

Performance of Piled Raft Foundation on Sand Bed

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ABSTRACT: The foundation concept of piled rafts differs from traditional foundation design, where the loads are assumed to be carried either by the raft or by the piles, considering the safety factors in each case. Piled raft foundations for important high-rise buildings have proved to be a valuable alternative to conventional pile foundations or mat foundations. Piled raft foundations are increasingly being recognized as an economical and effective foundation system for tall buildings. A laboratory study was conducted on model piled raft foundation to evaluate the influence of configuration of piles and number of piles of piledraft foundation on ultimate bearing capacity and settlement reduction. In this laboratory study, three sets of model piled raft foundation were studied consisting of 16, 24 and 32 number of piles having l/d ratio equal to 40. In each sets, five different configurations of piles were tested. Pile diameter, pile length, type of soil and size of raft were kept constant. The results of the parametric study are presented and a result for an optimized configuration of piled raft is arrived at. The results of tests conducted on raft and piled raft foundation with different configurations of piles were compared in terms of ultimate bearing capacity, load sharing ratio and settlement reduction ratio. It is concluded that the configurations of piles in a piled raft foundation has significant effect on ultimate bearing capacity, settlement reduction and load sharing ratio between the raft and piles.

KEYWORDS: Piled Raft Foundation, ultimate bearing capacity, load sharing ratio and settlement reduction ratio.

I. INTRODUCTION

Modern geotechnical engineering is continuously being developed to achieve more economical foundation along with safety of the structure. Piled-raft foundation has been most notably applied to high-rise buildings all over the world and increasingly being recognized as an effective and economical foundation system. The concept of piled raft foundation was born out of the fact that any structure has a certain magnitude of permissible settlement and the foundation system has to aim at reducing the settlement as close to the permissible value as possible rather than eliminating the settlement completely. The piled raft foundation system provides a skilful geotechnical concept wherein the applied load is transferred by means of a load sharing mechanism which is generated through a process of interaction between the pile, soil and the raft.

In this research work, laboratory model tests were conducted on plain raft and piled raft with different configurations of piles supported on medium dense sand condition. The laboratory model tests were carried out on a model raft of size 300 mm x 150 mm and thickness 10 mm. Tests were also conducted on model piled raft consisting of raft of same size and piles of 6 mm diameter and length to diameter ratio of 40. Five different configurations of piles were used in this study viz; piles uniformly distributes over raft area, piles in central portion of raft, piles in all corners of raft, piles in both central as well as corners of raft area and piles along the longer face of raft. Using identical standard testing procedure, the model tests were conducted on a raft alone and piled raft with different configurations of piles. From the test results, the effects of configurations of piles and number of piles on ultimate bearing capacity, load sharing ratio and settlement reduction ratio was studied.

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II. RELATED WORK

A review of previous studies on piled-raft foundations in terms of behavior, performance, analytical approaches and current design practice is carried out. The objective of this review is to identify the contributions established by researchers on piled-raft foundations and identify the gap in research for the present study.

Seoet *al.*¹ (2003) carried out analysis of piled-raft foundations and soil system using the computer program, PLAXIS to develop the design charts. From the study, it was concluded that, as the pile spacing decreased, the total settlement ratio R decreased until particular pile spacing, and thereafter it became independent of pile group to raft width (B_g/ B_r) ratio. Moayedand Safavian² (2007) conducted a parametric study on piled-raft foundations with piles of different dimensions by finite element method using ANSYS finite element software. The soil had been modelled as Drucker-pragerelastoplastic material. The obtained results showed that the total and differential settlements of pile raft foundation could be reduced with using piles with different diameters.

Singhand Singh³ (2011) conducted a study to investigate the load-settlement behavior of raft foundation when supported by both subsoil and piles by means of both simplified analysis and finite element analysis. It was observed that based on the simplified analysis, the load sharing ratio between piles and raft depends on the settlement of the piled raft, and thereafter no linear relationship between them was observed.

Bishtand Singh⁴ (2012) carried out a numerical analysis by using geotechnical finite element software, PLAXIS 2-D, to investigate the influence of raft thickness, pile length, pile spacing and number of piles. From the numerical analysis results, it was observed that the pile spacing was a factor which had a major influence on both overall and differential settlement. Both the settlement increased with increased in pile spacing.

Cao *et al.*⁵ (2004) conducted an experimental study on models of rafts resting on pile-reinforced sand. In their study, measurements of settlements, strains and bending moments in the raft were made. The results showed that for a given pile group, an increase in pile length was found to be effective for improving the stiffness of a pile-raft system.

