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Behavior of piled raft foundations on clay soil subjected to concentric loading

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ABSTRACT: More than 20 % of India is covered by black cotton soil, an area of almost 0.6 million sq km. Black cotton soil is seen as troublesome because of its potentially detrimental volume changes with variations in moisture content. It absorbs a lot of water, then shrinks as the water evaporates, and finally cracks as it dries up. The ground softens during the rainy season and hardens again when the rain stops. As a clay mineral, montmorillonite is responsible for this soil behavior. In this work, a model laboratory inquiry on a smaller size is used to examine the performance of PRF (Piled Raft Foundation) on clay soil. Based on the findings, a piled raft foundation's load carrying capacity improves from 9.20 % to 23.90 % to 40.0 % as the number of piles increases from 4, 6, 9 for 50 mm length of pile and for 100 mm length of pile, the LIR (Load Improvement Ratio) is increased from 66% to 74.76% to 78.72% whereas the SRR (Settlement Reduction Ratio) is significantly increased from76% to 80% to 88% respectively. However, for 50 mm length of piles, after increasing the number of piles in a piled raft system from four to six, the settlement reduction ratio decreased from 84 % to 76 %; this trend is likely attributable to the interaction effects between the piles and the soil.

Keywords: Piled raft foundation, black cotton soil, load bearing capacity and settlement reduction ratio

1. Introduction

The use of pile raft foundations has indeed become a common solution when the underlying soil does not possess sufficient bearing capacity. This type of foundation system is particularly employed in situations where the soil at a shallow depth is highly compressible and the water table is high. The pile-raft system proves to be highly beneficial in transferring the loads through weak, compressible strata or water onto stronger, more compact, less compressible and stiffer soil. Nemanja et al [5] presented the experimental analysis that was conducted on small -scale 1g physical models of piles raft foundation structures. The test program consisted of twelve experiments, with three experiments conducted on a raft alone and nine experiments conducted on piled rafts. The piled rafts were constructed with a group of 2 x 2 piles in loose sand. The experiments varied the pile distances at 3d, 4d and 5d (where d represents the pile diameter) and the pile length at 10d, 20d, and 40d. The study suggests that it is more economical to consider a low bearing capacity factor for the piles, treating them primarily as settlement reducers. This approach allows for the maximum utilization of the raft's bearing capacity to carry a portion of the external load. Bayram et al [6] Numerous empirical, numerical, and analytical studies have been conducted to ensure the reliable design of footing systems, including piled raft foundations. However, the attention is driven to the load sharing ratio (LSR) between the driven pile group and the raft. The tests measure the LSR between the piles and the raft, and also investigate the influence of pile length and relative density on this ratio. Additionally, a numerical model of the test setup is created using ABAQUS software to simulate the same loading conditions and material properties. The results obtained from the tests and finite element analysis indicate that rafts do indeed share the foundation loads at significant levels, and it is observed that vertical settlements of raft foundations at certain loads can be greater than the settlements of piled raft foundations subjected to the same loads. Furthermore, the relative density of the soil was found to have an effect on the LSR of the piles in piled raft foundation, particularly in the range of 1–2%. Additionally, the length of the pile was identified as a more influential factor on this load sharing ratio, particularly within the range of 11-14%. In a study conducted by Alwakil et al [1] analyzed more about the behavior of a piled raft foundation placed in sand. The researchers focused on investigating how piles can be utilized to reduce settlement in a raft's foundation. Small scale experiments were conducted as a modeling technique to simulate the behavior of the system. The experimental investigation primarily examined the effects of pile length and alignment on the maximum load capacity achieved. The results revealed that the carrying capacity of the raft decreases when shorter piles are used. Therefore, it is important to ensure an adequate length and sufficient number of piles to maintain the desired load bearing capacity. Further, the research indicated that the spacing between the piles and the width of the raft, represented as the 0.3 S/B ratio, was found to be the most effective and optimal configuration for reducing settlement. This finding suggests that the spacing between the piles should be approximately 0.3 times the width of the raft to achieve the best performance in terms of settlement mitigation. In summary, the study by Alwakil et al. [1] emphasized the significance of pile length, alignment and spacing in a piled raft foundation. Employing longer piles and an adequate number of piles is crucial to maintain the desired load bearing capacity, while a 0.3 S/B ratio is suggested as the optimal configuration for minimizing settlement. Garhy et al. [2] conducted lab tests on a model of a piled raft foundation on cohesionless soil, the influence of raft-soil interaction on settlement reduction was investigated. Different raft thickness and the pile combinations were tested to study the load-settlement behavior of the foundation system and the load transmission mechanism between the raft and the piles. Patil et al. [3]: This study focused on investigating the load-settlement behavior of piled raft foundations and the load transmission mechanism between the raft and the piles. Various raft thicknesses and pile configurations were examined to understand their influence on the foundation's performance. Eslami et al. [4]: This research utilized two-and three-dimensional finite element analysis to study settlement in multistory buildings supported by connected and non -connected pile-raft systems. The parametric analysis provided insights into optimal design, emphasizing concentrating the piles in the core section of the raft to minimize settlement and achieve shortest pile length. Paravira et al. [5]: The performance of model piled rafts on soft clay was investigated by varying pile parameters using PLAXIS 2D. The Load Improvement Ratio and Settlement Ratio were determined to assess the influence of different pile configurations on load-carrying capacity and settlement reduction. De Sanctis et al. [6]: This study focused on determining the bearing capacity of piled rafts on soft clay soils. A criterion was proposed to estimate the maximum vertical load supported by a piled raft based on the component capacities, which can be calculated using traditional bearing capacity theories. The analysis considered both experimental evidence and three-dimensional finite element studies, considering axial and eccentric column loading scenarios. In summary, these studies collectively contribute to understanding of piled rafts on different soil types.

