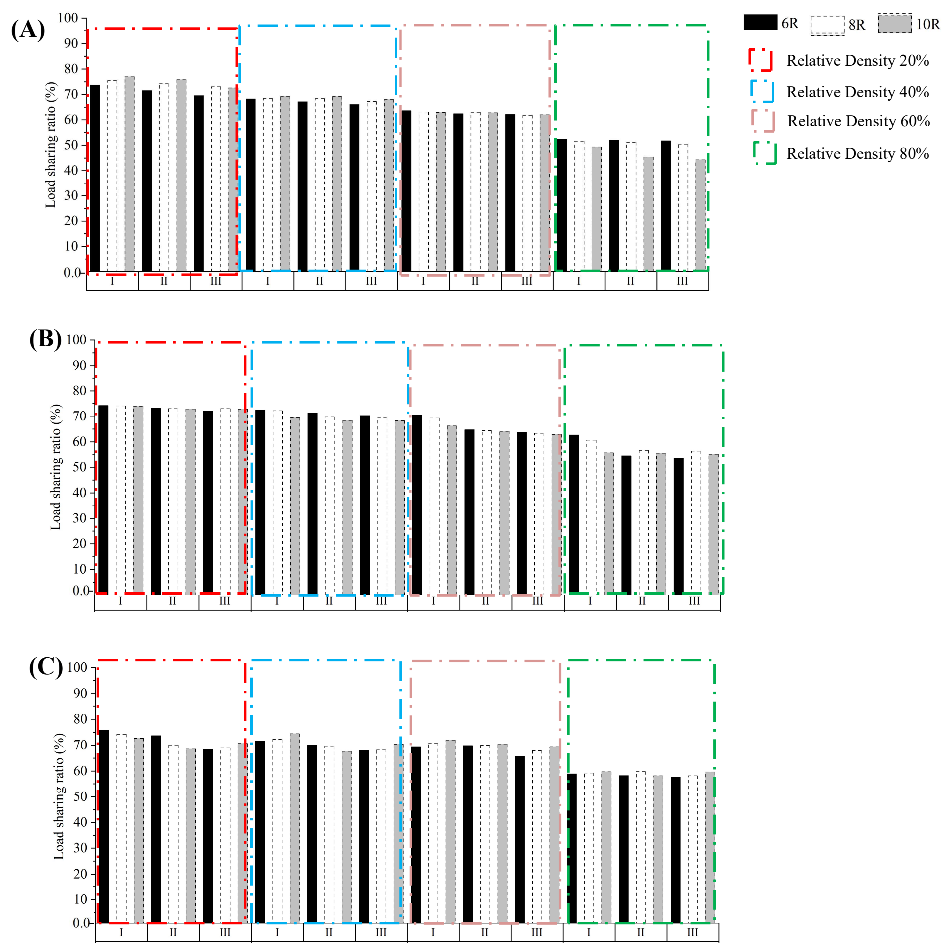
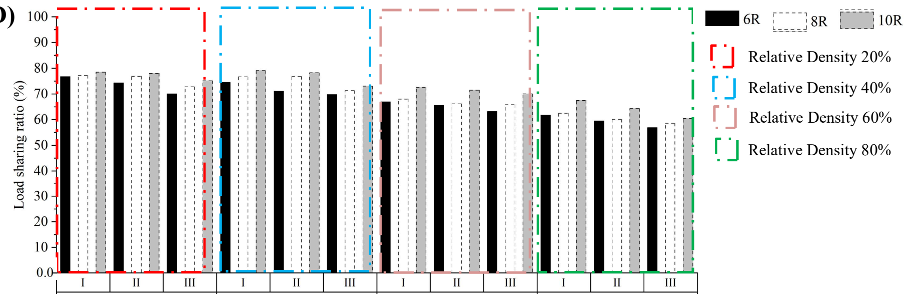


Figure 10 Load-sharing ratio for (A) V-type, (B) ^-type, (C) 10-cm equal length pile arrangement pattern. I 0.5 cm thick raft, II 1.0 cm thick raft, and III 1.5 cm thick raft.