Sawwaf⁶ (2010) carried out an experimental study of the effectiveness of using short piles either connected or unconnected to the raft (instead of long piles) on the behavior of an eccentrically loaded raft. The experimental study indicates that, the inclusion of short piles has a significant effect on improving the behavior of an eccentrically loaded model raft supported on sand.

Singh and Singh⁷ (2013) presented results of the experimental investigation on performance of piled raft foundation on sand. The results showed that when the load was taken by piles only under the raft, the settlement was quite faster with little load on the piled raft.

Patilet *al.*⁸ (2014) conducted an experimental model to study the behavior of piled raft foundation system subjected to vertical load. From the results of the study, it was concluded that the load bearing capacity of piled raft increased as the number of piles beneath the raft increased. The raft thickness had insignificant effect on the settlement and the loading sharing between piles and raft.

Rautet *al.*⁹ (2015) conducted an experimental model to study the load sharing ratio behavior of piled raft foundation. The model tests were carried out on unpiled raft, raft supported by 4 piles and 16 piles. From the results of the study, it was concluded that the load sharing ratio of piled raft foundation depends on stiffness of pile and raft.

III. METHODOLOGY

The present research work aimed to study the performance of piled raft foundation resting on sand bed with respect to its various parameters. For this purpose, experimental setup was developed to simulate the piled raft foundation with different parameter proposed.

The objective of present work was to study experimentally the effects of some of parameters of piled raft foundation on sand bed on the load bearing capacity, settlement response and load sharing in piled raft foundation. For this purpose, a laboratory study was conducted on model piled raft with differing number of piles and configurations of piles. The materials used for the study was sand, modelraft and model pile. These are discussed in following section:

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1. Test Material

- Test sand

For the model tests, cohesionless, washed, and dried sand was used as the foundation material. The geotechnical and engineering properties of sand were determined as per IS 2720 and are shown in Table1.

Table 1: Properties of sand

Sr.No.	Properties	Values
1	Specific gravity	2.69
2	γ_{max} (kN/m ³)	16.23
3	γ_{min} (kN/m ³)	15.37
5	Angle of internal friction (ϕ°)	36.5
6	Cohesion (kN/m ²)	3.0
7	Coefficient of uniformity (C_u)	2.63
8	Coefficient of curvature (C_c)	1.14
9	IS Classification	SP (Medium Sand)

- Model Raft

The model raft of rectangular size was fabricated by using mild steel plate having dimensions 300 mm x 150 mm and 10 mm thickness. Raft has little groove at the center to facilitate the application of load.

- Model Piles

The model piles of circular section were fabricated by using mild steel rods of diameter 6 mm and length to diameter ratio of 40.

1. Experimental Setup

For the experimental investigations, the model plate load tests were conducted in accordance with IS: 1888-1982. The apparatus required for these tests consisted of test tank having size 1600 mm x 800 mm in plan and 600 mm high. The loading frame used for applying loads on the model raft, consisted of a horizontal member and two vertical members made of Indian Standard Medium Weight Beam (ISMB) section as shown in Fig.1.



Figure 1: Loading Frame used in Experimental Investigations

The loads were applied to the raft by means of hydraulic jack. The capacity of jack was 50 tons. A proving ring of capacity 50 kN was used to measure accurately the load applied on the model raft. It was fixed to the lower end of the hydraulic jack. The linear variable differential transformers (LVDT) were used for measuring vertical displacement during testing. Two LVDT's were used, which were placed on raft opposite diagonally to record the average settlement of the raft.

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1. Test Procedure

The detailed test procedure adopted for experimental investigation is explained below-

- Preparation of Sand Bed

The tank was filled with sand up to a depth of 450 mm by using the sand rainfall technique. In the present investigation the height of fall was selected as 30 cm in rainfall technique and the corresponding relative density was maintained at 40 %. After completely filling the tank with the sand to the required level, the bed was levelled and checked using spirit level as shown in Fig.2.



Figure 2: Preparation of Sand Bed

In case of piled raft foundation, the sand bed was first prepared up to the level corresponding to the bottom level of piles. The locations of the piles were marked on the sand bed at the desired locations. Piles were placed vertically at the marked location as shown in Fig.3. Preparation of sand bed was then continued till the full depth of sand bed. The top surface of sand bed was then levelled and then model raft was kept over the sand bed, with the pile passing through the holes made in the raft. The piles were then fixed to the raft by bolts as shown in Fig.4, so that piles and raft acted as a monolithic structure.



