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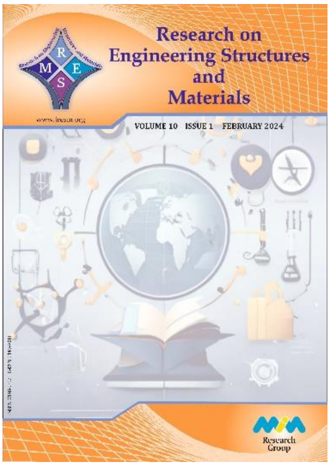

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Research Article

Load sharing behaviour in piled-raft foundations over sand and clay: An experimental investigation

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Abstract

Piled-raft foundations have gained increasing popularity in the past few decades, providing a viable alternative to traditional raft and pile foundations. Despite this, designers are reluctant to apply them frequently in practice due to their complex behaviour and the lack of well-defined guidelines specific to piled-raft foundations. Previous studies have demonstrated that piled-rafts are more effective in reducing settlement and can sustain heavier loads from superstructures. Experimental investigations have been conducted in the present study to ascertain the load-sharing behaviour in piled-raft foundations under vertical loading. Since experimental research on piled-rafts, especially over clay, is quite sparse, small-scale lab tests were conducted on piled-rafts over both sand and clay. Experimental comparisons of unpiled rafts and rafts with piles have been established for a better understanding of the individual and collective response of piles and rafts. Moreover, the effects of a few geometric parameters on the load-bearing capacity of the foundation have been observed. The results showed a significant contribution of the raft to load sharing in piled-raft foundations. It was also observed that the individual load-bearing capacities of the raft and the piles, when summed together, differ from that of the piled-raft foundation due to the interactions between the soil and the foundation components. Observations also supported the fact that increasing the length and number of piles enhances the load-bearing capacity of the foundation. The load-sharing ratio and load improvement ratio increase with the number of piles. Eventually, it can be concluded that piled-rafts are better at minimizing settlement and simultaneously carrying heavier loads.

1. Introduction

There is an increasing need for high-rise constructions due to the rising global population and fast urbanization. The foundations of such constructions are often subjected to tremendous stresses, yet there might not always be a rigid stratum everywhere to sustain them. Hence, they must be placed on soft soils, where settlement, especially differential settlement, is a major problem. The raft foundation has proven to be a good basis for overcoming bearing capacity restrictions, although it may still exceed the permissible differential settling. The conventional pile foundation might restrict the settlement to a permissible limit and transmit the superstructure load to deeper strata.

The conventional pile foundation design does not consider the raft's contribution to load sharing, and hence, several piles may be used to serve the purpose. Consequently, a combination of pile and raft foundations has become popular in recent years as a rational

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and economical foundation system. Such foundations have commonly been known as piled-rafts or piled-raft foundations. Piled-rafts can be used whenever the raft or pile foundation alone is not sufficient to counteract the upcoming stresses.

Since their introduction by Burland et al. [1] as settlement reducers, piled-raft foundations have drawn a lot of attention as an economical foundation system. Following that, several studies have extensively employed this approach [2-6]. In such an approach, the bearing capacity of the raft is utilized to withstand the applied load, and piles are used to reduce settlements, particularly differential settlements, to a reasonable limit. Another approach is the conventional pile design wherein the piles resist the entire load, and the contribution of the pile cap is completely ignored.

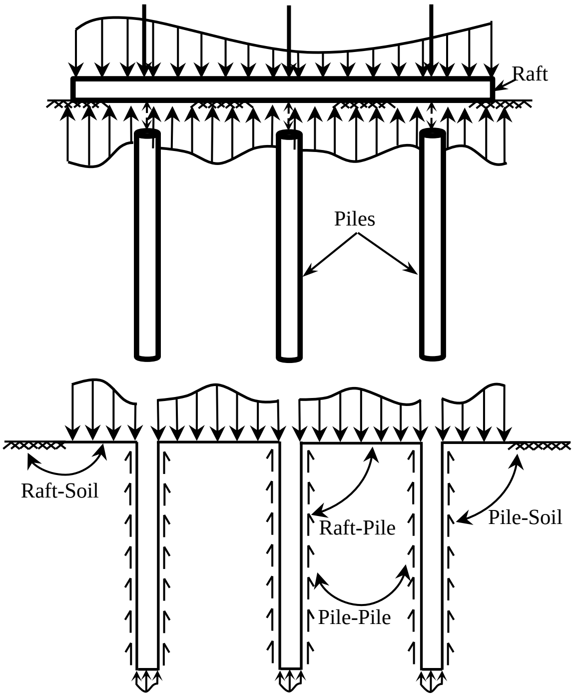


Fig. 1. Interaction mechanism in piled-rafts

High-rise constructions may be assured of having a safe and economical foundation by utilizing a midway strategy that makes use of both the raft and piles' load-bearing capacity. The load-sharing between piles and the raft in such an approach can be more advantageous in the case of strategically employed geometries and soil characteristics. With growing popularity, this approach has been adopted by several scholars [7-9]. Studies on the load-sharing behaviour of piled-rafts have primarily focused on the geometry and stiffness of the foundations [10, 11]. The load-sharing behaviour in piled-raft changes with the settlement as its load-bearing capacity depends on a specific settlement. Hence, it is necessary to consider the non-linear load response of the piled-rafts as well as the interactions between supporting soil and the foundation elements. Following that, a normalized load response model was proposed by Lee et al. [9].

Recent times have witnessed a growing exploration of eco-friendly practices. Rouhanifar [12] explores sustainable sand-rubber mixtures, focusing on mechanical behaviour parameters for low compaction efforts. Similarly, Fareghian [13] proposes recycling waste tire textile fibre (WTTF) to enhance soil properties, reflecting a broader shift toward environmentally conscious practices in the field.

Due to the interactions between soil and the foundation elements, it becomes very complex to understand the load distribution behaviour in piled-rafts (Fig. 1). However, it becomes feasible with modern technologies and high-speed computers to numerically analyse them through available commercial codes. Viggiani [4] broadly classified piled-raft foundations into small and large piled-rafts. Small piled-rafts refer to those in which the raft lacks the necessary bearing capacity to withstand the overall load. Piles are hence affixed to attain a reasonable level of safety. Due to the high rigidity of rafts in small piled-rafts, differential settlement is not a serious issue. Alternatively, those in which the raft alone carries the applied load satisfactorily and needs piles only for reducing the settlement are called large piled-rafts.

The strategic location of piles plays a key role in improving the load-bearing capacity of the raft and also serves to minimize the total and differential settlement. Moreover, due to recent technological advancements, piled-rafts are now not only limited to high-rise structures but can also find their application in bridges, thermal power plants, offshore structures, residential buildings, and oil storage tanks [14, 15]. Various approaches to piled-raft analysis have been briefly reviewed in the subsequent section.

2. Literature Review

Several approaches to piled-raft analysis have been developed since its inception. The initial theories viewed a raft as a plate or a succession of strips supported over spring. [16, 17]. Later on, simplified approaches have been developed. It includes a manual calculation approach by Poulos and Davis [18] which assumed a tri-linear load-settlement curve. Randolph [2] established approximate equations for the stiffness of piled-rafts that were mostly acceptable for traditional pile design.

For complex problems, researchers started using commercial codes based on numerical methods like BEM, FEM or their combinations. Finally, to validate the numerical results and evaluate the performance of piled-rafts under real-world conditions, experimental trials have been conducted. The most frequently used methodologies nowadays are the numerical techniques which may comprise of the finite difference method, finite element method, boundary element method or a hybrid amalgamation of these. The emergence of high-speed computing technology and the various commercial codes generated over time has boosted the use of these strategies. Researchers have used tools like PLAXIS, FLAC, and ABAQUS to simulate the complicated 2D and 3D problems involving interaction problems of piled-raft foundations. A benefit of 3D simulation is its capacity to analyse even the most complicated scenarios. Although using 2D simulation is quicker and easier than using 3D simulation, the underlying 3D problem must first be adequately simplified.

Reul and Randolph [19] conducted parametric investigations on piled-rafts exposed to uneven vertical loads using finite element analysis. de Sanctis & Mandolini [8] performed a 3D analysis to figure out the failure load coefficients that consider the interaction between the piled-raft components. A non-linear 3D study on piled-rafts supported over soft and stiff clay was done by Cho et al. [20]. The widely spaced piles were found more productive at lowering the average settlement. It was observed that the loading type mostly influences the differential settlement, whereas the pile geometries significantly affect both the average and differential settling. Sinha and Hanna [21] investigated the variations in soil properties and piled-raft geometry using a 3D model. Similarly, several other articles on numerical analysis of piled-rafts are listed in their references.