(D)



(E)

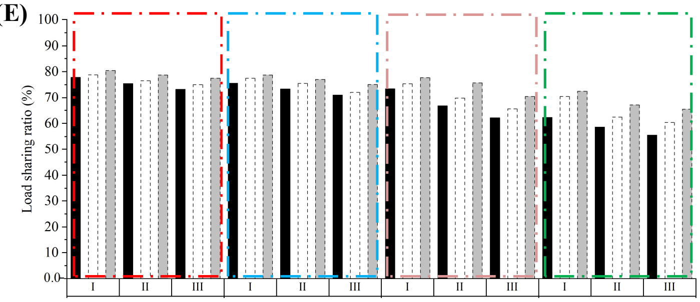


Figure 10 Load-sharing ratio for (D) 15-cm equal length, and (E) 20-cm equal length pile arrangement pattern. I 0.5 cm thick raft, II 1.0 cm thick raft, and III 1.5 cm thick raft.

Figure 10 shows that when the relative sand density, pile spacing, and raft thickness increase, the pile's load-sharing ability improves. It can be perceived that the average LSR of raft for ^-shaped pattern, 10-cm equal length, 15-cm equal length, and 20-cm equal length pattern is 0.99%, 2.60%, 10.81%, and 15.14% for 3d pile spacing; 0.82%, 2.26%, 11.57%, and 15.98% for 4d pile spacing; and 0.61%, 2.37%, 11.73%, and 16.71% for 5d pile spacing, with respect to the V-type of pile arrangement pattern. As the relative density, pile spacing, and raft thickness increase, the load shared by the pile decreases, and then the load shared by the raft increases. Normally, the piles are used as a settlement reducer.

Because of the wide range of PRF system parameters, the LSR between the piles and raft might be distinct. To examine the LSR of PRFs, some samples were taken from the existing literature and used as a basis for comparison (Table 3).

Table 3 Examples of load-sharing ratios.

Parameters					References
D_r	B (m)	L (m)	S/D	α_p	
0.38	0.46	2.30	4.0	0.303	[38]
0.62	0.80	2.30	8.0	0.138	
0.20	0.28	0.64	4.2	0.149	[39]
0.27	0.26	1.00	4.0	0.796	[40]
0.47	0.26	1.00	4.0	0.772	
0.76	0.26	1.00	4.0	0.766	
0.52	9.00	15.00	4.0	0.224	[23]
0.30	0.16	0.20	4.0	0.406	[37]
0.30	0.16	0.30	4.0	0.542	
0.70	0.16	0.20	4.0	0.424	
0.70	0.16	0.30	4.0	0.534	
0.20	0.16	-	3.0, 4.0, 5.0	0.251, 0.224, 0.199	Present study
0.40	0.16	-	3.0, 4.0, 5.0	0.284, 0.257, 0.218	
0.60	0.16	-	3.0, 4.0, 5.0	0.389, 0.343, 0.278	
0.80	0.16	-	3.0, 4.0, 5.0	0.478, 0.547, 0.389	

These include vertically loaded, heaped rafts that lie on cohesionless soils [38-41]. From these analyses, we can conclude that rafts considerably increase the load-bearing capacity of PRFs.

4. Conclusion

Previous settlement investigation demonstrates various factors that affect pile-supported raft settlement. Raft thickness seems to affect settlement minimally. Pile spacing, length, and sand unit weight reduce overall settling. Several factors affect load-sharing. Pile length and spacing increase load-carrying capability under the same loading and soil conditions: raft thickness and density impact a raft and piled raft behavior. The cohesionless soil is loaded with model foundations with varying geometric features. As the raft thickness increases, the load shared by the raft increases, and the settlement of PRFs reduces. Raft thickness reduced settling by 10-25%. Pile arrangement and plie layout also play a very important role in reducing the settlement of PRFs. It also affects the load-sharing ratio of the raft. V- type with 5d spacing PRFs system reduces the settlement of raft by 20% then the ^- type PRFs system. 20 cm equal length PRFs system reduces the settlement of raft various between 21-42% of a raft than PRFs system. The relative density of cohesionless soil also plays a vital load in the load-sharing ratio of the raft. As the relative density increases, the load shared by the raft increases. The load-sharing ratio of PRFs resting on cohesionless soil with $R_d = 0.8$ varies between 32-53% depending on the raft thickness, pile arrangement pattern, and pile spacing. Raft thickness, pile spacing, and relative density of soil play an important role in reducing raft settlement. As the pile length increases, the raft's settlement decreases. The settlement reduction ratio for 5d pile spacing, with 80% relative density of soil and 15 mm thick raft, varies between 24-45% depending on the pile arrangement pattern.

5. Acknowledgements

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