Indeed, piles in a piled-raft foundation serve a dual purpose of preventing excessive settlement and enhancing the overall stability of the foundation. By connecting the piles to the raft, the system's rigidity and stiffness are increased, leading to several benefits such as reduction in settlement and the internal bending moments within the raft can be minimized. The increased stiffness and load distribution provided by the piles contribute to a more stable and reliable foundation system, particularly in cases where the underlying soil has inadequate bearing capacity.

1.1 Materials

Soil: The black cotton soil utilized in this study was dug up at a depth of 1.5 meters in the village Suluhu, close to the Hubli district, as shown in fig 1. The results of the fundamental soil properties are summarized in Table 1; they include the results of tests for grain size, specific gravity, Atterberg limits, standard proctor compaction, unconfined compression shear strength, and so on. The soil was designated as CH by both the USCS and IS:1498-1970. In Table 2 below, you will see the chemical makeup of the soil.

Figure 1: Black cotton soil was obtained from 1.5 metres below the surface.

Table 1: Geotechnical Properties Soil

Properties	Results
Location	Hubli
Specific Gravity, G	2.4

Grain size distribution Gravel, % Sand, % Silt, % Clay, %	 1.8 11.4 35.08 51.72
Liquid limit, LL, %	83
Plastic limit, PL, %	37.1
Shrinkage limit SL, %	8.5
Plasticity index PI, %	45.9
Classification as per IS	CH
Free swell index, %	80
Maximum dry unit weight, γd, kN/m³	13.7
Optimum moisture content, w, %	32
Unconfined Compressive Strength, kN/m²	49
Cohesion, kN/m²	25

Table 2 Chemical Soil Properties

PARAMETERS	BLACK COTTON SOIL
pH Value	8.24
Chloride content (Cl) mg/kg	140.0
Total soluble Sulphate (SO4) mg/kg	24.0
Organic matter (%)	18.66
Silicon Oxide (%)	60.45
Iron Oxide (%)	11.46
Aluminium Oxide (%)	6.32
Magnesium Oxide (%)	1.21
Calcium Oxide (%)	0.49
Sodium Oxide (%)	0.28

1.1.1 Models of mild steel piles with a 10 mm diameter ranging in height of 50 mm, 100 mm and 150 mm are used for the laboratory experiments, emulating a L/D ratio (Length of pile to diameter of pile) of 5, 10, and 15. The steel pile models used in this investigation is depicted in Figure 2 below.

