STUDY OF DIFFERENTIAL LENGTH OF PILE ON CARRYING CAPACITY OF MODEL CIRCULAR PILED RAFT

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Abstract: When the structural loads are heavier, then it is advisable to adopt raft foundations. When settlements are beyond the permissible limits, raft foundation can be used with pile foundations. With increasing technology and sophisticated engineering designs and decisions, the best solution is piled raft foundations. The layout and the combinations become very important to produce the desired settlement reduction and load sharing with minimum required piles in the design. This paper presents the effect of differential length of pile on load carrying capacity of model circular piled raft based on the model study. Different 9 combinations have been taken for the analysis and based on that, load-settlement characteristics, bearing capacity analysis, efficiency analysis and settlement analysis have been done.

***Keywords* - Model piled raft, pile, pile group, circular piled raft, combinations, settlement, bearing capacity analysis, efficiency analysis**

I. INTRODUCTION

Where a conventional raft foundation does not provide adequate support, it can be enhanced by the addition of piles as piled raft foundation. Piled raft foundations are classically used for large structures, and in circumstances where soil is not suitable to prevent excessive settlement. Burj Khalifa in Dubai, the Petronas twin towers, Kuala lumpur are the famous example of the piled raft.

In piled raft foundation role of raft foundation is to provide adequate bearing capacity and role of pile foundation is mainly to act as settlement reducers. This system is very complex which involves interaction factors such as pile-to-soil, pile-to-pile, pile-to-raft, and raft-to-soil. Zeavert (1957) was one of the earliest to prepare the concept of using deep foundation elements particularly piles to reduce the raft settlement and Burland (1977) proposed a concept of settlement reducing piles, but due to limited understanding of piled raft behavior under loading and complex design, piled raft system has been not used more.

Many attempts have been made by earlier researchers to understand the behavior of piled raft. Turek and Katzenbach (2003) investigated the bearing behavior of a combined pile-raft foundation on sand. Poulos (1968) established that it might be useful to replace the pile group by an equivalent pier. O'Neill et al (1977) developed the hybrid approach for the analysis of offshore pile group by modifying the boundary element approach. Randolph (1983) proposed an approximate method for the analysis of piled raft foundation. Cooke (1986) concluded that the distribution of load between the piles of piled raft foundation was influenced by the stiffness of the structure-foundation system and the structural loading. Thaher and Jessberger (1991) investigated the effect of pile length, pile number and pile diameter on the load bearing behavior of piled rafts through centrifuge model tests conducted on 1/150 scale models. They concluded that the pile spacing and the number of piles influenced the load carried by the pile group. However, the effect of length of the piles in the group was much less than the spacing of the piles and the number of piles. Horikoshi and Randolph (1996) conducted a series of centrifuge model studies on piled raft supported on over consolidated clay. No comparison has been made in the field between structures designed both by the conventional and the latest design philosophy such as Katzenbach et al (2000) and Clancy and Randolph (1993). V. Balakumar and K. Ilamparuthi (2006) studied 1g model on a circular piled raft. Nirmal John Joy, Hashifa Hassan (2014) stated that the Combined pile raft foundations provide an economical foundation option for circumstances where the raft foundation can satisfy the bearing capacity requirement but fails to keep differential as well as maximum settlement below the maximum allowable limit. Though it is well known that model tests conducted in a geotechnical centrifuge provide more relevant information than 1g model tests, the research on piled raft foundation using centrifuge technique is also scarce, which is supposed to the best alternative method to field test on prototype foundation.

Till now the effect of the differential length of the piles on the carrying capacity of the piled raft has not been studied so the present investigation was focused on this subject and particularly the raft shape was taken as circular. The scope of the experimental study was to observe the load-settlement behavior and investigate the effect of the different combinations, spacing and differential length of the piles inserted under the raft and effect of interaction mechanism of piled raft. The objectives were to examine load – settlement characteristics of mild steel solid raft only, Single pile, Pile group and piled raft of differential length combinations by spacing 3d and 4d, to analyses load sharing mechanism between piles and raft and for different combinations, the Efficiency analysis for pile group and piled raft for different combinations, Settlement analysis for the piled raft for the different combination from the above investigation.

