Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam
Visakhapatnam Chapter

Parametric Study on Performance of Piled Raft Foundation on Dense Sand underlain by Soft Clay

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Abstract. In foundation design, it is common to consider the use of a shallow foundation system such as a raft to support a structure, if raft is not capable of carrying the super structural loads we have to consider the use of conventional pile foundation system consisting of a large number of piles inter-connected through a pile cap and forming a pile group. Piled raft foundation is a composite foundation in which piles are added to the raft to limit the settlements. A piled raft foundation is preferable whenever stiff or dense bearing stratum present at top layer and weak soils are present underneath that. Many researchers studied behaviour of piled raft foundation on homogenous soils and not many extensive studies on layered soil. The present study focused on the performance of piled raft foundation in layered soil i.e., dense sandy stratum underlain by soft clay in terms of load carrying capacity and settlement reduction by varying the non-dimensional parameters such as spacing between the piles, number of piles, length of piles and thickness of top dense sand layer. Quantification of relative effect of each parameter is analysed by a statistical tool called factorial analysis and based on dominating factors and their interactions model equations were developed by performing multiple linear regression analysis. The results showed that the load improvement ratio and settlement reduction ratio varies from 7-74% and 8-56% respectively for various piled raft configurations.

Keywords: Raft, Piled-Raft foundation, layered soil, Settlement, Load Carrying Capacity

1 Introduction

In foundation design, it is common to consider first the use of a shallow foundation system, such as a raft, to support a structure and then, if this is not adequate, to consider the use of a fully piled foundation system, consisting of a large number of piles, inter-connected through a pile cap and forming a pile group. Recently there has been an increasing recognition that the behaviour of a mat or raft can be enhanced effectively by the addition of a limited number of piles, giving rise to the concept of a pile-enhanced raft or a piled raft. The piled raft foundation is a geotechnical composite construction consisting of three bearing elements: piles, raft and subsoil. Compared to the traditional foundation design where the structural load is transferred either by the raft or by the piles, this is an innovative design concept where both the raft and the piles contribute to the foundation performance. In particular, both the raft and the piles are able to transmit loads directly to the subsoil and, therefore, piles are usually not required to ensure the overall stability of the foundation, but to act as settlement reducers (Burland et al., 1977), since the raft alone usually provides sufficient load capacity. Cooke (1986) [4] defined a design approach for piled raft foundations, where piles are used for settlement limitation. The concept of piled raft foundations was originally described by Sievert (1957) [1] and encouraged the designers to adopt this approach for high-rise building foundations. The concept of using piles as settlement reducers was first proposed by Burland et al. 1977 [2]. Several reports were published on the use of piles as settlement reducers (Poulos and Davis 1980 [3]; Clancy and Randolph 1993 [5]; Horikoshi and Randolph 1996) [7]. Cooke (1986) [4] conducted elaborate model tests on rafts (unpiled), free standing pile groups and piled rafts on over consolidated clay bed. Cooke established that very little advantage could be obtained by designing the piled raft with spacing lesser than 4d and also indicated that the block behaviour occurred at even much wider spacing (i.e. 6d to 8d) than what was being traditionally accepted for piled raft design. Horikoshi (1995) [6] and Horikoshi and Randolph (1996) [7] conducted a series of centrifuge model studies on piled raft supported on over consolidated clay. This study showed that piled rafts could be designed for negligible differential settlements by introducing a pile group over the central 16-25% area of the raft and the piles could share about 40-70% of the total load, depending on the pile group area ratio and Poisson's ratio of the soil. Poulos (2001) [8]has examined number of idealized soil profiles and found that the soil profiles consisting of relatively stiff clay/dense sand at top are favourable.Kim et al (2001) [9]conducted three series of tests on standard sand (Jumujin sand) with relative density of 68.3% to bring out effects of stiffness of raft, spacing between the piles and arrangement of piles and reported that the load sharing ratio decreased gradually with settlement ratio. The load sharing ratio of the raft increased with thickness and size of the raft. Bisht and Singh (2012) [10] carried out numerical analysis by 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. Karim et al(2012) [11] studied the percentage of load shared by pile and piled raft by performing experimental work and the same is compared with PLAXIS 3D and ANSYS software. They stated that the total load carried by piles depends on piles number in group and interaction between the piles is affected by pile spacing.

From the literature it is clear that only a few investigators studied the effect of thickness and density index, (I_D) of top dense sand layer underlain by soft clay on load carrying capacity and settlement behavior of piled raft foundation resting on layered deposits. Spacing of piles, length of piles and number of piles supporting the raft are the other parameters which require attention to understand and assess the behavior of piled raft foundation. Also, little information is available on quantification of relative effect of each parameter and interaction effects that are known to influence piled raft behavior. The present work aims to study experimentally the performance of piled raft foundation by varying the non-dimensional parameters namely spacing between the piles (S/D), number of piles (N), length of piles (N) and thickness of top dense sand layer (H_1/B). A total of 22 loading tests are conducted for raft, individual piles and piled raft combinations. The details of the tests conducted are presented in Table 1. The configurations of the piled raft are presented in Fig. 1.