Case studies on piled-rafts over Frankfurt clay have been the focus of numerous investigations [22, 23]. Yamashita [24] examined certain constructions on piled-rafts in Japan that were subjected to seismic loading. Additionally, Japan has released a design standard for piled-raft foundations [25]. Reports on the behaviour of piled-rafts under actual structures have also been published [26, 27].

In contrast to numerical analysis, there is limited information available about experimental studies on piled-rafts, especially those supported over clayey soil. It is evident from the literature that experimental studies of piled-rafts can be conducted either using small-scale model tests or centrifuge tests.

Unsever et al. [28] conducted experimental studies on a piled-raft in the sand under combined loadings. Lateral and vertical tests were carried out on a piled-raft with three piles and the results were later verified using PLAXIS 3D software. It was evident that the interaction between raft and piles has a significant impact on how a piled-raft behaves. Kumar [29] studied the impact of raft size, pile length, and number of piles on the settlement of a foundation system in dry sandy soils with relative density of 70% through an experimental study. Deb et al. [30] analysed two variations of small-scale piled raft models are created, featuring 2 × 2 and 3 × 3 pile configurations. The experimentation involves modifying the spacing between piles and the thickness of the clayey soil to explore diverse scenarios. Chandiwala & Vasanwala [31] investigates a 160 mm x 160 mm pile-raft model, revealing that optimal pile spacing and length enhance bearing capacity while reducing raft settlement. The findings suggested that careful consideration of pile spacing and length in pile-raft systems has the potential to markedly impact lateral load distribution, presenting a more cost-effective and efficient foundation option for skyscrapers.

Piled-raft behaviour in the sand was analysed experimentally in the laboratory using small model foundations by Elwakil & Azzam [32]. It was discovered that the percentage of load shared by raft increased with a reduction in pile numbers and lengths. Moreover, the optimum performance of settlement-reducing piled-raft was achieved at a settlement ratio of 0.7% and the percentage of load taken by raft was 39%. Kumar and Kumar [33] experimentally examined the piled-raft behaviour in which the relative density of sand was varied. The differential settlement ratio was observed to decrease while the load improvement ratio increased with the number of piles. It was determined that the raft in combination with piles was found to be very effective in reducing the settlements.

Variations in relative density and number of piles were also investigated by Sosahab et al. [34] through lab experiments on piled-rafts. In contrast to the pile numbers, the former parameter proved to be more influential. Besides, the load improvement ratio was noticed to be more pronounced in the case of loose sands. A study on load eccentricity was conducted and it was revealed that the ultimate bearing capacity of the piled-raft gets reduced when the eccentricity of load increases.

Bajad & Sahu [35] performed 1g laboratory model tests to examine the effects of interaction among the raft and piles in a vertically loaded piled-raft supported on locally available soft clay. Mandal & Sengupta [36] inspected the behaviour of piled-rafts on soft clay under eccentric loading. For the same e/B ratio, the average settlements for rafts with piles were lowered significantly when compared to unpiled-rafts. Additionally, it was determined that piled-rafts were quite beneficial in minimizing the differential settlement. Hoang & Matsumoto [37] studied the long-term consolidation in clays. Although ground creep caused the foundation to continue settling, the load supported by the raft and piles remained steady.

A number of centrifuge tests were performed by Park and Lee [38] to explore several interaction effects of piled-rafts over silica sand. Load-displacement curves demonstrated that the response of a piled-raft first resembled that of piles and with the later settlement, it became more comparable to those of rafts. According to load response, the influence of raft-pile interaction was more pronounced in the upper soil zone. Azizkandi et al. [39] conducted centrifuge tests in the sand to examine the impact of relative density on the interaction between two piles. The findings indicated that the relative density of soil has a significant impact on the interaction coefficients. Consequently, the consideration of the relative density to modify the Randolph and Wroth equation proved to outperform the earlier approaches.

A parametric study using a centrifuge test was also conducted on connected and non-connected piled-rafts by Rasouli et al. [40]. The parameters involved were pile spacing, pile numbers and thickness of the granular layer. Several centrifuge experiments were performed by Sahraeian et al. [14] to analyse an oil tank over piled-raft foundation on dry and saturated sand. It was observed that using piled-rafts to support an oil tank can effectively lessen the tank settlement and rocking motion.

Horikoshi et al. [41] and Nakai et al. [42] performed dynamic centrifuge model tests to examine the dynamic response of pile groups and piled-rafts. Shake-table tests were performed by Matsumoto et al. [43] to examine the response of piled-rafts beneath a superstructure. The effect of moments and lateral loads have also been observed on a piled-raft in the sand by Sawada and Takemura [44] using centrifuge tests. Due to the raft's contact with the supporting soil, the horizontal resistance of piled-raft was found to be greater as compared to group piles. Cyclic lateral loading tests were conducted by Hamada et al. [45] to investigate the behaviour of vertical load during the seismic activity. The findings demonstrated that the majority of the lateral forces were resisted due to the friction of the raft when there was significant earth pressure below it. Horikoshi et al. [41, 46] examined load sharing in laterally loaded piled-rafts over loose sand while considering various pile head fixities.

In the current paper, the performance of piled-rafts in sandy and clayey soil was investigated under vertical loading. Several small-scale tests were performed on a raft, group piles and piled-rafts to observe the load-sharing behaviour under vertical loading. For this purpose, an experimental setup was prepared and several trials were conducted using a model raft with piles of three different lengths, namely, 160mm, 260mm, and 360mm. The number of piles used to perform parametric analysis on sand and clay varied from 1 to 9. Finally, the load improvement ratio (LIR) and the load sharing ratio were evaluated with the number of piles.

3. Test Materials and Equipment

The expense of large field tests makes it challenging to conduct several trials in a brief amount of time. For this reason, laboratory tests have traditionally been prevalent. Further, it is easier to monitor and achieve desired soil characteristics under controlled laboratory circumstances. With a proper understanding of the model's behaviour, it can be more feasible to apply it in the field reliably and cost-effectively.

The objectives of the current study focus on the load-settlement behaviour of piled-rafts with various layouts. The following sections provide details on test materials, model configurations, and testing techniques that have been used.

Several numbers of test-trials were performed on both sand and clay to attain the objectives of the study. To verify the outcomes, the tests were repeated twice wherever required. The dimensions of the box used for the tests were chosen in a way such that the boundaries shouldn't have any impact on the test results. Hence, it was decided to use a soil bin with a depth at least twice the longest pile length [21]. Also, the bin width was assumed to be five times the raft width.

3.1 Test Soils

Locally available Son River sand and clay from the Ganga basin were used in the current investigation. The Son River is one of the Ganges' largest tributaries, and its sand is widely used in civil engineering purposes across India. The sand particles are yellowish-brown and coarser in size. The used sand and clay were collected from the nearest construction site. Undesirable materials such as roots, plastics or organic wastes were physically removed from the soils and were completely dried. Fig. 2 displays the clay and sand samples that were used.

Fig. 2. Sand and clay

The Index properties of soils used in engineering establish their classification and identification. Table 1 lists some of the key index properties of the soil utilised in the current research. **Hata! Başvuru kaynağı bulunamadı.**3 shows the particle size distribution curves of the used sand. Such a curve represents the distribution of the soil sample into different fractions depending on their sizes. Fig. 4 graphically illustrates the relationship between the density index and the voids ratio for the sand.

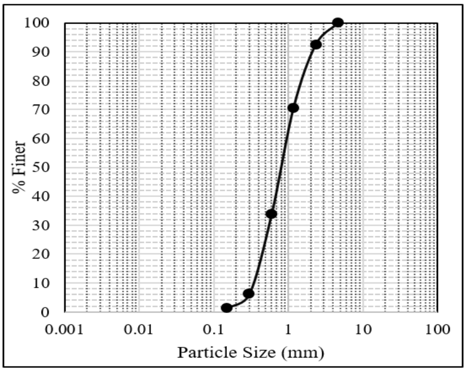


Fig. 3. Particle size distribution curve of sand

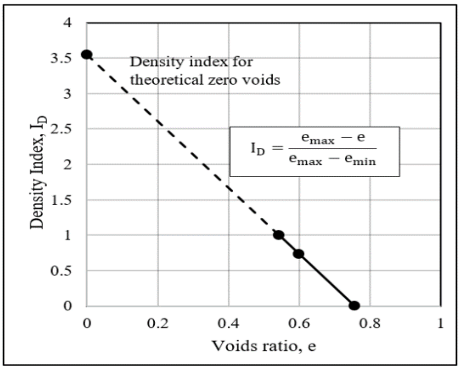


Fig. 4. Density index v/s voids ratio

The coefficient of uniformity (C_u) and coefficient of curvature (C_c) were obtained as 2.71 and 0.91, respectively. Consequently, the sand sample can be categorized as poorly graded sand (SP) as per IS1498-1970 [47]. Direct and triaxial shear tests are widely adopted methods to determine the shear parameters [48]. Shear parameters of sand were computed using direct shear tests and triaxial tests as per IS 2720 (Part 13)-1986 and IS

2720 (Part 11)-1993 [49], respectively. The friction angle was found approximately to be 39°. Specific gravity was obtained to be 2.67 using the Pycnometer method. The minimum and maximum dry unit weights of the sand sample were determined as per IS 2720 (Part 14)-1983 as 1.52 and 1.73. Finally, the relative density of sand was discovered to be 65%, indicating dense sand.