II. Materials of Investigation

The sand used for the model tests was clean and dry sand obtained from Bahadarpur near Sankheda district, Vadodara, Gujarat. A grain size distribution characteristic of sand is shown in **Figure 1** and the various index and engineering properties are tabulated in **Table 1**.

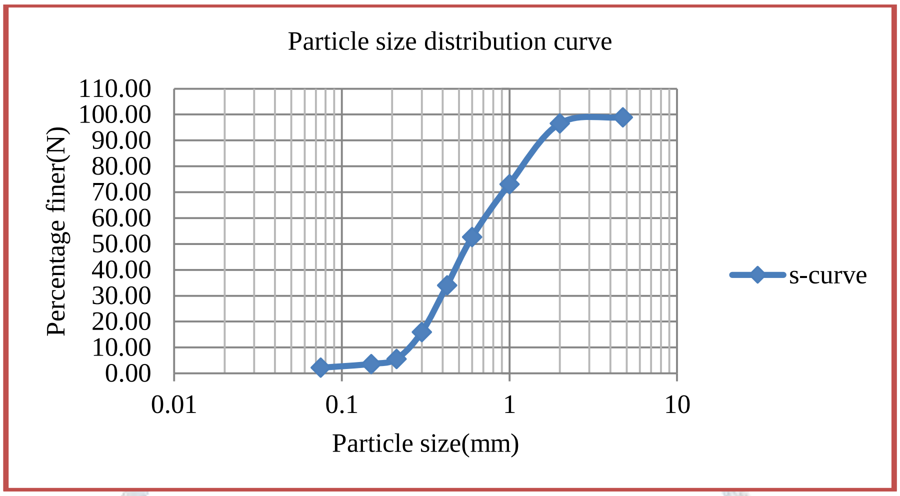


Figure 1: Grain size distribution characteristics of Bahadarpur sand

Table 1: Engineering properties of sand

Sr. No.	Properties of Sand	Value
1.	D_{10} (mm)	0.32
2.	D_{30} (mm)	0.51
3.	D_{60} (mm)	0.71
4.	Coefficient of Uniformity (C_u)	2.22
5.	Coefficient of Curvature (C_c)	1.14
6.	Fine Sand	19.00%
7.	Medium Sand	74.10%
8.	Coarse Sand	6.90%
9.	IS Soil Classification	SP
10.	Specific Gravity	2.61
11.	Experimental Density (γ_d) (g/cc)	1.73
12.	Maximum Density ($\gamma_{d\ max}$) (g/cc)	1.9
13.	Minimum Density ($\gamma_{d\ min}$) (g/cc)	1.47
14.	Experimental Relative Density	66%
15.	Angle of Internal Friction (ø)	36º
16.	Angle of Soil-Pile Friction (δ)	22°

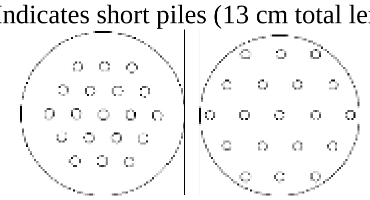
III. Model Study

The laboratory tests were conducted for different pile length, pile spacing. Pile diameter and size of raft are kept constant and settlements are measured under sustained loading. The size of the model tank was 122 cm x 122 cm x 108 cm. Tests were done on single pile, circular raft, pile group having several combinations and piled raft having several combinations. The diameter of the circular raft was 180 mm and thickness was 20 mm. The mild steel solid piles had 10 mm diameter. Table 2 shows the model piled raft parameters. Embedded Pile lengths were 10 cm and 25 cm. Pile spacing were 3d and 4d. The different types of combinations that had been in this investigation was given in below figures from **Figure 2 to 10**.