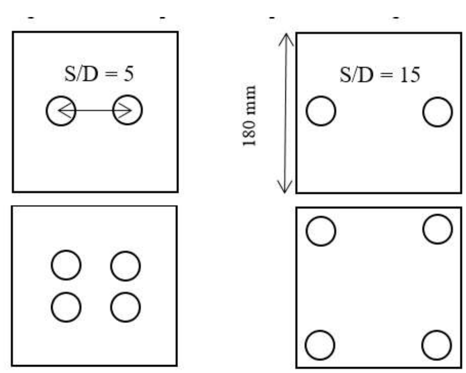


Table 1 Details of the model tests

Model	H_1/B	L/D	S/D	No. Tests
Raft	0.3	-	-	1
	0.6	-	-	1
Pile	0.3	10, 40	-	2
	0.6	10, 40	-	2
Raft+2piles	0.3	10, 40	5, 15	4
	0.6	10, 40	5, 15	4
Raft+4piles	0.3	10, 40	5, 15	4
	0.6	10, 40	5, 15	4

Fig. 1. Configurations of Piled raft

Test Material

Locally available river sand is used as test material for the present study. The sand was tested for specific gravity, grain size distribution and relative density. Test results are shown in Table 2 and grain size distribution was shown in Fig. 2. As per IS: 1498-1970 [12] the soil was classified as "SP".

Table 2. Properties of Sand

Parameter	Value
Specific Gravity	2.60
Iinimum dry density	.76 kN/m^3
Iaximum dry density	.11 kN/m^3
efficient of Uniformity	2.5
efficient of Curvature	1.06

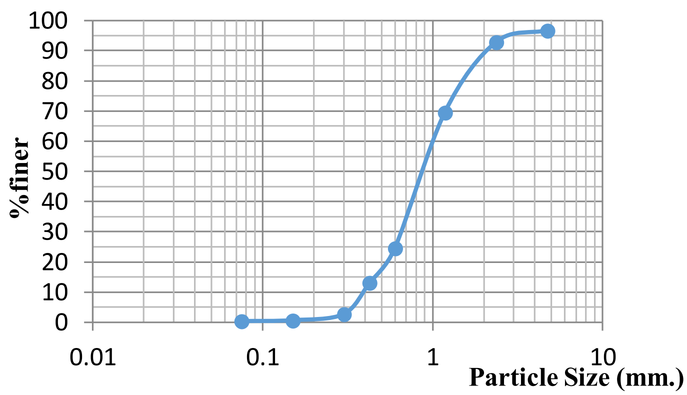


Fig. 2. Grain size distribution curve for Sand

Locally available clay is used as test material for the present study. The soil was tested for Liquid Limit, Plastic Limit, Free Swell Index and shear parameters namely cohesion. All the tests were conducted respective IS code provisions. The tests results are presented in Table 3. As per the IS: 1498-1970 [13] the soil was classified as "CH".

Table 3. Properties of Clay

Parameter	Value
Gravel (%)	0.24
Sand (%)	2.02
Sand (%)-425µ passing	1.05
Silt + Clay (%)(-75µ)	97.74
Liquid Limit (%)	56
Plastic Limit (%)	29.5
Plasticity Index (%)	26.5
Free Swell Index (%)	40
Cohesion(C_{UCC}) in kN/m^2 for I_C=0.5	2.15

Mild steel rods of diameter 10 mm and with length 100mm and 400mm are used as model piles. The model rafts were made up of mild steel plates having a square shape of size 180mm x 180mm and thickness of 10mm.

Experimental Set-Up

The size of the tank was chosen by considering the dimensions of the pile and the raft to minimize the boundary effects. A circular steel tank of diameter 600mm and height 550mm is used for all the experiments. The loading frame consists of four vertical columns, two on each side and four horizontal beams connecting all columns. Two beams are provided at the centre for mounting hand operated loading jack fixed at the centre. Calibrated Proving ring of 50 kN capacity was attached to the jack to measure the load. Four Dial gauges of 0.01 mm accuracy were located at each corner of the raft to measure vertical displacement.

Method of Test bed preparation

A known amount of air dried and pulverized soil passing through 4.75mm is mixed thoroughly with enough quantity of water so as to get homogeneous paste of desired consistency i.e., I_c= 0.5. In the first instance, the soil thus prepared was used in packing layers to form the clay bed

Fig. 3. Experimental Setup

through hand compaction in order to get as the natural bed formation in the model test tank. The top layer of sand is prepared by pouring the sand by rainfall method from a height of 80cm in order to achieve dense condition. Test beds were prepared for I_c = 0.5, H_1/B=0.3 and 0.6 as layered soils having dense sand over soft clay.

Test Procedure

The load test is conducted in accordance with the procedure mentioned in IS 1888-1982[13]. The model raft fitted with required number of piles, dial gauges and proving ring were placed as shown in Fig. 3 and load test is carried out as per standard procedure. Load deformation curves were drawn for all the conducted tests.

Results and Discussions

A total of 16 load tests were conducted on piled raft system varying, S/D, N, L/D and H_1/B over two levels. Apart from these 16 tests, load tests are also conducted on raft only (without piles) and individual piles (without raft) in order to assess the contribution of interaction between piles and raft on the load carrying capacity of piled raft system. Typical load deformation plots obtained from load tests are presented in Fig. 4.