Table 1. Physical properties of sand and clay

Parameters	Sand	Clay
Specific Gravity (G)	2.67	2.58
Minimum dry unit weight, $\gamma_{d,min}$(kN/m^3)	14.90	-
Maximum dry unit weight, $\gamma_{d,max}$(kN/m^3)	16.96	-
D_{10}(mm)	0.35	0.004
D_{30}(mm)	0.55	0.015
D_{60}(mm)	0.95	0.075
Uniformity Coefficient (C_u)	2.71	18.75
Coefficient of Curvature (C_c)	0.91	0.75
Liquid Limit (w_L)	-	40.50%
Plastic Limit (w_P)	-	22.68%
Soil Type	Poorly graded sand (SP)	Intermediate plasticity clay (CI)

In the case of clay, sieve analysis and hydrometer analysis were performed in accordance with IS 2720 (Part 4)-1985. The corresponding curves are illustrated in Fig. 5 and Fig. 6. The liquid limit and plastic limit tests were performed using procedures mentioned in IS 2720 (Part 4)-1985 [49] and were found to be 40.50% and 22.68%. Finally, according to IS1498-1970 [47], the Casagrande plasticity chart identified the used clay as clay with intermediate plasticity (CI).

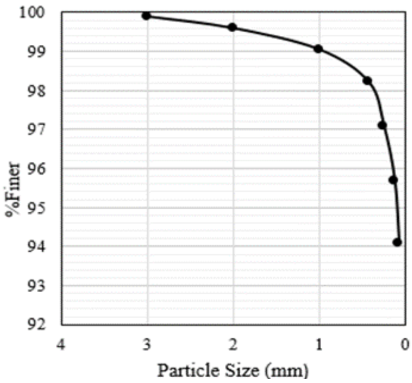


Fig. 5. Sieve analysis

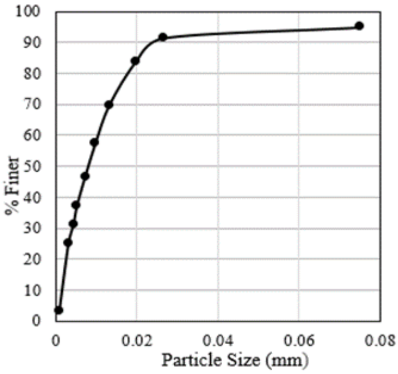


Fig. 6. Hydrometer analysis

3.2 Raft and Piles

A square steel plate with sides of 150mm and a thickness of 10mm was used to model the raft. To fasten the model piles in prescribed layouts, 9 similar holes with 50mm spacings were made. Depending on the required configurations, the piles were fastened to these holes and tightened using the nuts through threads. The threaded portion in the piles is confined to the upper section, leading to a minimal impact on the overall behaviour of the system. The bolts were used to plug holes in the raft. Fig. 7 depicts a model piled-raft with 9 piles attached in a proper arrangement. The current investigation used 1, 4, 5 and 9 piles with lengths of 160mm, 260mm, and 360mm. The cross-sections of all 27 model piles were circular, with a diameter of 12mm. Elastic modulus and Poisson's ratio of the piles were found to be 200GPa and 0.28, respectively.

Fig. 7. Model piled-raft

Table 2 provides other mechanical properties of the model steel piles. These piles were threaded on the upper side and attached to the raft using nuts. To achieve total fixity, the bolts were provided on both sides of the raft and tightened with a wrench. The different configurations of model piled-rafts used in the study are shown in Fig. 8.

Table 2. Mechanical properties of the steel piles

Parameters	Values
Unit weight (kN/m^3)	72.43
Minimum yield strength (N/mm^2)	355.53
Minimum ultimate strength (N/mm^2)	511.62
Minimum % elongation	23.33

Based on the relative stiffness factor (K_{rc}), Poulos and Davis [18] categorised piles into two types: rigid and flexible. Mathematically, the relative stiffness factor K_{rc} is defined as follows in Eq (1):

$$K_{rc} = \frac{E_p I_p}{E_s L^4} \tag{1}$$

Here, E_p represents the elastic modulus of the model pile and E_s denotes the secant modulus of the supporting soil. L denotes the embedded length of pile and I_p represents the moment of inertia of the model pile. A pile is considered rigid if K_{rc} is greater than (10^{-2}) and while it is classified as flexible if K_{rc} is less than (10^{-2}). With L/D ratios of 13.33, 21.67, and 30, the piles considered for the present study fall into the category of flexible piles.

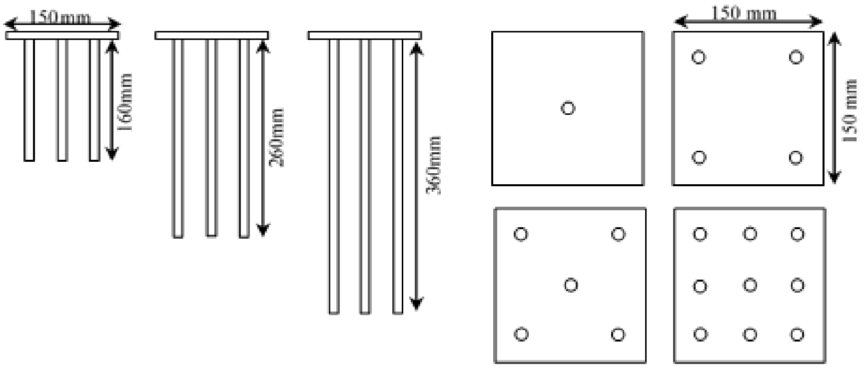


Fig. 8. Different configurations of model piled-raft

3.3.1. Scaling Law

The dimensions and proportions of the model need to be adjusted to accurately represent the prototype. To achieve this, scaling is performed using specific scaling laws. Various researchers have suggested scaling laws to imitate the prototype using an equivalent experimental model. Both laboratory and prototype models exhibit direct proportionality in dimensions such as length and width. However, parameters like moment of inertia and flexural rigidity cannot be directly scaled proportionally. Hence, distinct scaling laws are utilized to accommodate these variations. The present study applies the scaling law proposed by Alnuaim et al. [50], which can be represented in Eq (2) and Table 3 below.

$$(EI)_p = n^{3.64}(EI)_m \tag{2}$$

Table 3. Scaling factors used in the present study

Parameters	Scaling factors
Pile length	$1/n$
Pile diameter	$1/n$
Raft thickness	$1/n$
Density	1
Flexural rigidity, $(EI)_m$	$(EI)_p/n^{3.64}$
Stress	$1/n$
Strain	1

Here, EI represents the flexural rigidity of the pile, while p and m denote the prototype and model, respectively. The scaling factor is denoted by 'n'. It is important to note that the primary objective of this paper is not to replicate a specific prototype. Instead, it aims to investigate and analyse the behaviour of piled rafts within layers of sand and clay. Moreover, the existing literature on experimental analysis has utilized raft dimensions of 150mm × 150mm [29] and 300mm × 300mm [30]. Therefore, it is reasonable to justify the adoption of a square raft with dimensions of 150mm × 150mm in the current paper.

3.3 Soil Bin

The entire experimental work was carried out in a soil bin with dimensions of 750mm × 750mm × 800mm. Wooden plies were used to construct the bin and an iron framework was used to stiffen the bin. The framework was made up of multiple iron rods that were welded together and wrapped around the wooden bin to prevent the connections from opening. The dimensions of the bin were chosen to ensure that the influence zone of the foundation remained within the boundaries.

3.4 Loading Mechanism

A manually operated hydraulic jack was used to load the foundation model. The mechanism of the hydraulic jack is designed to pull self-lubricating fluid from its reservoir and release it into a cylinder that further applies the loads. This fluid being incompressible helps in creating pressure between the reservoir and the cylinder through a pump plunger. On each stroke, the plunger assists in drawing the fluid from the reservoir via a suction valve. The fluid is then released into the cylinder after being pushed via a check valve. The suction valve closes after the fluid has passed through the check valve, creating oil pressure inside the cylinder. This oil pressure pushes the cylinder to exert loads.

To measure the amount of load applied, a proving ring with a maximum capacity of 15kN was mounted at the centre of the raft. Two dial gauges of accuracy 0.01mm were attached to the raft to determine its vertical settlement. Dial gauge comprised of a gauge for assessing the displacement that the needle has gone through during the entire process. The gauge was fixed to steel rods to adjust the position and height of the needle. Needles of dial gauges were placed at the extreme corners of the raft and the gauge was clamped using a magnetic base.