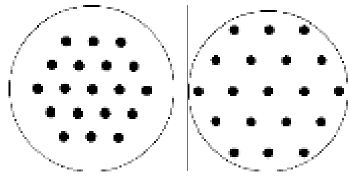
Table 2: Model piled raft parameters

Raft size, diameter(mm)	180
Raft thickness (mm)	20
Diameter of Pile (D) (mm)	10
Total Length of Pile (L) (cm)	13,28
Embedded Length of Pile (cm)	10,25
Spacing of piles	3d,4d

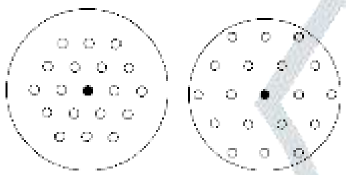
● Indicates long piles (28 cm total length; 25 cm embedded length) and
○ Indicates short piles (13 cm total length; 10 cm embedded length)



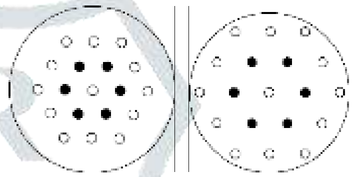
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 2: Combination A (All short piles)



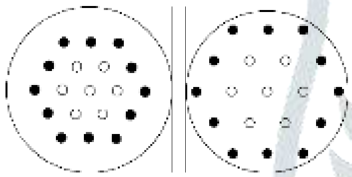
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 3: Combination B (All long piles)



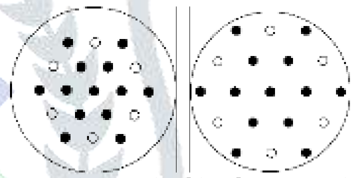
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 4: Combination 1 (Central long pile, other short piles)



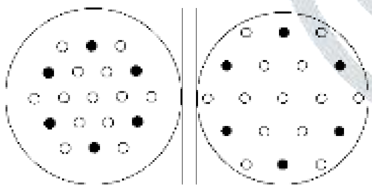
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 5: Combination 2 (Piles next surrounding Central pile are long, other short piles)



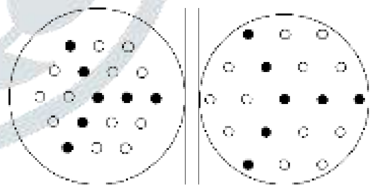
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 6: Combination 3 (Outer periphery long piles, other short piles)



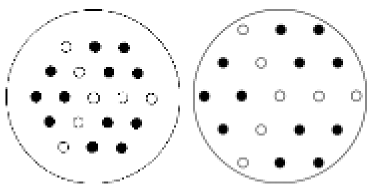
(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 7: Combination 4 (Long piles at Centre concentrated, other short piles)



(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 8: Combination 5 (Opposite of combination 4)



(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 9: Combination 6 (Long piles at Centre concentrated but alternatively, other piles short)



(a) 3d spacing (30 mm), (b) 4d spacing (40 mm)
Figure 10: Combination 7 (Opposite of combination 6)

The sand was filled in the tank according to the 66% relative density that is achieved for the experimental study. **Figure 11** shows the model foundation experimental setup. The sand was filled in the tank in the three layer of 20 cm and compacted using small surface vibrator having standard vibrations, vibrated for 1 minute, 1.5 minutes and 2 minutes respectively. Then the Centre of the square tank was find out by plumb bob. Then circular piled raft was inserted into the sand using hammer and then checked that mechanical screw jack and circular raft are aligned with plumb bob in vertical line. If it was not then circular piled raft model was removed and process was repeated. Horizontal level of the circular raft was checked by spirit level. Proving ring for measuring load was placed centrally between jack and circular raft along with solid steel ball to fill the gaps. Then vertical loading arrangement done on the piled raft. **Figure 12** shows the loading arrangement of piled raft. After each test, tank was emptied and refilled for the next test.