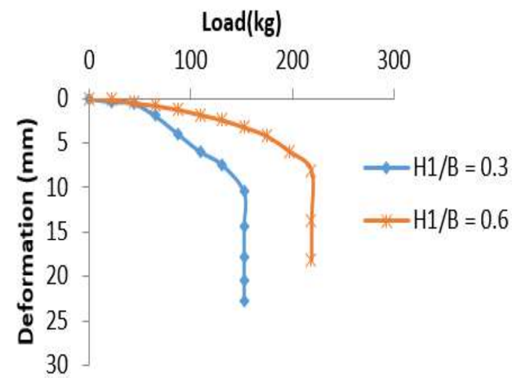


Fig. 4(a). .Load deformation curve for Raft

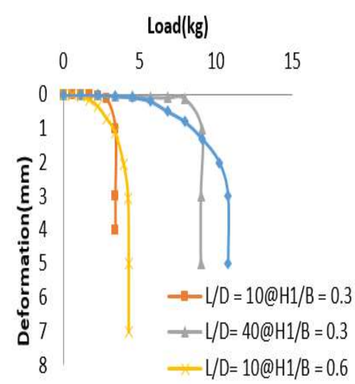


Fig. 4(b). Load deformation curves of piles

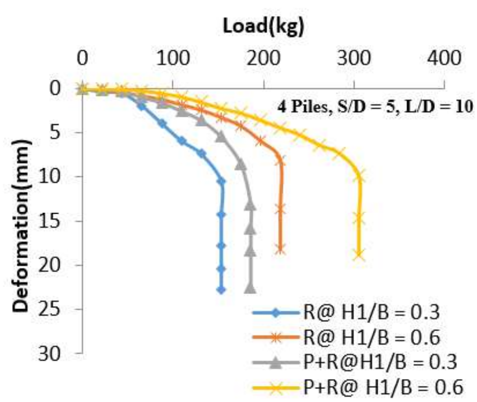


Fig. 4(c). Typical Load deformation curves of Raft and Piled raft

Table 5 Ultimate load carrying capacities

Test	H1/B = 0.3	H1/B = 0.6
	Ultimate Load (kg.)	Ultimate Load (kg.)
Pile (L/D = 10)	3.4	4.3
Pile (L/D = 40)	9.1	10.8
Raft	153	220
Raft + 2, 5, 10	175	284
Raft + 4, 5, 10	185	305
Raft + 2, 15, 10	164	273
Raft + 4, 15, 10	175	295
Raft + 2, 5, 40	190	350
Raft + 4, 5, 40	200	382
Raft + 2, 15, 40	180	328
Raft + 4, 15, 40	195	344

From the Table 5 it is clear that load carrying capacity increases with increase in S/D, N, L/D and H_1/B. The load carrying capacity of piled raft system is expected to be equal to the sum of individual capacities of raft and piles in the absence of interaction between piles and raft. But the ultimate load carrying capacities of any piled raft configuration is greater than the sum of individual capacities of raft and piles. This additional load carrying capacity is due to interaction between the raft and piles. This increase in load carrying capacity can be presented in terms of load improvement ratio for different piled raft configurations.

Load Improvement Ratio

Load improvement ratio is a non-dimensional parameter which is defined as the ratio of load carried by the piled raft to the load of un-piled raft. The load improvement ratios for piled rafts of different configurations considered in the present study are summarized in Table 6 and it's variation at failure load, with respect to various parameters namely spacing between piles (S/D), number of piles (N), length of piles (L) and thickness of top dense layer (H_1/B) are shown in Fig. 5 to Fig. 8.

Table 6. Load improvement ratios of piled raft configurations

Configuration	Load Improvement Ratio	
	At failure load (kg.)	At failure Load (kg.)
Raft + 2, 5, 10	1.14	1.29
Raft + 4, 5, 10	1.21	1.39
Raft + 2, 15, 10	1.07	1.24
Raft + 4, 15, 10	1.14	1.34
Raft + 2, 5, 40	1.24	1.59
Raft + 4, 5, 40	1.31	1.74
Raft + 2, 15, 40	1.18	1.49
Raft + 4, 15, 40	1.27	1.56

Variation of Load Improvement Ratio with spacing between the piles (S/D)

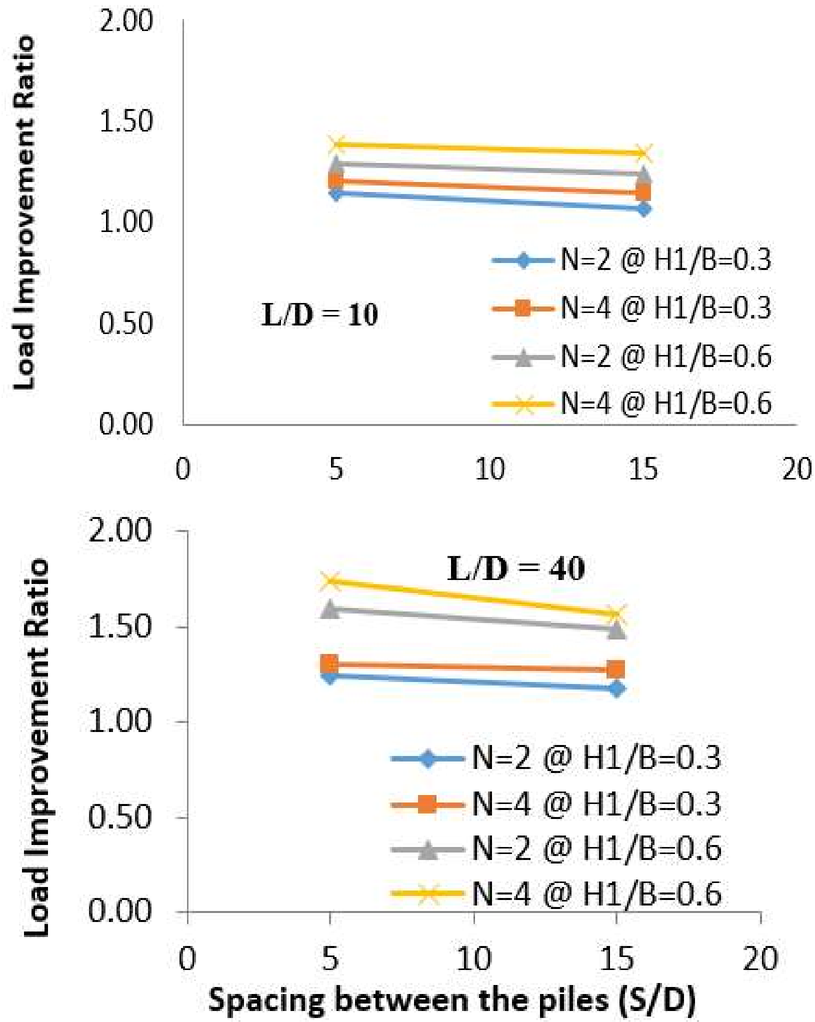


Fig. 5. Variation of Load Improvement Ratio with spacing between the piles (S/D)of L/D = 10 & 40

From Fig. 5 it is clear that as spacing between the piles increases from 5 to 15, the load improvement ratio decreases for L/D= 10 as well as 40.