4. Test Procedures

The following sections cover all of the test procedures for the current experimental investigation. The unpiled-raft was investigated first, then the piled-raft, and finally the group piles. Figs. 9 and 10 illustrate the schematic diagram and the actual experimental arrangement.

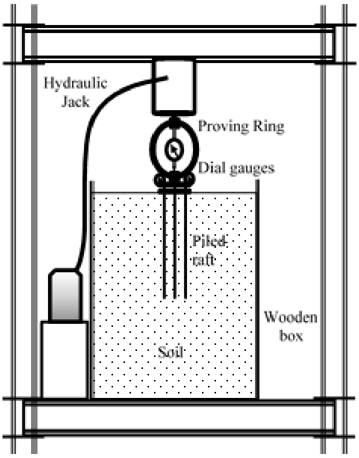


Fig. 9. Schematic diagram of the experimental arrangement

Fig. 10. Actual experimental arrangement

4.1 Preparation of Soil Bed

Soil bed preparation is a crucial step in conducting experimental analyses of small-scale model piled rafts. It involves meticulous planning and execution to ensure accurate representation of real-world soil conditions. The soil is carefully selected based on its gradation and properties, such as particle size, shape, and angularity, to closely resemble the target soil profile. The soil is then evenly spread and compacted layer by layer, ensuring uniform density throughout the bed. The behaviour of small-scale model piled rafts under various loading situations can be thus precisely modelled in an experimental setup by carefully preparing the soil bed.

The soil bed was prepared using the dry pluviation method, where the soil was allowed to fall freely from a predetermined height at a consistent rate. By employing a pluviation height of 750mm, a relative density of 70% was achieved. To create the sand bed, regular intervals were marked within the container, and a measured amount of sand was added up to each marking to maintain the desired density. A 4.9kgs circular plate with a diameter of 150mm and a thickness of 25mm was used to compact the sand. This activity was repeated until the bin's full height of 750mm was reached. The top 50mm of the soil bin was left empty to prevent any overflow during loading. The respective densities were maintained throughout the soil bin with a tolerance of 0.5%. The topmost layer of the soil surface was properly levelled and verified using a spirit level to ensure the proper placement of the raft. The aforementioned process was repeated for each set of tests.

The clay bed preparation followed a procedure similar to that described by Rao et al. [51]. The clay was combined with the appropriate amount of water in a separate mixing tank until it reached a consistency (I_c) of 0.30, representative of the clay used in the study. The same procedure was adopted for clay as discussed above for sand in order to compact the clay in layers. Measurements were taken of the water content, density, and undrained shear strengths at different depths within the soil bed to confirm homogeneity.

4.2 Driving of Piled-Raft

The model foundation was positioned at the centre and slowly inserted into the soil using the hydraulic jack. In the case of piled-rafts, the process was continued until the raft's bottom came into contact with the soil and thus completely supported over it. Likewise, the raft was kept 30mm above the surface in the case of group piles

4.3 Taking Observations

The jack was lowered until it came in contact with the proving ring and dial gauges started responding. Further, the readings in all the dial gauges were corrected to zero. Centring of the raft was done using a plumb bob suspended through the centre of the jack to ensure no eccentricity. Concentric vertical loading was hence employed through the jack in increments. The load was continued till the full extension of the jack length. Since the loading was concentric and rotation of the raft was not allowed, hence the dial gauge readings were nearly identical.

The load readings were observed at every 5 divisions of the proving ring having a calibration factor of 1.18. Corresponding settlements in dial gauges were noted down. These dial gauge readings were averaged to acquire the average settlement. Ultimately, the load versus settlement curves were potted for each model configuration.

5. Results and Discussion

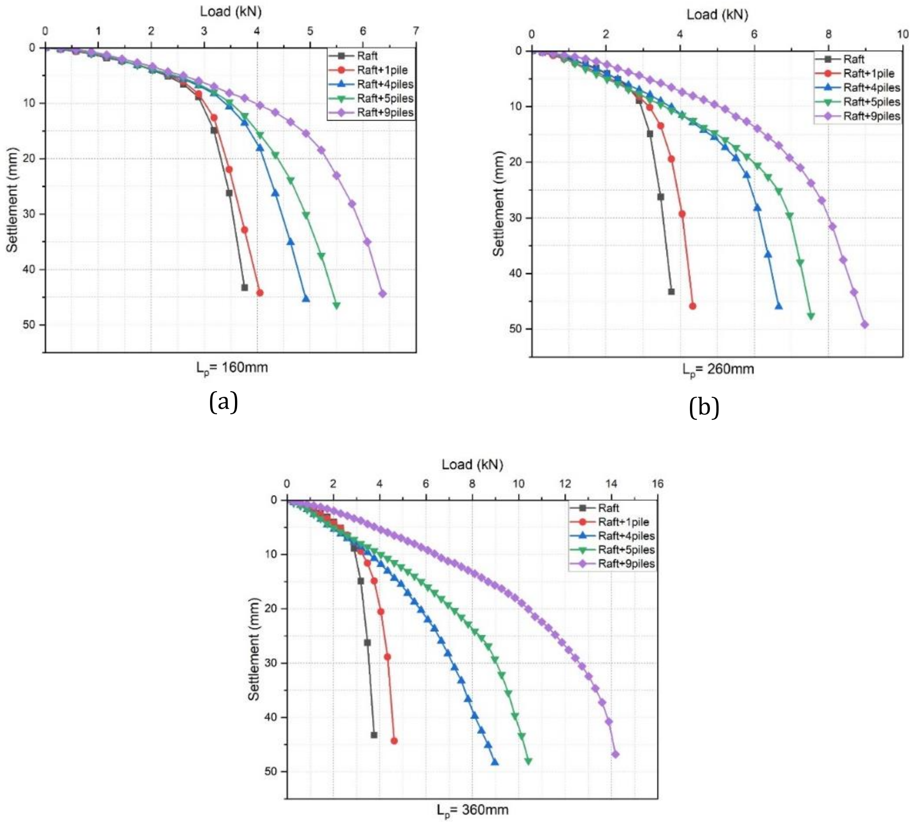
The following sub-sections discuss the behaviour of piled-rafts with different configurations. In the current experimental investigations, the variation in pile lengths and pile numbers is analysed and plotted as load-settlement curves.

El-Garhy et al. [52] used 10mm and 25mm as the index parameters for the experimental study. Bowles [53] adopted the ultimate load capacity as the load at 60mm of settlement. However, the load-settlement curves in the present study do not show a considerable change at the initial phases of settlement and the change may be better noticed in the later stages. Besides, the observations are restricted to 50mm due to the limitation of dial gauges. As a result, a higher settlement of 40mm has been chosen as the index parameter in the current research.

5.1 Effect of Number of Piles

The model raft was initially rested on the foundation soil, and its behaviour was assessed. It was important to examine the raft's behaviour to compare it with the behaviour of model piled-rafts. To analyse the effectiveness of attached piles, the number of piles (n_p) varied from 1 to 9.

Fig. 11 and Fig. 12 indicate that as the number of piles increases, the load-bearing capacity of the piled-raft also increases. It was observed that an unpiled-raft in the host sand has a load-bearing capacity of 3.6kN at 40mm settlement. This capacity increased to 4.5kN, 8kN, 10kN, and 14kN, when the number of piles affixed to the raft varied, measuring 1, 4, 5, and 9, respectively. Similarly, the load capacity improved from 3.6kN to 5.2kN, 7.9kN, 8.8kN and 10.2kN, in the case of clay. The results are anticipated as the additional piles begin interacting with the underlying soil over a wider surface area. Consequently, the piles can resist a greater amount of the load. It can be confirmed by the literature reported [30].