Figure 2: Piles of length 50 mm

Figure 3: Piles of length 100 mm

1.1.2 Models of mild steel piles of 10 mm diameter ranging in height of 50 mm,100 mm and 150 mm were used for the laboratory experiments, emulating a L/D ratio (Length of pile to diameter of pile) of 5, 10 and 15. The steel model piled rafts are prepared by fixing the piles to the raft as depicted in the following figures 6 -7 below. The model square steel raft used in the experiments, with dimensions of 100 mm × 100 mm and a thickness of 10 mm.

Figure 5: Fixing of four piles to the raft

Figure 6: Fixing of six piles to the raft

Figure 7: Fixing of nine piles to the raft

1.1.3. A square, mild steel model test tank is used to simulate real-world conditions. Fig. 8 depicts the experimental model test tank that was used for this study, which measures 500 mm in width and 500 mm in depth.

Figure 8: Model steel test tank

Spacing of Piles:

Arrangement of piles**:** IS: 2911(Part I & II) – 1979.

As per IS standards, spacings are provided in between piles ranges from (3-4) D where 'D' represents the diameter of piles. The spacing of piles 3D is followed here. The four numbers piles are arranged with spacing of 4D c/c between the piles and nine numbers by providing appropriate spacing of 3D c/c. The schematic representation in Fig 10 and arrangement of the piles for the present study is as shown in Fig 9 and 10.

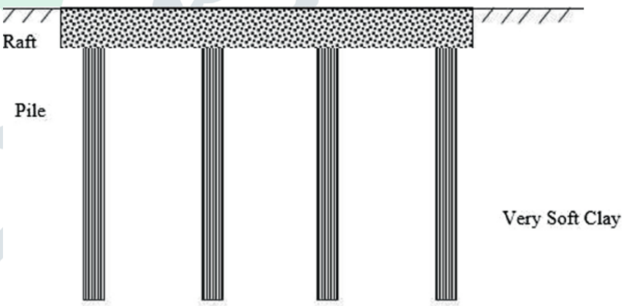

Figure 9: Schematic representation of connected piled raft system

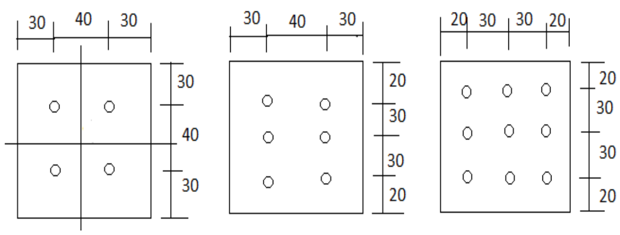

Figure 10: Arrangement of piles (4 - piled raft, 6-piled raft and 9-piled raft)

The loading frame designed to apply a maximum compressive load of 500 kN. It is strain controlled equipment capable of applying constant rate of strain.

A circular base plate of 32 mm thickness and 250 mm diameter is attached to a vertical stem. The stem has threads and connected to a worm wheel arrangement. The tank containing the soil is placed over the base plate and is made to butt against the upper rigid arm of the loading frame through proving ring. A vertical movement of the base plate thus induces a compressive load on the soil and the load is read by the proving ring reading.

The proving ring has a maximum capacity of 50 kN and capable of measuring least compressive load of 0.063 kN. A pictorial view of the proving ring is shown in Figure 11.