Variation of Load Improvement Ratio with number of piles (N)

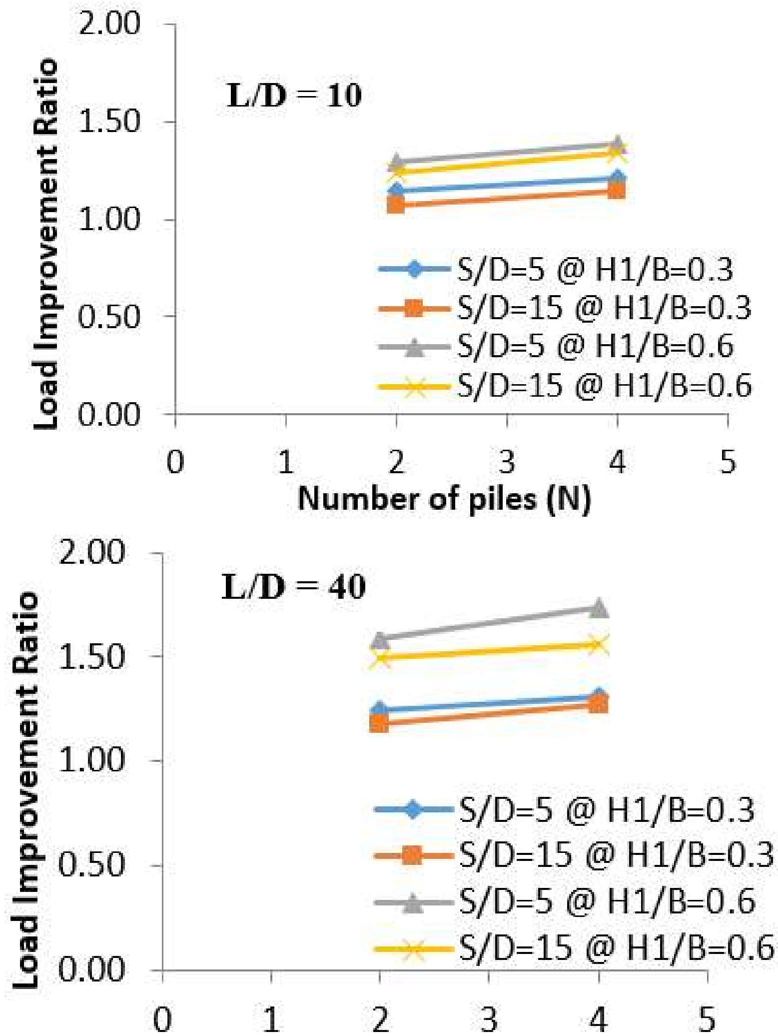


Fig. 6. Variation of Load Improvement Ratio with number of piles (N) of L/D = 10 & 40

From Fig. 6 it is clear that the load improvement ratio increases as the number of piles increases from 2 to 4.

Variation of Load Improvement Ratio with length of piles (L/D)

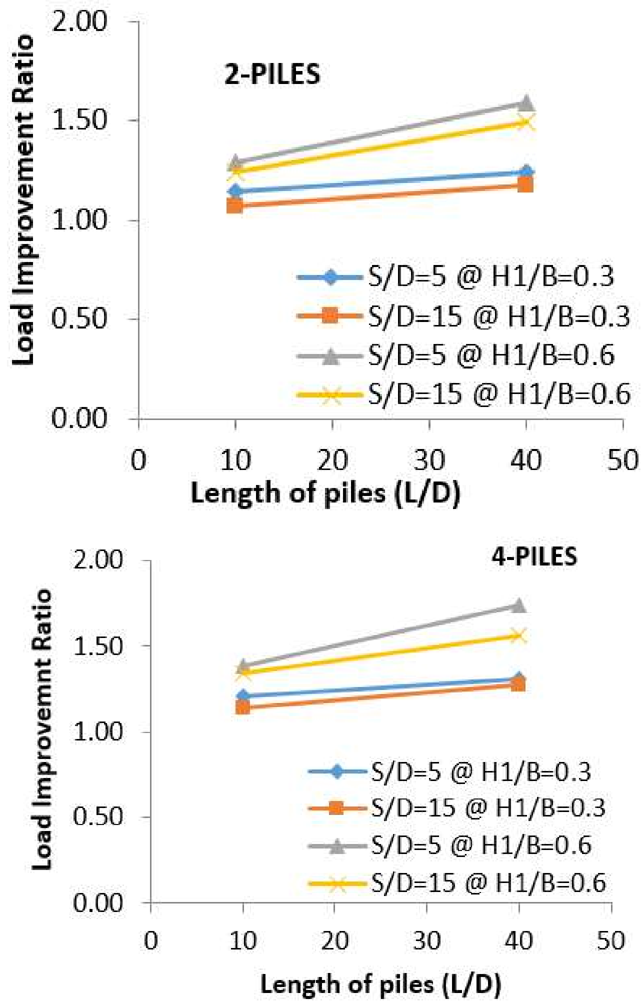
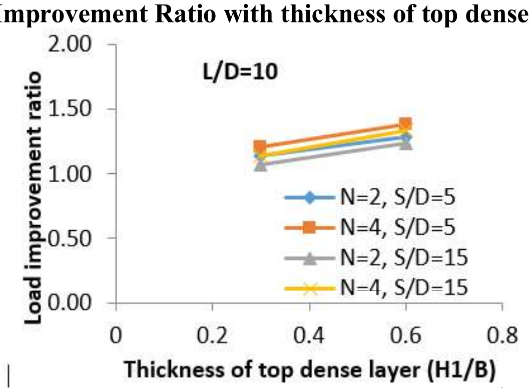