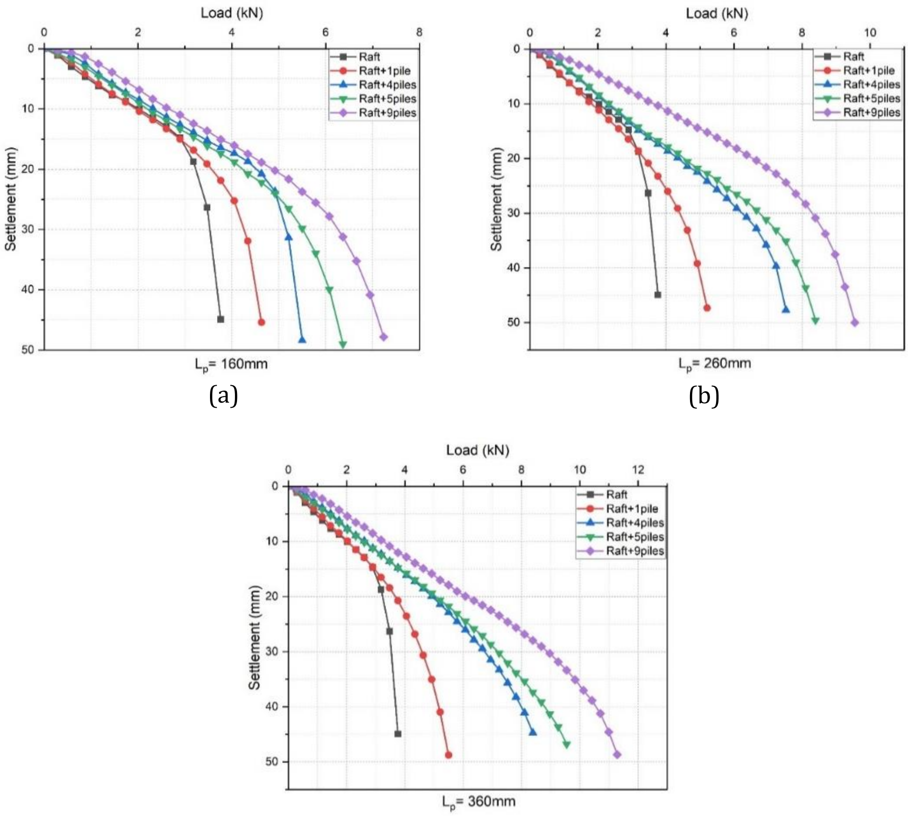


(a)

(b)

(c)

Fig. 11. Effect of number of piles in sand



(a) (b)

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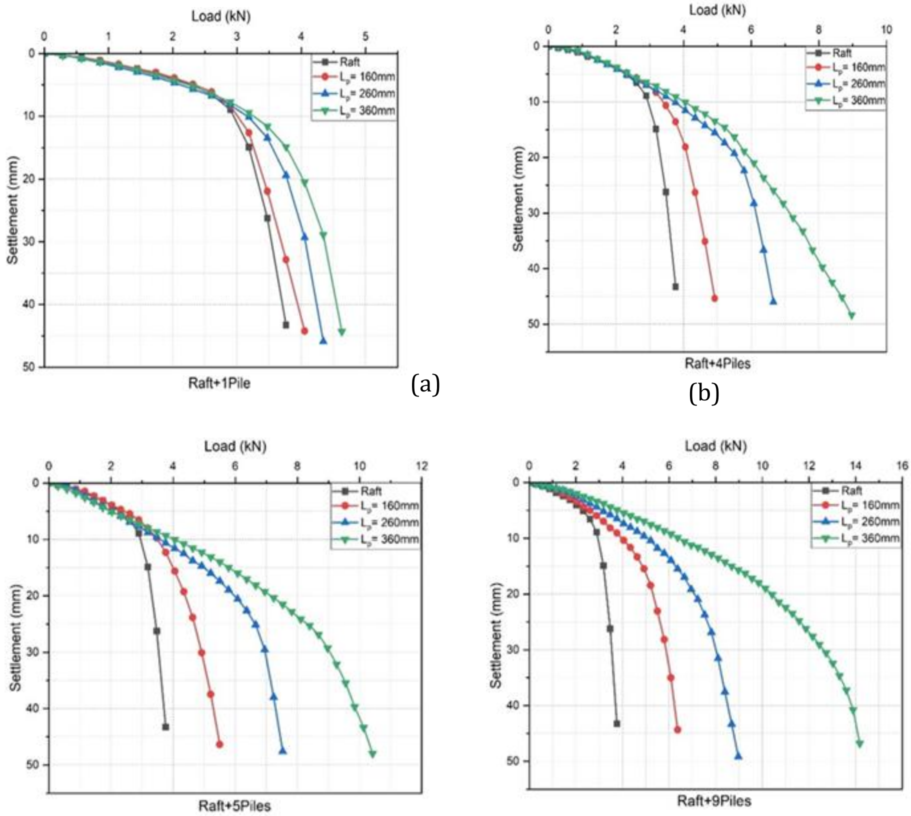
Fig. 12 Effect of number of piles in clay

However, Poulos [54] noted that adding more number of piles to improve the performance of a piled-raft foundation may not always be advantageous. This is due to the fact that once a certain threshold is crossed, very little benefit is observed, and this could result in an uneconomical decision.

5.2 Effect of Pile Length

The impact of varying pile lengths has been presented using load-settlement curves in Fig. 13 and Fig. 14. The experimental setup involved the unscrewing of one set of piles while substituting them with piles of different lengths attached to the raft. As the pile length increased, we observed a corresponding improvement in the overall load-carrying behaviour. This relationship is indicative of the enhanced support and structural stability provided by longer piles.

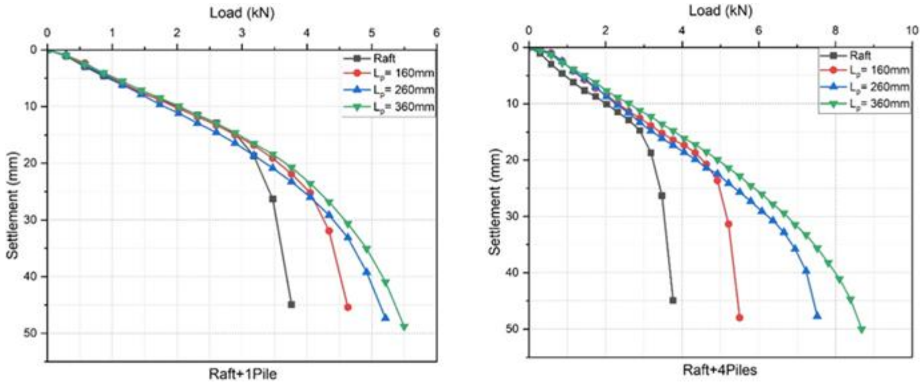
The increased pile length contributed to a more substantial interaction with the underlying soil, effectively distributing and transmitting loads more efficiently. This phenomenon led to a higher load-bearing capacity as longer piles exhibited improved resistance to settlement and deformation. As the length of the piles (L_p) affixed to the raft varied, measuring 160mm, 260mm, and 360mm, the load capacity in the case of sand further improved to 6.2kN, 8.5kN, and 13.8kN, respectively at 40mm settlement. Although this load capacity is for a piled-raft with 9 piles, similar increases can be noticed for different numbers of piles as well. It can also be observed that piled-rafts over sand and clay with any number of piles exhibit a similar trend, and the load capacity in the clay case also enhanced by almost 92%, 150%, and 192%, respectively.



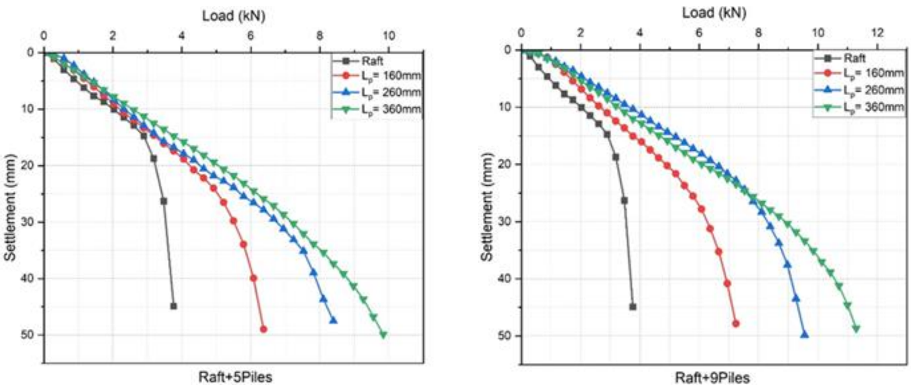
(a) (b)

(c) (d)

Fig. 13. Effect of pile length in sand



(a) (b)



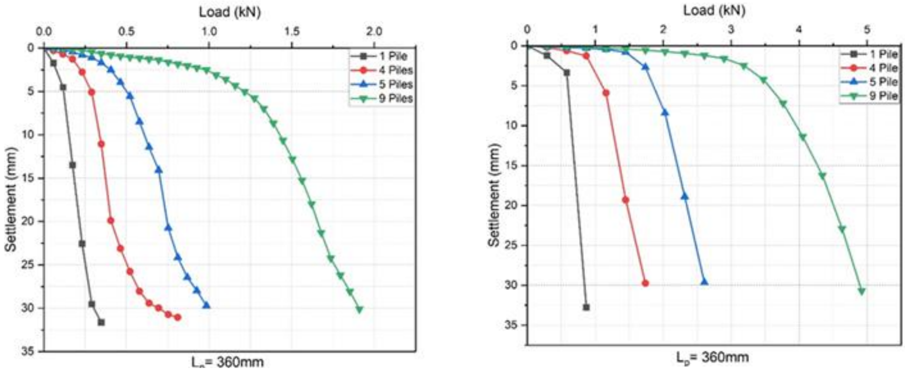
(c) (d)

Fig. 14. Effect of pile length in clay

It is evident that when pile lengths increase, surface area increases as well. It suggests an improvement in shear strength and eventually an increase in the load capacity. This supports the findings that have been documented in the literature [34] reporting that piled-rafts with longer piles sustain greater loads.