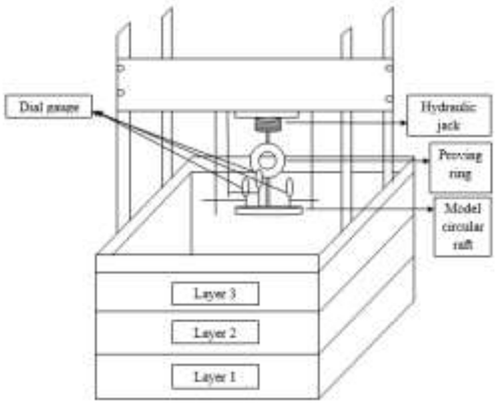


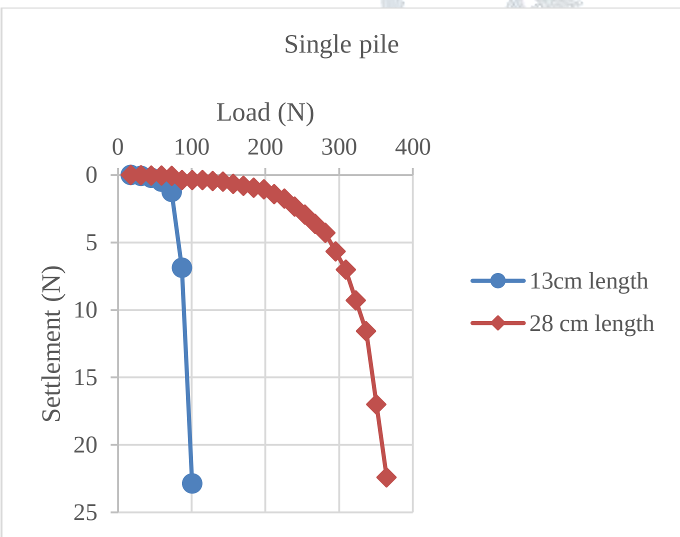
Figure 11: Model foundation test setup

Figure 12: Arrangement of vertical loading of circular piled raft and dial gauges

IV. Results and Discussion

4.1 Analysis of circular raft and single pile

Figure 13 shows the load vs pile head settlement for piles of diameter embedded lengths 10 mm and 25 cm. It can be observed that as the load on the single pie increases the settlement of pile in both the cases is also increases. Short pile has 80 N ultimate load and Long pile has 308 N ultimate load. **Figure 14** shows load vs raft settlement of diameter 180 mm and thickness 20mm. It is seen that as the load on raft increases, the settlement of raft also increases. Ultimate load of the raft was 5550 N**.**



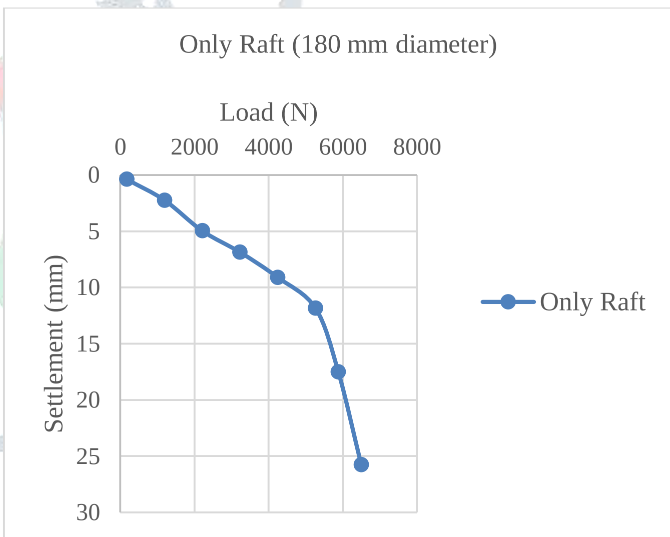


Figure 13: Load-settlement characteristics for single pile of different length (Diameter=10 mm)

Figure 14: Load-Settlement characteristics of raft

4.2 Analysis of pile group

Load-settlement characteristics of pile group

Figure 15(a) and 15(b) shows the load vs settlement characteristics for the combinations A, B, 1 to 7 respectively of 3d and 4d spacing which consists of different configurations as per **Figure 2 to 10**. As the spacing increases in pile group load carrying capacity decreases in all the combinations. Also, it is seen that combination B has a higher load carrying capacity compared to other combinations in 3d and 4d spacing because of the all long piles. In the other different configurations, combination 3 and 4 has a higher load carrying capacity compared to other combinations in 3d and 4d spacing respectively in pile group.