Fig. 7. Variation of load Improvement ratio with length of piles of N = 2 & 4

For all the configurations of piled raft, keeping S/D, N and H1/B as constant and varying the length of piles from 10 to 40, it might be concluded that as length of piles changes from 10 to 40 the load improvement ratio increases linearly. The rate of increment is observed to be more in the case of raft with 4 piles of spacing 5 with $H_1/B = 0.6$

Variation of Load Improvement Ratio with thickness of top dense layer (H_1/B)



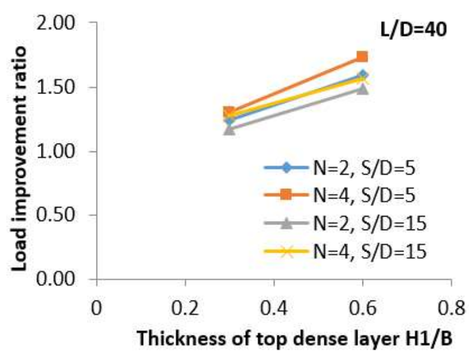


Fig. 8. Variation of Load Improvement ratio with thickness of top dense sand layer (H_1/B)of L/D = 10 & 40

As we seen from the above graphs we conclude that as thickness of top denser layer increases from 0.3 to 0.6 the load improvement ratio increases for L/D = 10 and L/D = 40. But the rate at which it increases is more when L/D = 40 when compared L/D = 10.

Settlement Reduction

The main objective of addition of piles to the raft in a piled raft system is to reduce the settlement. In the present study the reduction of settlement attained at a load equal to the ultimate load of un-piled raft is presented in terms of settlement reduction ratio. The magnitude of settlement for various configurations of piled raft system at ultimate load of un-piled raft and corresponding settlement reduction ratio values are presented in table 4 and the variation of settlement reduction ratio with respect to various parameters such as thickness of top dense layer (H_1/B), number of piles (N), length of piles (L) and spacing between piles is shown in Fig. 8 to Fig. 11.

Settlement reduction ratio

Settlement reduction ratio is a non-dimensional parameter which is defined as the ratio of settlement of piled raft and un-piled raft at a given load.

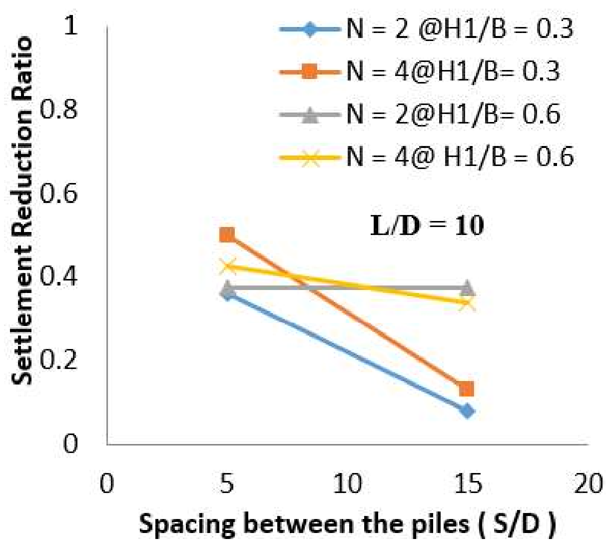
Settlement reduction ratio $=\frac{\delta_r-\delta_{pr}}{\delta_r}$

Where δ_r and δ_{pr} represents the settlement of unpiled raft and piled raft for a given load.

Table 7. Settlement Reduction Ratios for piles raft system

Configuration	Settlement Reduction Ratio			
	H1/B = 0.3 (@ 153 kg)		H1/B = 0.6 (@ 220 kg)	
	δ(mm)	SRR	δ(mm)	SRR
Raft	10.4	-	8	-
Raft + 2, 5, 10	6.7	0.36	5	0.38
Raft + 4, 5, 10	5.2	0.50	4.6	0.43
Raft + 2, 15, 10	9.5	0.08	5	0.38
Raft + 4, 15, 10	9.1	0.13	5.3	0.34
Raft + 2, 5, 40	6	0.42	3.5	0.56
Raft + 4, 5, 40	4.3	0.59	4.5	0.44
Raft + 2, 15, 40	9	0.14	3.9	0.51
Raft + 4, 15, 40	5.6	0.46	4.7	0.42

Variation of Settlement Reduction Ratio with Spacing between piles (S/D)