5.3. Effect of Pile Numbers in Pile Groups

The behaviour of pile groups was first studied to compute the load sharing in piled-rafts. Fig. 15 illustrates the comparison of model pile foundations with different numbers of piles. The pile length of 360mm was only considered. The pile foundation model was inserted into the soil such that the raft serving as the pile cap was not in contact with the soil surface and raised 30mm above it.



(a) (b)

Fig. 15. Effect of pile numbers in pile group in (a) sand and (b) clay

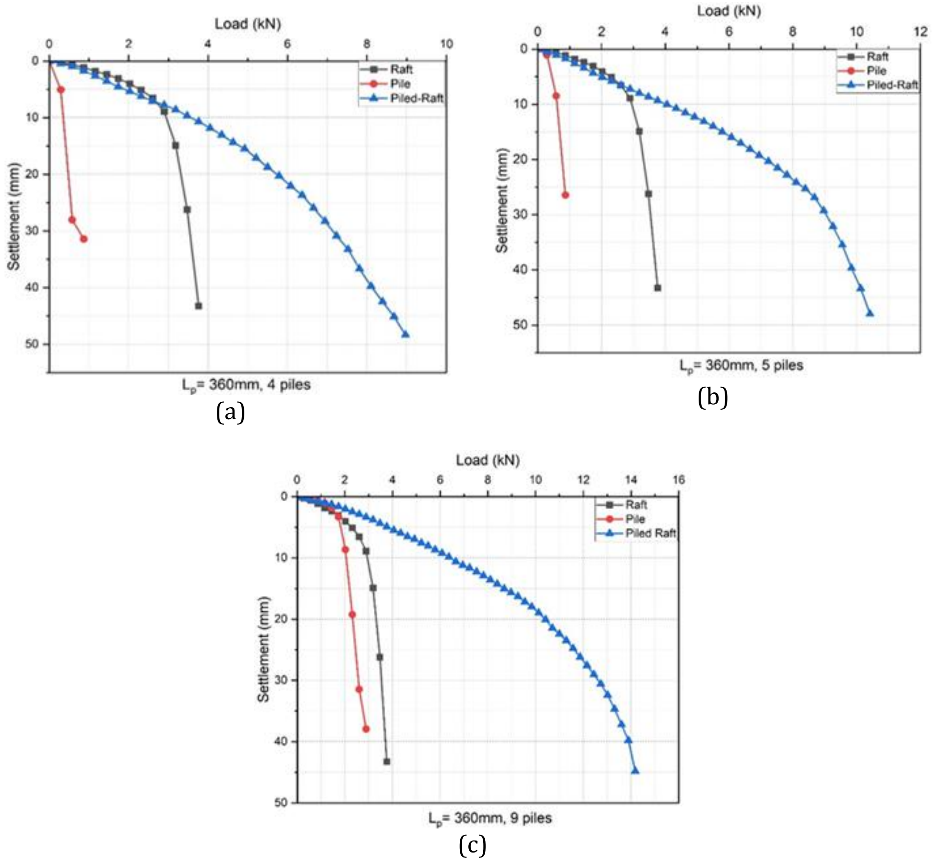
Using 25mm as the reference settlement level in the pile group over sand and clay, the single pile carried a load of 0.25kN and 0.75kN, respectively. It was found that the pile group comprising of 9 piles carried more than 7 and 6 times higher load than a single pile. Similar to the piled-raft case, it was also found that the load-bearing capacity of the pile group gets improved with an increase in the number of piles. Moreover, the deviation in the curve after 30mm settlement indicates that the raft has made contact with the soil surface, and has started taking loads.

5.4. Comparison Between Raft, Piles and Piled-Raft

To study the combined behaviour of the raft and piles in a piled-raft, load-settlement curves depicting raft and group piles are individually plotted and then compared with the piled-raft. In the case of group piles, it was ensured that the piles are freestanding and that the bottom surface of the raft does not touch the supporting soil. When the raft was unpiled, it was resting directly over the supporting soil, without any piles attached to it. It was discovered from Fig. 16 and Fig. 17 that the combined load-bearing capacity of the raft and group piles does not equal the piled-raft's capacity. It can also be supported by the observation in literature [34] that the load carried by piled-raft exceeds or is equal to the combined load carried by the raft and the pile. This indeed results from the interactions between the foundation components and the supporting soil. Mathematically, the load-bearing capacity of piled-raft system can be given by Eq (3).

$$Q_{PR} = Q_R + Q_P = \alpha_{pr} Q_{UR} + \alpha_{pr} Q_{PG} \tag{3}$$

Here, Q_R and Q_P represents the load that the raft and the piles are carrying. α_{pr} and α_{rp} are the interaction factors that characterize interactions between pile and raft and vice-versa, respectively.



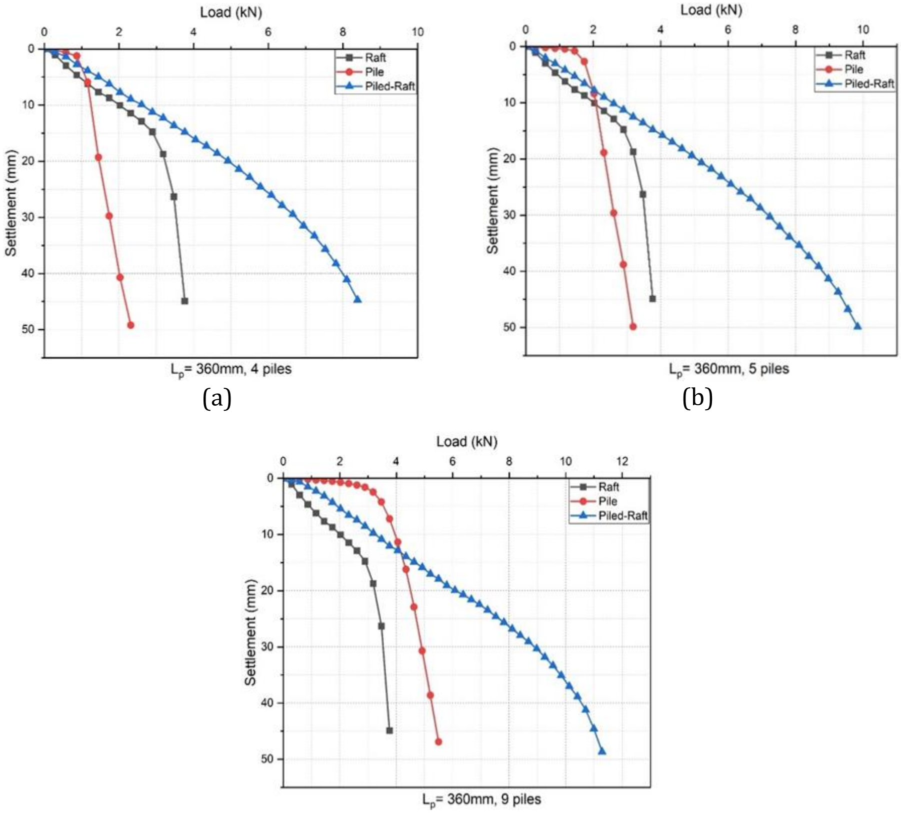
(a)

(b)

(c)

Fig. 16 Comparison between raft, pile group and piled-raft in sand

The subscripts UR, PG, and PR stand for unpiled-raft, pile group, and piled-raft, respectively, whereas Q represents the load capacity. The current study, however, is limited to the load sharing in piled-rafts over sand and clay and does not include the evaluation of these interaction factors. The future objectives of the study could include assessing such interaction factors.