Figure 3: Placing of Piles in appropriate positions



Figure 4: Placement of Raft with piles passing through holes made in Raft

- Model Plate Load Test

For the experimental work, the model plate load tests were conducted on sand as per IS 1888:1982 to evaluate the ultimate bearing capacity. After the preparation of sand bed along with piled raft the load was applied on the raft in increments of one-tenth of estimated ultimate bearing capacity and the settlements were recorded. Each load increment was kept constant till the rate of settlement became less than 0.02 mm/min. The next increment of load was then applied and the settlement was measured. The test was continued till the failure of foundation or until settlement reached to 10 % of width of raft i.e. 15 mm. The experimental test setup is shown in Fig. 5.

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Figure 5: Experimental Setup of Piled Raft Foundation

2. Test Program

The details of parametric study are given in Table 2.

Table 2: Details of Parametric Study

Sr. No.	Parameters	Details of Parameter
1	Number of piles (N)	N = 16, 24, 32
2	Configuration of piles	i) Uniformly distributed over a plan area. [Configuration A] ii) Distributed over the central area. [Configuration B] iii) Distributed over the corners of plan area. [Configuration C] iv) Distributed over the central as well as corners of the raft. [Configuration D] v) Distributed along longer face of the raft. [Configuration E]

The various configurations of piles in the piled raft foundation, used in the study are shown in Fig. 6 (a) to (e).

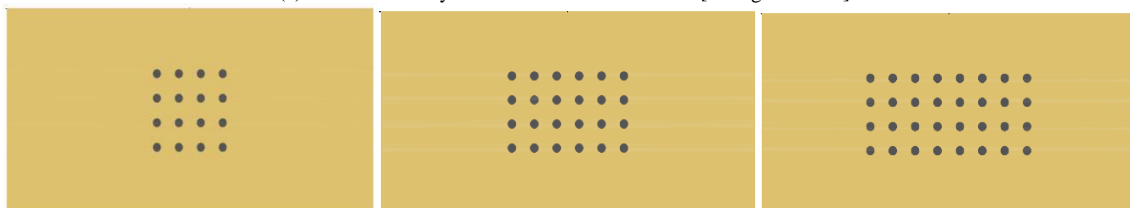


a) N = 16

b) N = 24

c) N = 32

(a) : Piles uniformly distributed over a Plan Area [configuration A]



a) N = 16

b) N = 24

c) N = 32

(b) : Piles distributed over the Central Portion of raft Area [configuration B]

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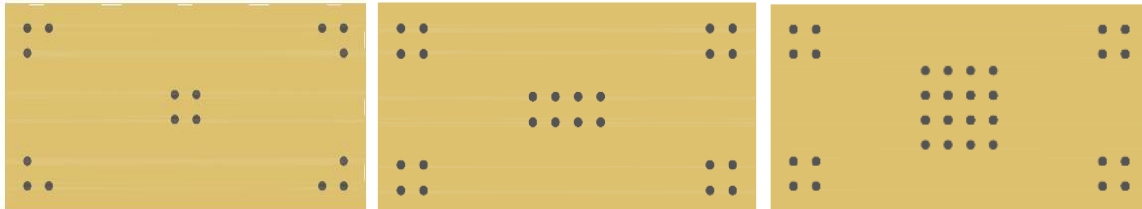


a) N = 16

b) N = 24

c) N = 32

(c) : Piles Distributed over the Corners of Plan Area [configuration C]

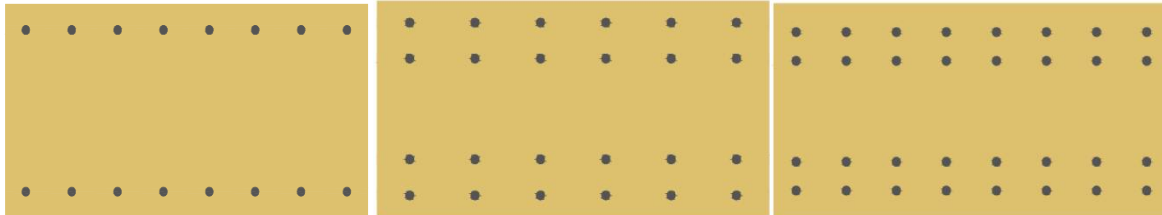


a) N = 16

b) N = 24

c) N = 32

(d) : Piles Distributed over the Central as well as Corners of the Raft [configuration D]



a) N = 16

b) N = 24

c) N = 32

(e) : Piles Distributed along Longer Face of the Raft [configuration E]

Figure 6: Various configurations of piles in the piled raft foundation

IV. EXPERIMENTAL RESULTS

The model tests results obtained from laboratory tests are analyzed and discussed in this section. Comparisons were made with that of unpiled raft.