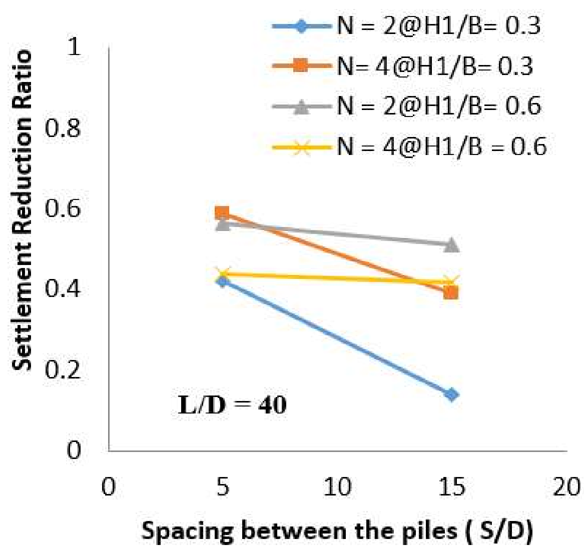
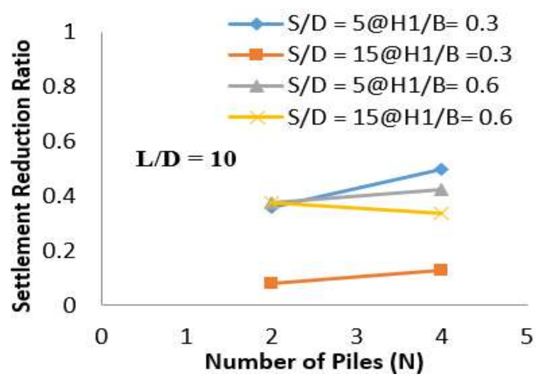


Fig. 8. Variation of settlement reduction ratio with spacing between the piles (S/D)of L/D = 10 & 40

As we seen from the above figures the settlement reduction ratio decreases with increase in S/D from 5 to 15 of both cases L/D = 10 & 40. The rate of decrease is more when H_1/B = 0.3 as we can see a steep decrease in settlement reduction ratio for L/D = 10 as well as 40. Whereas for H_1/B = 0.6 the rate of decrease is less when compared to H_1/B = 0.3. From the above we can conclude that S/D of 5 with H1/B = 0.6 gives better results.

Variation of Settlement Ratio with number of piles (N)



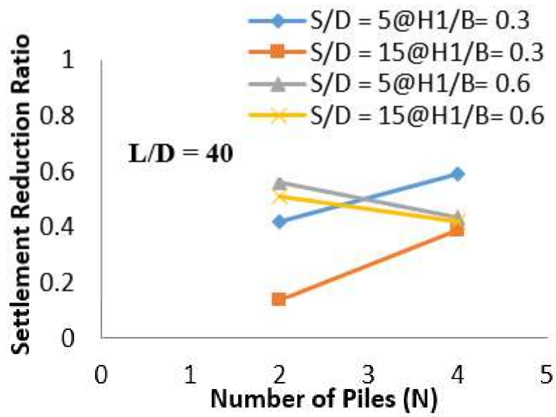
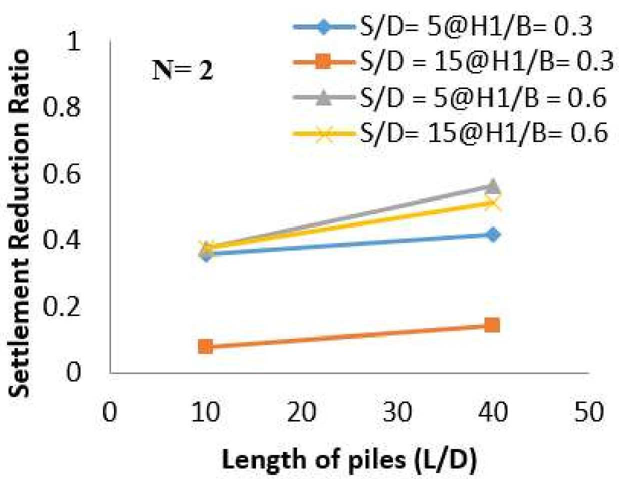


Fig. 9. Variation of Settlement reduction ratio with number of piles (N) of L/D = 10 & 40

From the above graphs, as number of piles increases from 2 to 4 the settlement reduction ration increases when L/D = 10 except when S/D = 15 of $H_1/B = 0.6$. Where as in the case of L/D = 40, for H1/B = 0.3 the settlement reduction ratio increases with number of piles. Conversely when H1/B = 0.6 the settlement reduction ratio decreases with increase in number of piles.

Variation of Settlement Reduction Ration with Length of piles (L/D)



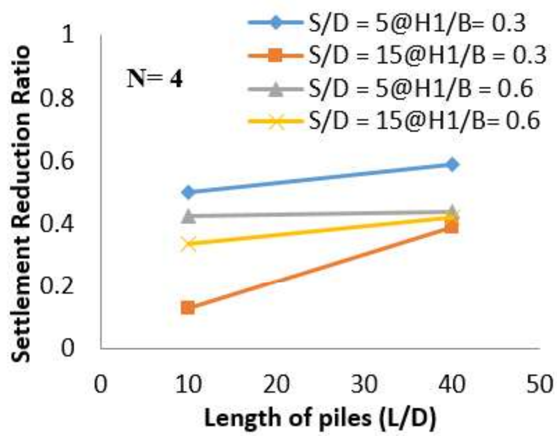
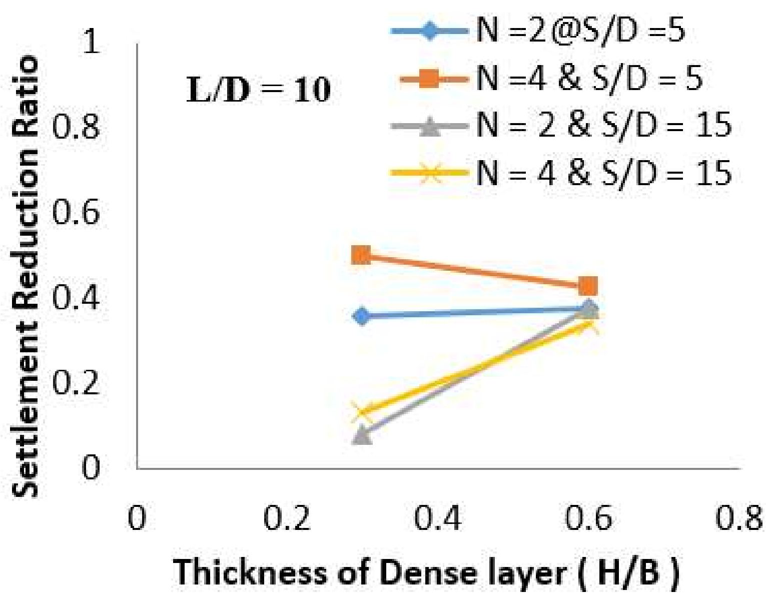