(a)

(b)

(c)

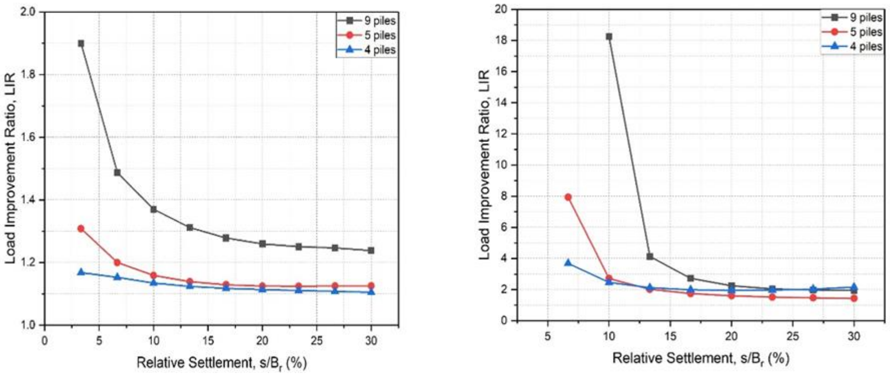
Fig. 17. Comparison between raft, pile group and piled-raft in clay

5.5. Load Improvement Ratio

An increase in the load-bearing capacity of the foundation due to the addition of piles can be defined by a dimensionless parameter, known as load improvement ratio (LIR). It is expressed as the ratio of the load carried by piled-raft (Q_{PR}) to that by the unpiled-raft (Q_{UR}) at constant settlement.

$$LIR = \frac{Q_{PR}}{Q_{UR}} \tag{4}$$

Fig. 18 shows the variation of LIR with the settlement in the case of sandy and clayey soil. It is observed that with an increase in the number of piles, LIR increases. Also, the LIR value is high at the early stages and decreases with an increase in settlement value. In the case of sand, the piled-rafts with higher pile numbers show a sudden decrease initially and finally after a certain value, such decrease becomes gradual. This implies the mobilization of piles after initial loading, leading to a reduction in LIR. Similar outcomes can be observed in earlier pieces of literature [34, 55]. Moreover, in the case of clay, the LIR values converge to roughly the same value regardless of the number of piles and do not significantly vary in later phases.



(a) (b)

Fig. 18. Variation of load improvement ratio in (a) sand and (b) clay

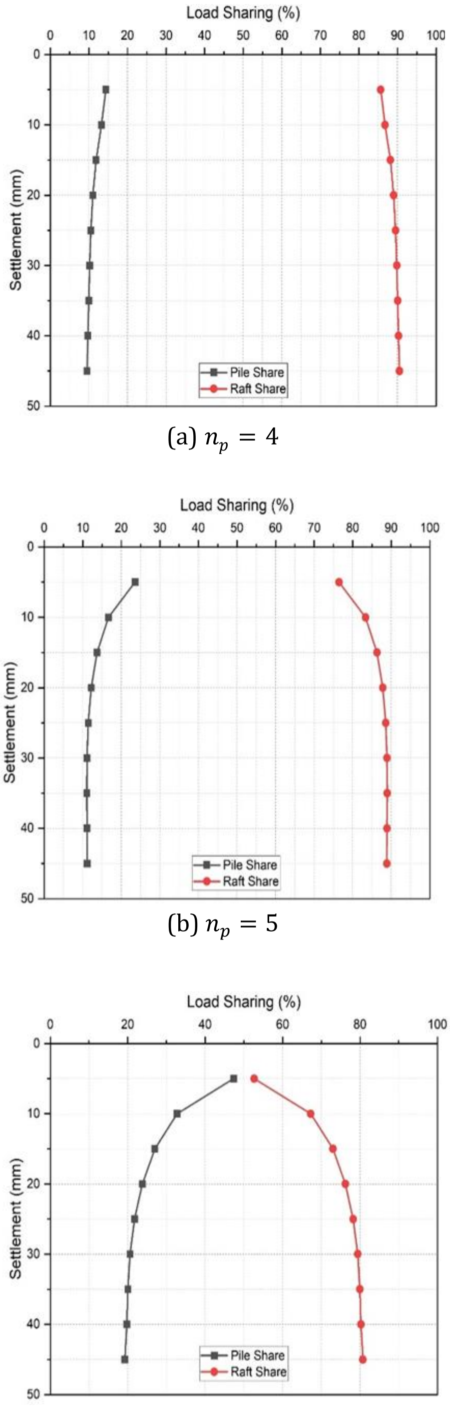
5.6. Load Sharing Ratio (α_p)

It is now widely accepted that in pile-raft foundations, the anticipated load from the superstructure is shared among the piles and the raft. Such a complex load-sharing mechanism is governed mostly by load sharing ratio. Load sharing ratio represents the load-sharing behaviour in piled-rafts and is usually defined as the percentage of the total load imposed on piled-raft (Q_{pr}) that is carried by piles (Q_p). It can be defined by the following equation:

$$\alpha_p = \frac{Q_p}{Q_{pr}} = 1 - \frac{Q_r}{Q_{pr}} \tag{5}$$

where Q_r and Q_p denotes the load resisted by raft and piles, respectively. The variation of load sharing ratio for the present case of sand and clay with the settlement is depicted in Fig. 19 and Fig. 20, respectively. Individual share of load carried by piles and the raft is presented for different configurations. The load share of a raft on sand is initially high and rises until it reaches a fixed limit. Even when there are higher number of piles, the piles share of load is comparatively better but still less than the rafts share. Thus, it can be inferred that neglecting the load shared by rafts in the analysis process will not be a wise decision.

It is evident that in the case of clay, initially the load share of piles is high and gradually the load is transferred to the raft at higher settlements. At initial settlement, the bottom of the raft had inadequate contact with the supporting clayey soil and hence lesser raft share is observed. On the contrary, since the piles are in direct contact with the soil, it leads to confinement of soil and results in a higher proportion of pile share during initial settlement. The density of the soil beneath the raft increases as the piled-raft model settles more. As a consequence, the raft and soil make better contact with each other, increasing the raft's share of the load. A higher percentage of load sharing ratio can also be observed initially in the case of the piled-raft with a greater number of piles due to the greater resistance offered by them.

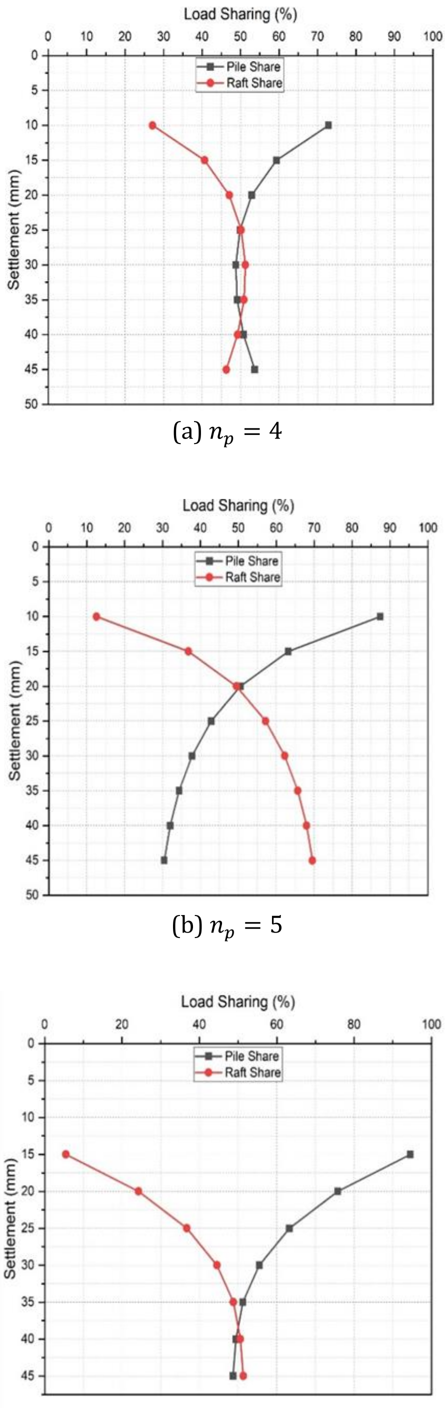


(a) $n_p = 4$

(b) $n_p = 5$

(c) $n_p = 9$

Fig. 19. Variation of load sharing in sand



(a) $n_p = 4$

(b) $n_p = 5$

(c) $n_p = 9$

Fig. 20. Variation of load sharing in clay

6. Validation with Numerical Results

In response to the formidable challenges arising from the cost and time limitations inherent in laboratory or in-situ testing, the scientific community has embraced numerical modelling techniques as a practical alternative. Various commercial codes, such as PLAXIS, FLAC, ABAQUS, and others, have been developed to assist the creation of numerical models [56]. These codes play a crucial role in accurately simulating complex scenarios, with a specific focus on piled raft foundations supported over soil.

The present study uses PLAXIS 3D to validate the experimental study. The dimensions of both the soil continuum and the piled-raft model were matched with those of the experimental model. The test sand was simulated using the elasto-plastic Mohr-Coulomb model obtained from the PLAXIS library. Two models, an unpiled raft and a piled-raft with four piles, were created to validate the experimental findings. The square raft was represented as a plate element, while the pile was modelled as an embedded beam element. The properties of the soil and piled-raft were consistent with those observed in laboratory tests. A medium mesh was generated, comprising 7686 elements and 12450 nodes for the raft and 8019 elements and 13009 nodes for the piled-raft model supported on soil. To mitigate boundary effects, the width of the soil model was set to five times the raft size, and the depth was more than twice the pile length. Fixed boundary conditions were applied to the bottom, while lateral movement was restricted on the sides. Incremental loading was applied to the foundation system through the imposition of vertical pressure.