Figure 11: Proving ring used for the test

Figure 11: Testing model piled raft

1.2.1 Methodology:

1.2.1 Preparation of Soft clay bed:

The soft clay bed is prepared by compacting the clayey soil in layers of 90 mm height leaving 50 mm gap from the top of the test tank. For each layer the required amount of soil equal to 1370 kgs of soil per cubic meter is mixed with weight of water equal to optimum moisture content to produce a desired density equal to 1.37 g/cm^3 is weighed and then placed in the test tank and compacted in layers. Each layer is compacted by a tamping rod to the required density. The prepared soft clay bed is allowed to consolidate for two days under its own self weight by covering it by a polythene sheet and the density is maintained throughout the experiment. Using the sampling tube sampler the density of the soil was checked. The soil sample is collected using sampling tube extractor and checked for its unconfined compressive strength, q_u = 49 kN/m^2 (c = 25 kN/m^2). The conduction of the test is as shown in figure 11. The piles are screwed to the raft where provision was made for fixing the piles to the raft and the piled raft is driven in to the soil by applying load through the jack.

Mild steel square raft of 100 mm x100 mm and thickness 10 mm which is connected to piles with a circular load connecter is used as model footing.

Figure 12: Uniform settlement is observed during the test.

A model test is conducted on raft foundation (100 mm X 100 mm) by applying the load through hydraulic jack to determine the average bearing pressure of raft foundation on soft clay bed prepared in square test tank of breadth 500 mm and 500 mm height. Gradually the load is increased till maximum settlement of 25 mm is observed. The bearing pressure versus settlement is plotted as shown in fig 10-11.

Figure 12: Maximum settlement is observed

Experimental Program

1) The Model footing test is conducted to study the performance of raft foundation in clay soil when it is loaded concentrically. This test aims to understand how the raft foundation behaves under concentric loading conditions in soil.
2) The Model footing test is conducted to investigate the behavior of piled-raft foundation with different lengths of piles and length – to -diameter(L/D) ratios of 5 and 10. This test aims to study the influence of pile length and L/D ratio on the performance of the piled raft foundation.
3) The model footing test is conducted for raft only and piled raft for different floating & intermediate depth.
4) Load settlement characteristics of clay soil is analyzed for different pattern of arrangement and different number of piles.
5) Based on the experimental results conclusions will be drawn.

Results and Discussion:

Steel test tanks measuring 500 mm in width and 500 mm in depth were used for the laboratory investigations. There wouldn't be any boundary effects because the tank's boundary was five times bigger than the raft.

Group of Piled Raft Foundation Characteristics for Load Settlement on Soft Clay:

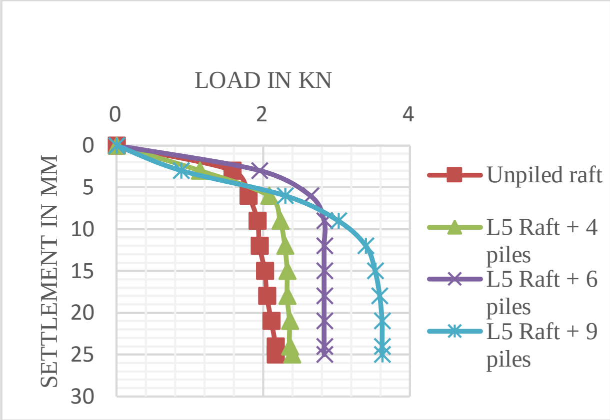

Figure 10: Comparison of four, six and nine numbers of piles of length 5 cm with raft only to compare the load settlement characteristics of a piled raft.