1. Unpiled Raft

The load settlement relationship for unpiled raft is shown in Fig.7. The ultimate load was found to be 155 kPa and corresponding settlement of 5.8 mm.

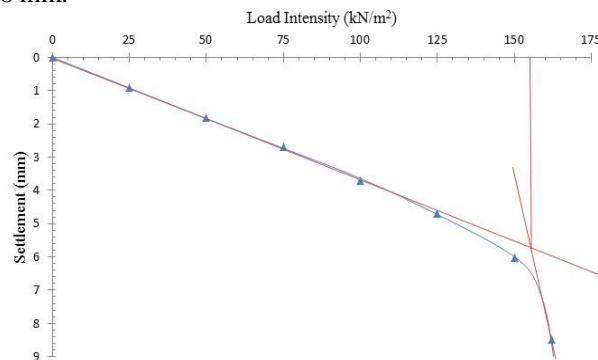


Figure7:LoadSettlementCurve forRaft only

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2. Pile

The ultimate load carrying capacity of a single model pile of diameter 6 mm and length 240 mm ($l/d = 40$) was determined separately and it was found to be 88 N. This value was used to determine the load sharing ratio in further analysis.

3. Piled Raft

The ultimate bearing capacity, load sharing ratio and reduction in settlement were obtained from the load vs settlement relationship of piled raft foundation and are shown in Table 2. 'Load sharing ratio' (LSR) is the ratio of difference of UBC of sand with piled raft and UBC of sand with raft only to that of sand with piled raft. 'Bearing capacity ratio' (BCR) is the ratio of UBC of sand with piled raft to that of sand with raft only. 'Settlement reduction ratio' (SRR) is defined as the ratio of difference of settlement of the unpiled raft and settlement of piled raft to the settlement of unpiled raft only under specified load.

Table 2: Ultimate load, load sharing and settlement reduction value from experimental study

Sr. No.	Number of Piles	Configuration of Piles	UBC (kN/m ²)	BCR	Load Sharing Ratio (%)		Settlement Reduction Ratio (%)
					Pile group	Raft	
1	0	Raft only	155	-	-	100.00	-
2	16	A	390	2.52	60.26	39.74	13.79
		B	320	2.06	51.56	48.44	13.79
		C	380	2.45	59.21	40.79	17.24
		D	475	3.06	67.36	32.64	31.06
		E	440	2.84	64.77	35.23	17.24
3	24	A	440	2.84	64.77	35.23	34.49
		B	430	2.77	63.95	36.05	27.58
		C	480	3.10	67.71	32.29	31.03
		D	570	3.68	72.81	27.19	44.83
		E	440	2.84	64.77	35.23	31.03
4	32	A	690	4.45	77.53	22.47	55.17
		B	630	4.07	75.40	24.6	51.72
		C	700	4.52	77.85	22.15	55.17
		D	740	4.77	79.05	20.95	65.51
		E	700	4.52	77.85	22.15	58.63

4. Effect of configuration of piles

Tests were carried out for five different configurations of piles distributed over the raft area for each set of piles to bring out its effect on load-settlement response. Fig. 8 shows the effect of configurations of piles on UBC.

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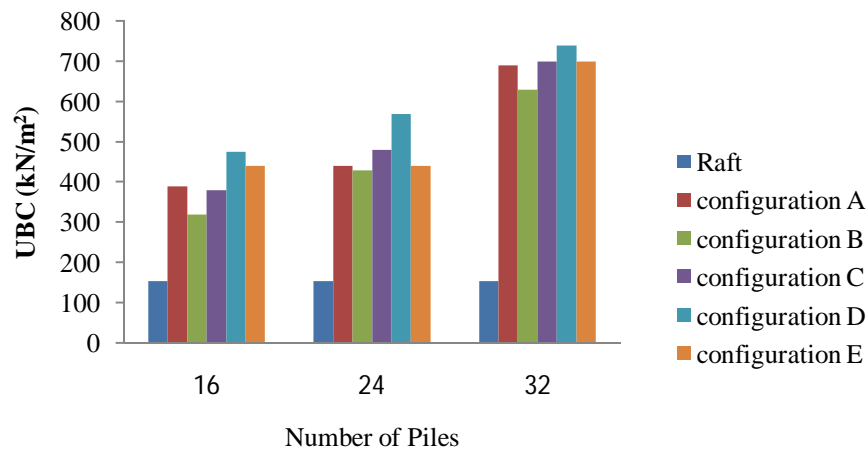


Figure 8: Ultimate Bearing Capacities of PRF for Different Configuration of Piles

From the figures, it is observed that a configuration of piles has significant effect on UBC of piled raft foundation. The piled raft foundation with piles distributed over the central as well as corners of the raft area (configuration D) resulted in the highest value of ultimate bearing capacity, while piles distributed over the central portion of plan area of raft (configuration B) resulted in lowest ultimate bearing capacity, among the configurations tested. Thus UBC of piled raft foundation may be enhanced by providing suitable configuration of the piles in the following order:

- i) Piles distributed over the central area of raft
- ii) Piles distributed uniformly over a plan area of raft
- iii) Piles distributed along longer face of the raft
- iv) Piles distributed over the corners of plan area of raft
- v) Piles distributed over the central as well as corners of the raft.