Fig.10. Variation of Settlement reduction ratio with length of piles (L/D) of N = 2 & 4

As we can see from the figures, as the length of piles increases from 10 to 40 the settlement reduction ratio is increases for N = 2&4. The rate of increase in reduction is observed to be more when raft with 4 piles of S/D = 15, L/D = 40 and $H_1/B = 0$.

Variation of Settlement Reduction ration with thickness of top dense sand layer (H1/B)



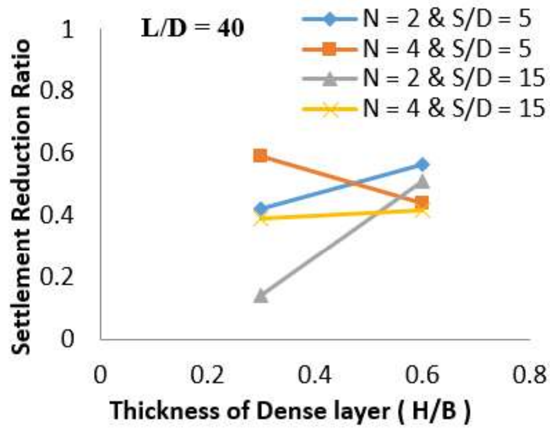


Fig. 11. Variation of Settlement reduction ratio with thickness of dense sand layer (H_1/B) of L/D = 10 & 40

From the above graphs it is clear that for L/D of 10, when number of piles are 2 as H1/B is increased from 0.3 to 0.6 settlement reduction ratio increases in both cases of S/D i.e, 5 and 15. But when number of piles are 4, it decreases when S/D is 5 and increases when S/D is 15. Hence it is a better option to provide 4 piles at spacing of 5 when H1/B is 0.3 and at a spacing of 5 when H1/B is 0.6.

2 Quantification

In order to quantify the relative effect of each parameter on ultimate load carrying capacity and its settlement at load equals to the ultimate load of raft, a statistical tool called factorial analysis is used. In the present experimental study the main factors considered are Spacing of piles(S/D), Length of piles (L/D), number of piles (N) and thickness of top dense layer (H1/B). For the factorial analysis the factors under consideration are taken at two levels as presented in Table 8 and the data for factorial analysis is as shown in Fig. 12 and Fig. 13 for ultimate load and settlement respectively.

Table 8. Factors Considered for 2^4 Factorial Experimentation

Factor	Low Level	High Level
Spacing of piles (S/D)	5	15
Number of piles (N)	2	4
Length of piles (L/D)	10	40
Thickness of top Dense Sand (H_1/B)	0.3	0.6

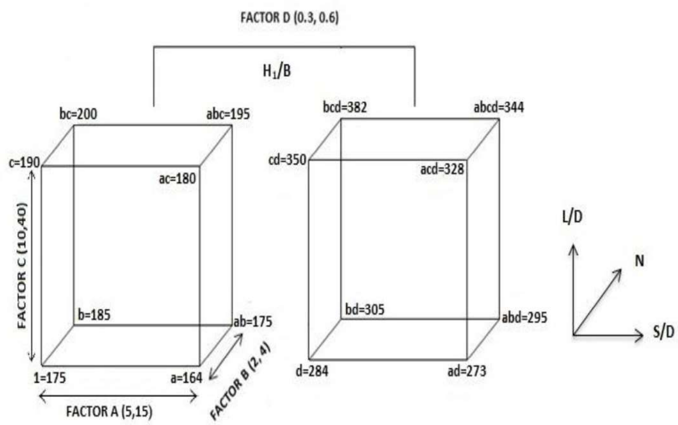


Fig. 12. Data for 2^4 Factorial design of Ultimate load

Effects Estimation

Contrast of A = [(abcd+abc+abd+ab) + (acd+ac+ad+a) + (-bcd-bc-bd-b) + (-cd-c-d-1)]

Contrast of AB =[(abcd+abc+abd+ab) + (-acd-ac-ad-a) + (-bcd-bc-bd-b) + (cd+c+d+1)]

Contrast of ABC=[(abcd+abc-abd-ab) + (-acd-ac+ad+a)+ (-bcd-bc+bd+b) + (cd+c-d-1)]

Contrast of ABCD =[(abcd-abc-abd+ab)+(-acd+ac+ad-a) + (-bcd+bc+bd-b) + (cd-c-d+1)]

$$\text{Average Effect} = \left(\frac{1}{8n}\right)(\text{Contrast})$$

$$\text{Sum of Squares} = \left(\frac{1}{16n}\right)(\text{Contrast})^2$$

Where n is the number of replicates (n = 1)

The values obtained on substitution are summarized in Table 9 and Table 10 for ultimate load and settlement of piled raft respectively.