Table 2: For L/D Ratio = 5, Load Improvement Ratio by the Piled Rafts over raft only.				
Description	Load carried by the raft only	Load carried by piled raft over raft only.		
Number of piles		4	6	9
Load (kN)	2.17	2.39	2.84	3.62
LIR (%)		9.20	23.59	40.0

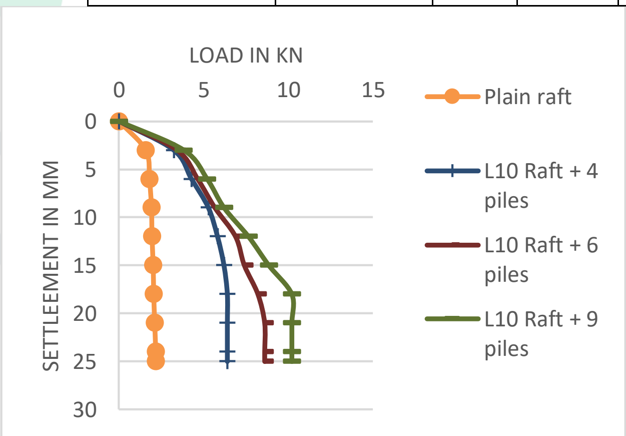

Figure 11: Comparison of four, six and nine numbers of piles of length 10 cm with raft only to compare the load settlement characteristics of a piled raft.

Table 4: For L/D ratio = 5, Settlement reduction ratio by the piled raft compared to raft only.

Description	Settlement occurred for raft only at ultimate load.	Settlement occurred for raft with piles at ultimate load.		
Number of piles		4	6	9
Settlement (mm)	25	6	4	6
SRR (%)		76	84	76

Table 5: For L/D ratio = 10, Settlement reduction ratio by the piled raft compared to raft only.

Description	Settlement occurred for raft only at ultimate load.	Settlement occurred for raft with piles at ultimate load.		
Number of piles		4	6	9
Settlement (mm)	25	6	5	3
SRR (%)		76	80	88

2. Conclusions

Results from a series of small-scale laboratory model tests conducted on clay soil to study load-settlement behavior of the piled raft and raft only. that following conclusions can be made considering the investigation's findings:

1. At a given pile length of 50 mm, adding 4, 6, or 9 piles to a simple raft improves its capacity for carrying load by 9.20 %, 23.59 %, or 40.0 %, respectively.

2. For a pile length of 100 mm, adding 4, 6, or 9 piles to the plain raft improves its load bearing capacity by 66%, 74.76% and 78.72 % respectively.

3. However in case of 50 mm length of 4 numbers and 6 numbers the settlement reduction ratio increased from 76% to 84% and then decreased to 76%. Settlement reduction ratio decreases due to the interference of pressure between the piles since the spacing between the piles is reduced from spacing to diameter ratio 4 to 2. This is because of the effects of pile-soil interaction.

4. The settlement reduction ratio is found to be increasing in case of 4 numbers,6 numbers and 9 numbers of 100 mm length in percentages of 76 %, 80% and 88%.

5. As this study shows, piled rafts have a much greater impact on load bearing capacity and settlement reduction than plain rafts do.

6. It can be concluded that building piles for a longer length in weak soils, with the load handled fully by piles, results in an inefficient design. Since the piled-raft system reduces settlements and pile length, it is more cost-effective to design as the acceptable settlement for clay soil is 65 mm.

List of Abbreviations:

LIR - Load Improvement Ratio.

SRR - Settlement Reduction Ratio.

L/D -Length of pile to Diameter of pile ratio.

S/D – Spacing of piles to Diameter of pile ratio.

Table 3: For L/D Ratio = 10, Load Improvement Ratio by the Piled Rafts over raft only.

Description	Load carried by the raft only	Load carried by piled raft over raft only.		
Number of piles		4	6	9
Load (kN)	2.17	6.40	8.60	10.20
LIR (%)		66.0	74.76	78.72

Declarations:

Ethics approval and consent to Participate

Aruna T and K V S B Raju have given consent for approval.

Consent for publication

Not Applicable.

Availability of data and material:

All data generated or analysed during this study are included in this study.

Competing interests

We have no conflict of interest.

Funding

Not Applicable

Authors' contributions

A T has made a substantial contribution to the experimental work and have drafted and revised the manuscript.

K V S B R has provided his consent for the manuscript to be published.

All authors have read and approved the manuscript.

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