Table 3 shows the percentage increase in ultimate bearing capacity of piled raft foundation with configurations D i.e. piles distributed over the central as well as corners of raft area for each sets of piles as compared to piles uniformly distributed over a plan area of raft (configuration A).

Table 3: Comparison of UBC between configuration A and D

Number of piles	UBC (kN/m ²)		% increment in UBC
	Configuration A	Configuration D	
16	390	475	21.80
24	440	570	29.55
32	690	740	07.24

5. Effect of Configuration of Piles on Settlement Reduction Ratio

In the experimental studies conducted, the effect of piles in piled raft foundation towards reducing the settlement had been studied through settlement reduction ratio. The specified load was taken as 155 kN/m² which was the ultimate load intensity for raft foundation. Fig.9 represents the effect of the configurations of piles on the settlement reduction ratio with different number of piles.

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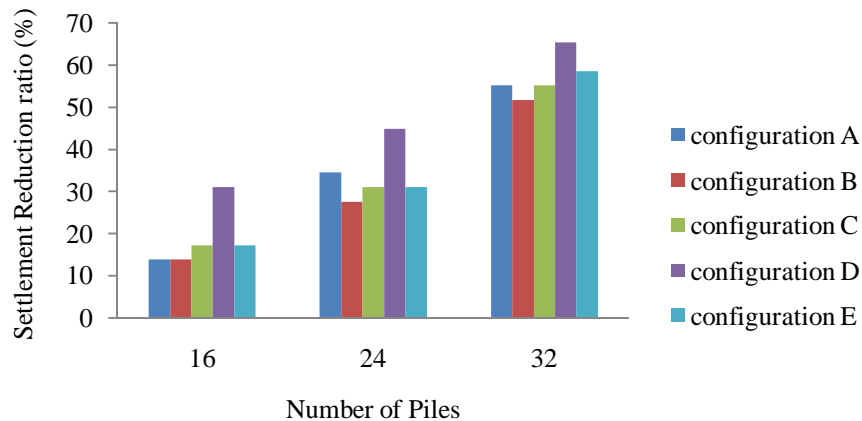


Figure 9: Variation of settlement reduction ratio with configurations of piles for different number of piles

From the figure, it is clearly seen that the percentage reduction in settlement was found to be significant when the number of piles increased from 16 to 32 in each piled raft configuration. The settlement reduction ratio is also influenced by the configuration of piles. Configuration D (piles distributed over central as well as corners of the raft area) gives the higher settlement reduction ratio, indicating that settlement of the foundation is lowest among the all configurations of piles studied. Table 4 shows the percentage reduction in settlement of piled raft foundation with configurations D i.e. piles distributed over the central as well as corners of raft area for each sets of piles as compared to piles uniformly distributed over a plan area of raft (configuration A).

Table 4: Comparison of settlement reduction ratio between configuration A and D

Number of piles	Settlement (mm)		% reduction in Settlement
	Configuration A	Configuration D	
16	5	4	25.00
24	3.8	3.2	18.75
32	2.6	2	30.00

From the table, it is evident that there is considerable reduction in settlement of the piled raft foundation by providing suitable configurations of piles over the plan area.

V. CONCLUSIONS

Based on experimental investigations, the following broad conclusions are drawn:

- i) The increases in number of piles in a piled raft foundation results in increase in ultimate bearing capacity and decrease in settlement.
- ii) The change in configuration of piles over the raft area has a significant effect on the ultimate bearing capacity of piled raft foundation. The ultimate bearing capacity of piled raft foundation may further be improved to the extent of 30 % by providing suitable configuration of piles in a piled raft foundation.
- iii) The change in configuration of piles over the raft area has also significant effect on settlement reduction ratio of the piled raft foundation. There is considerable reduction in settlement of the piled raft foundation to the extent of 30 % by providing suitable configurations of piles over the plan area.
- iv) The pile raft foundation with piles distribution over central as well as corners of raft area found to be the optimum for pile load sharing, ultimate bearing capacity, and settlement reduction ratio.

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