Table 9. Summary of Effect Estimate for ultimate load

Factor	Contrast	Average Effect	Sum of Squares	% Contribution
A	-117	-14.625	855.5625	0.995582
B	137	17.125	1173.0625	1.365043
C	313	39.125	6123.0625	7.125148
D	1097	137.125	75213.0625	87.52225
AB	-9	-1.125	5.0625	0.005891
AC	-33	-4.125	68.0625	0.079201
AD	-45	-5.625	126.5625	0.147275
BC	9	1.125	5.0625	0.005891

BD	45	5.625	126.5625	0.147275
CD	181	22.625	2047.5625	2.382662
ABC	-13	-1.625	10.5625	0.012291
ABD	-21	-2.625	27.5625	0.032073
ACD	-45	-5.625	126.5625	0.147275
BCD	1	0.125	0.0625	0.0000727
ABCD	-21	-2.625	27.5625	0.032073
Total			85935.9375	100

From the above table based on percentage contribution the main factors for regression analysis are C, D and interaction effect of AD i.e., L/D, H_1/B and interaction effect of L/D*H_1/B. After performing multiple linear regression analysis the model equation obtained for ultimate load carrying capacity is,

$$\mathbf{Q_u = 69.83 - 0.958(\frac{L}{D}) + 331.39\ (\frac{H_1}{B}) + 5.03(\frac{L}{D} * \frac{H_1}{B})}$$

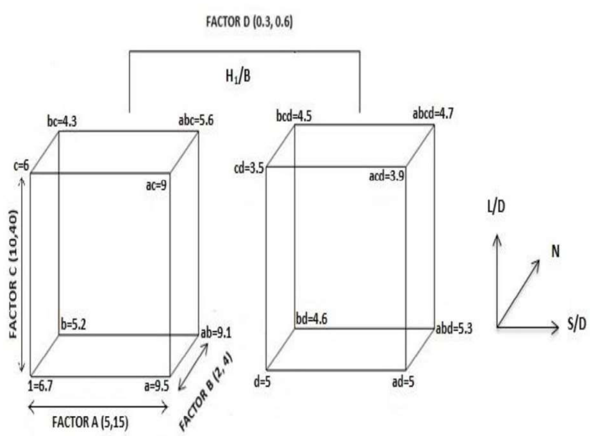


Fig. 13. Data for 2^4 factorial design of settlement

Table 10. Summary of Effect Estimate for settlement

Factor	Contrast	Average Effect	Sum of Squares	% Contribution
A	12.15	1.531	9.3789	17.6474
B	-5.35	-0.669	1.7889	3.366016
C	-8.95	-1.119	5.0064	9.420082
D	-18.95	-2.369	22.4439	42.23058
AB	-0.15	-0.019	0.0014	0.002646

AC	-2.55	-0.319	0.4064	0.764696
AD	-9.75	-1.219	5.9414	11.17983
BC	-1.35	-0.169	0.1139	0.214327
BD	8.65	1.081	4.6764	8.799152
CD	2.25	0.281	0.3164	0.595352
ABC	-3.75	-0.469	0.8789	1.653755
ABD	1.05	0.131	0.0689	0.129654
ACD	2.25	0.281	0.3164	0.595352
BCD	5.05	0.631	1.5939	2.999103
ABCD	1.85	0.231	0.2139	0.402487
Total			53.1461	99.99999

From the above table based on percentage contribution the main factors for regression analysis are S/D, N, L/D, H_1/B, ($N*H_1/B$) and ($S/D*H_1/B$). After performing multiple linear regression analysis the model equation obtained for the settlement of piled raft system at the ultimate load of plain raft (without piles) is obtained as,

$$\delta = 11.26 - 0.3275\left(\frac{S}{D}\right) - 0.3375(N) - 0.06542\left(\frac{L}{D}\right) - 5.33\left(\frac{H_1}{B}\right) + 0.5583\left(\frac{S}{D} * \frac{H_1}{B}\right) + 0.4583\left(N * \frac{H_1}{B}\right)$$

3 Conclusions

On the basis of experimental study on models the behaviour piled raft system resting on layered soil may be predicted. The important conclusions drawn from the present study are mentioned below:

1. In comparison to the load carrying capacity of plain raft (without piles) there is a considerable increase in the load carrying capacity of piled raft. The percentage increase is more when thickness of top dense layer of sand (H_1/B) is 0.6 in comparison to that when H_1/B is 0.3.
2. Maximum increase in the ultimate load carrying capacity is obtained when 4 piles of length (L/D) 40 are placed at a spacing (S/D) of 5 and H_1/B is 0.6.
3. The Load Improvement ratio is increases with increased in number of piles (N), length of piles (L/D) and thickness of top dense sand layer (H_1/B). Conversely the load improvement ratio decreases with increase in pile spacing (S/D).
4. For ultimate load carrying capacity, based on factorial analysis the significant contribution comes from three factors namely length of piles(L/D), thickness of top dense layer of sand (H_1/B) and interaction effect of ($L/D* H_1/B$).
5. Maximum reduction in settlement is obtained when 4 piles of length (L/D) 40 are placed at spacing (S/D) of 5 for H_1/B of 0.3 and 2 piles of length (L/D) 40 are placed at spacing (S/D) of 5 for H_1/B of 0.6. Magnitude of settlement reduction is more when H_1/B is 0.6 when compared to that when H_1/B is 0.3.

6. The settlement reduction ratio is increases with increased in length of piles (L/D) and decreases with increased in spacing of piles (S/D).
7. For settlement, based on factorial analysis the significant contribution comes from the factors namely spacing of piles (S/D), number of piles (N), length of piles (L/D), thickness of top dense layer of sand (H_1/B), and interaction effects of (N*H_1/B) and (S/D*H_1/B).

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