Bearing capacity analysis of pile group

Figure 16(a) shows the ultimate load of all combinations in 3d spacing. It is observed that combination B has a highest load carrying capacity and combination 1 has a least load carrying capacity. Combination A has ultimate load 1250 N, combination B has 3700 N. Combination 1,2,3,4,5,6,7 has ultimate load 1180 N, 2720 N,3200 N, 3250 N, 2250 N, 2720 N, 3230 N respectively. When comparing other combinations with combination B, it is observed that reduction in load carrying capacity in combination 1,2,3,4,5,6,7 is 68.1%, 26.5%, 13.5%, 12.2%, 39.2%, 26.5%, 12.7% respectively.

Figure 16(b) shows the ultimate load of all combinations in 4d spacing. It can be observed that combination B has a highest load carrying capacity and combination A has a least load carrying capacity. Combination A has ultimate load 750 N, combination B has 3300 N. Combination 1,2,3,4,5,6,7 has ultimate load 1170 N, 1700 N, 2950 N, 3000 N, 2050 N, 2200 N, 3200 N respectively. When comparing other combinations with combination B, it is observed that reduction in load carrying capacity in combination 1,2,3,4,5,6,7 is 64.5%, 48.5%, 10.6%, 9.1%, 37.9%, 33.3%, 3% respectively.

Efficiency analysis of pile group

For combination A and B, Efficiency of pile group = Q_{gu} / (n × Q_u)

For other combinations, two formulas used. Formula 1, Efficiency of pile group = Q_{gu} / ((a × $Q_{u\,(short)}$) + (b × $Q_{u\,(long)}$))
Formula 2, Efficiency of pile group = Q_{gu} / (($a_{\%\,(short)}$ × $Q_{gu\,(short)}$) + ($b_{\%\,(long)}$ × $Q_{gu\,(long)}$))

Where, Q_{gu}=ultimate load of the pile group, n=number of piles, a=number of short piles, b=number of long piles, Q_u=ultimate load of single pile, $Q_{u\,(short)}$=ultimate load of single short pile, $Q_{u\,(long)}$=ultimate load of single long pile, $Q_{gu\,(short)}$=ultimate load of pile group having all short piles (combination A), $Q_{gu\,(long)}$=ultimate load of pile group having all long piles (combination B), $a_{\%\,(short)}$=fraction of number of short piles to the total number of piles, $b_{\%\,(long)}$=fraction of number of long piles to the total number of piles.

Figure 17 shows the efficiency of the different combinations having 3d and 4d spacing. It can be observed that combination 2 has the highest efficiency.so we can say that when there are more number of short piles in the particular combination then efficiency of that pile group is lesser, combination 7 has the highest efficiency in 4d spacing.so we can say that in the 4d spacing the utilization of long piles is more.

Figure 18(a) shows the efficiency of the different combinations having 3d and 4d spacing. It can be observed that combination 2 has the highest efficiency. When there are more number of short piles in the particular combination then efficiency of that pile group is lesser. **Figure 18(b)** shows the efficiency of the different combinations having 4d spacing. It is observed that combination 7 has the highest efficiency.