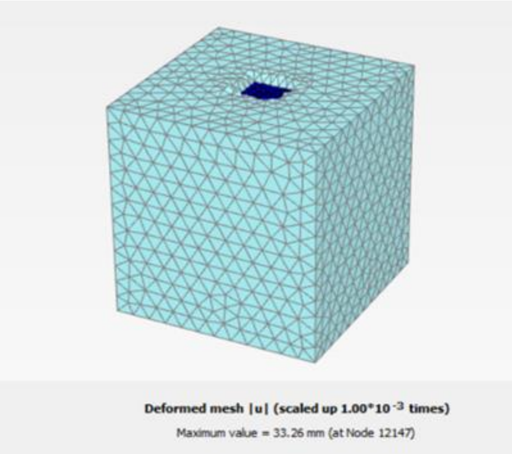


Fig. 21. Numerical model of piled-raft in PLAXIS 3D

In the numerical simulation, the soil-pile interface was modelled with fictitious thickness elements, displaying elasto-plastic behaviour under Coulomb's failure criteria. A strength reduction mechanism, determined by the factor (R_{inter}), was applied to the interface elements [57]:

$$tan\phi_i = R_{inter} \times tan\phi_{soil} \tag{6}$$

This comprehensive approach ensures that the numerical models closely mimic real-world conditions, providing a robust foundation for validating the experimental results. Figure 21 illustrates the deformed mesh of the current numerical model utilized for validation. The results obtained from the numerical simulation were systematically compared with the experimental data derived from laboratory tests, as depicted in Figure 22. Notably, the plot demonstrates a good level of agreement between the numerical and experimental results.

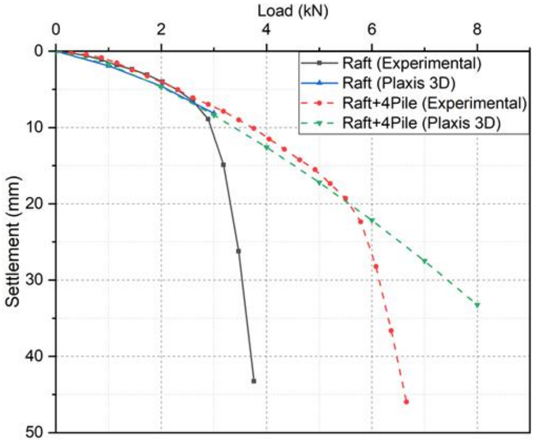


Fig. 22. Validation of the experimental model

7. Limitations of the Experimental Study

The limitations of the present experimental study encompass several factors:

- Dimensional Scaling: Scaling down model pile and raft dimensions from real-world counterparts can introduce inaccuracies due to the behaviour of physical phenomena at smaller scales, potentially affecting findings' applicability to full-scale scenarios. The study adheres to scaling laws, necessitating the use of scaled-down models. While valuable, these models may not fully replicate real-world behaviour at full scale, possibly leading to scale-dependent discrepancies.
- In-situ Stress Representation: Replicating in-situ stress conditions accurately in the testing tank is challenging. Differences between the laboratory setup and actual field conditions can impact the realism and relevance of experimental data. Soil density variations across test scenarios may introduce uncertainties, affecting result comparability.
- Material Differences: The use of steel piles in experiments may not perfectly mimic the behaviour of commonly used reinforced concrete (RC) piles. Material property differences can impact the accuracy of findings related to RC pile foundations.
- Deviation from Natural Soil Conditions: Experiments conducted in a controlled laboratory setting may not fully capture the complexities of real-world scenarios, and the use of artificial soil substitutes could introduce deviations from natural soil conditions, potentially impacting the study's ability to replicate the intricate properties of real soils.
- Exclusion of Pore Pressure Effects: Pore pressure effects, which significantly influence soil behaviour, are omitted from the experiments. This simplification may limit the study's ability to account for the full range of factors influencing piled-raft behaviour in practical applications.

Acknowledging these limitations is essential for interpreting the study's results accurately and for considering the applicability of its findings to real-world engineering scenarios.

8. Future Scope

The findings underscore the need for future research in several key areas. These include:

- Effect of soil variability: The behaviour of piled rafts exhibits notable variations contingent upon the specific type of soil, its inherent properties, and the underlying stratigraphy. Even the present study underscores significant distinctions in the behaviour of piled rafts above sandy and clayey soils. Consequently, there arises a compelling necessity to investigate and comprehend the behaviour of piled rafts in soils characterized by different properties.
- Emphasis on Total Settlement vs. Differential Settlement Models: Current studies on piled rafts tend to concentrate on overall or total settlement, often overlooking differential settlement, which refers to differential movements between different parts of the foundation. By focusing more on differential settlement models, researchers can gain insights into how non-uniform settling might affect the performance of the foundation and surrounding structures, especially in uneven or complex soil conditions.
- Dynamic loading: The current study focuses solely on piled raft foundations under static loads. However, it's essential to recognize that numerous structures experience dynamic and cyclic loading conditions. Therefore, future research endeavours should delve into the analysis of piled-raft foundations subjected to dynamic loads and assess their response to such forces.
- Complexity of Numerical Models vs. Simplified Analytical Models: While advanced 3D numerical models have been developed to capture the intricate behaviour of piled rafts, there is a lack of simplified analytical models and standardized guidelines. This absence hinders the adoption of new design approaches and techniques. Developing simplified yet accurate analytical models and codified guidelines can bridge the gap between complex numerical simulations and traditional design methods, making advanced analyses more accessible and applicable in practical engineering design.

Furthermore, there is a need for more field monitoring and testing to validate the performance of piled raft foundation in real-world applications. With continued research in these areas, piled raft foundation systems can become even more reliable and efficient, providing a sustainable and economical solution for various construction projects.

9. Conclusions

The current experimental research provides the analysis of piled-raft foundation systems employing small-scale model tests. Notably, the absence of standardized practices in this domain prompted our investigation. There was a lack of comprehensive studies, particularly in the local region, focusing on load-sharing behaviour in both sand and clay soils. By conducting experiments in both sand as well as clay, our study broadens the scope of knowledge regarding piled-raft foundations' effectiveness as a choice for load-sharing. The inclusion of both soil types enhances the applicability of the findings to diverse geological conditions. Load improvement and load-sharing behaviour were then studied in those cases.

Based on the current experimental investigations, the following conclusions could be inferred:

- The observations of the present lab experiments showed that the piled-rafts substantially reduce the settlement and resist more as compared to the raft foundations. The reason behind this is that the piles alone resisted the majority of the load in piled-rafts.

- Even a few piles added to the raft enhance the load-bearing capacity of the foundation. Also, such enhancement gets stronger with an increase in pile numbers. In both the sand and clay cases, the observed raft capacity against 40mm reference settlement was found to be around 3.6kN. In the case of sand, improvements of up to 4.5kN, 8kN, 10kN, and 14kN, respectively, can be seen for 1, 4, 5, and 9 piles. The corresponding load capacity in clay was found to improve from 3.6kN to 5.2kN, 7.9kN, 8.8kN and 10.2kN.
- Piled-rafts with longer piles typically exhibit greater bearing capacity. The present case showed up to a 300% increase in the load-bearing capacities for the longest length of pile. In comparison to the unpiled-raft carrying a load of 3.6kN, piled-raft having 9 piles and 360mm pile length resisted about 13.8kN and 10.6kN for the sand and clay case, respectively.
- The load improvement ratio has been noticed to rise as the number of piles increases. The load improvement ratio (LIR) was found to be larger in the early phases and decreases with an increase in settlement value, suggesting the mobilization of piles after the initial loadings.
- The findings also demonstrated that the raft significantly contributed to the load sharing in piled-raft foundations; as a result, its significance in the analysis and design process cannot be unappreciated.
- In the majority of cases, piled-rafts over clay exhibited patterns resembling those over sand. However, it was found that the raft contributed a larger portion of the load in the sand than in clay. Raft's share of the load in sand reached about 90% when piles were lesser, and decreased as the pile numbers increased. In the clay case, the influence of the piles on load sharing was higher, and the raft's share improved with the settlement.
- The experimental findings also revealed that the load-bearing capacity of the combined piled-raft system is greater than the simple addition of the load capacities of the raft and the piles, hence proving its complex behaviour of load-sharing. Such complexity arises due to the interactions between soil and the foundation components. Moreover, these interactions have a considerable impact on the behaviour of piled-rafts.
- To restrict the maximum settlement, an optimization of the piled-raft geometries should be established to prevent an irrational and uneconomical design.
- Since the current study is only capable of testing the piled-raft behaviour at 1g, centrifuge tests could provide a more comprehensive analysis.
- The soil-dependent nature of load-sharing in piled-raft foundations necessitates further exploration within distinct soil types until region-specific guidelines are established for these foundation systems.
- Furthermore, a concise literature survey on several experimental studies on piled-raft foundations has also been provided.

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