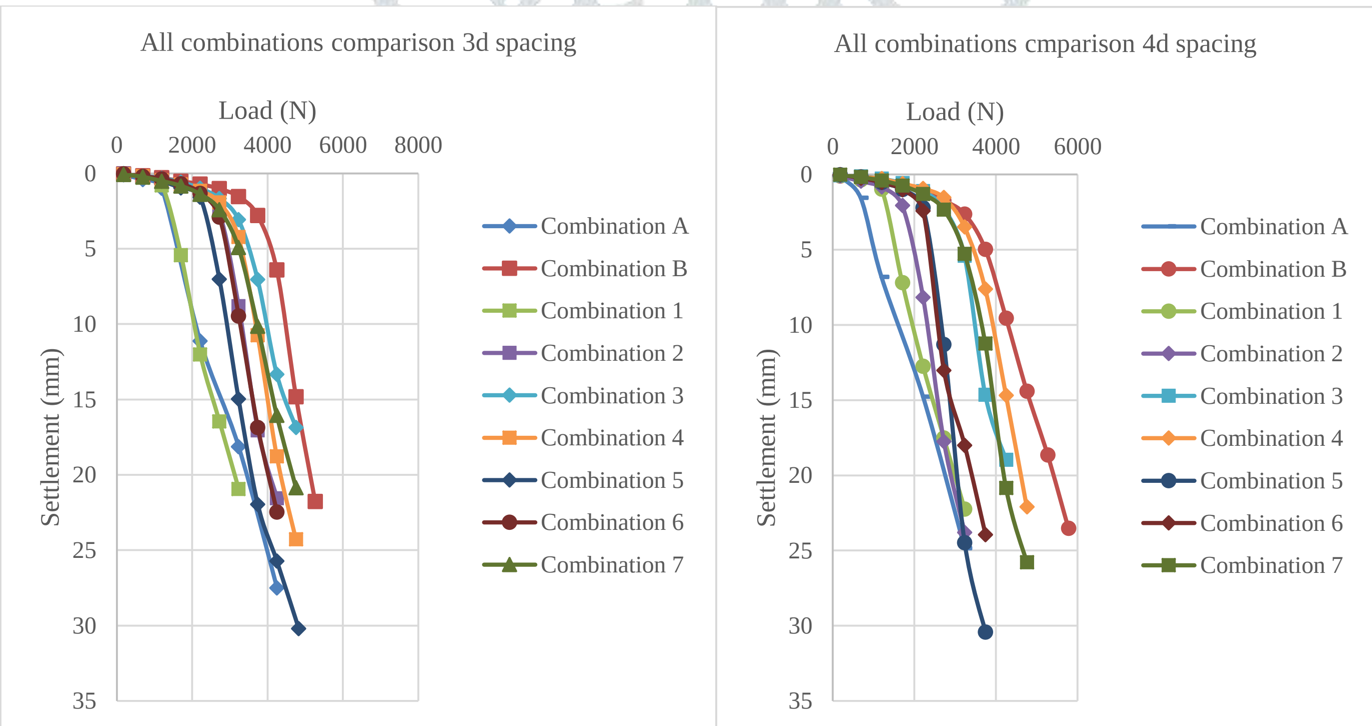


Figure 15: Comparison of load-settlement characteristics of all combinations in pile group ((a)3d spacing and (b)4d spacing)

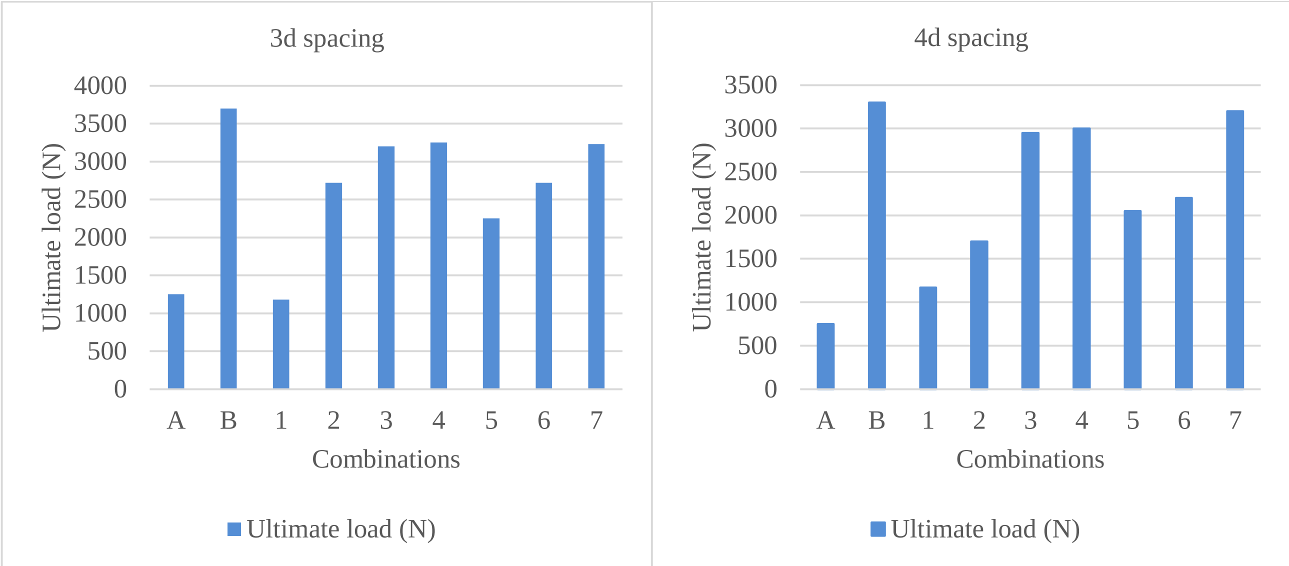


Figure 16: Ultimate load of all combinations ((a)3d spacing and (b)4d spacing)

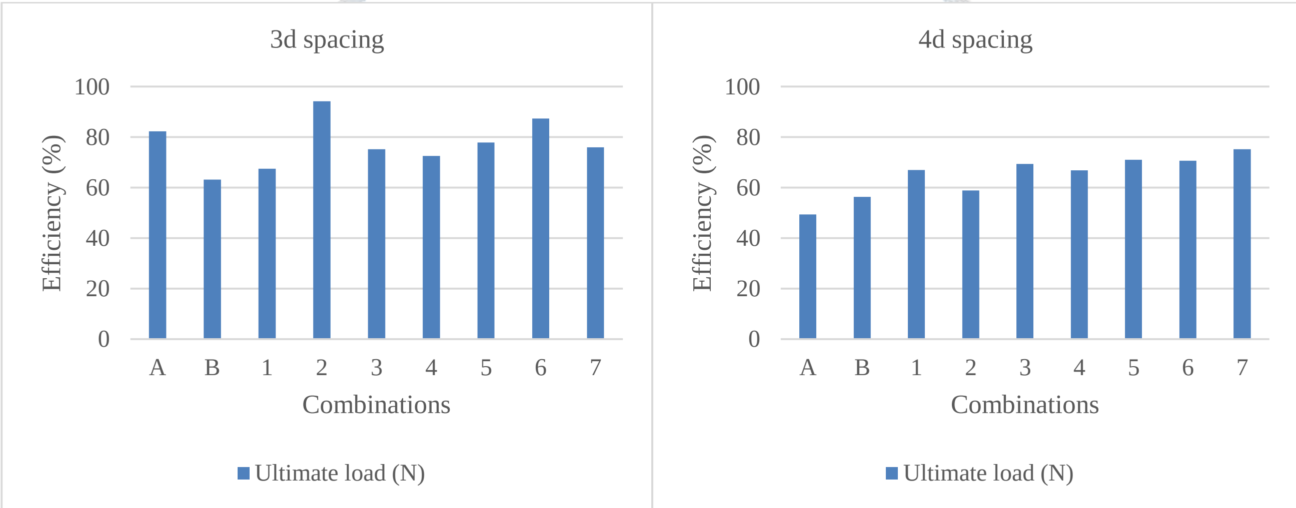


Figure 17: Effect of combinations on the efficiency of pile group ((a)3d spacing and (b)4d spacing) by formula 1

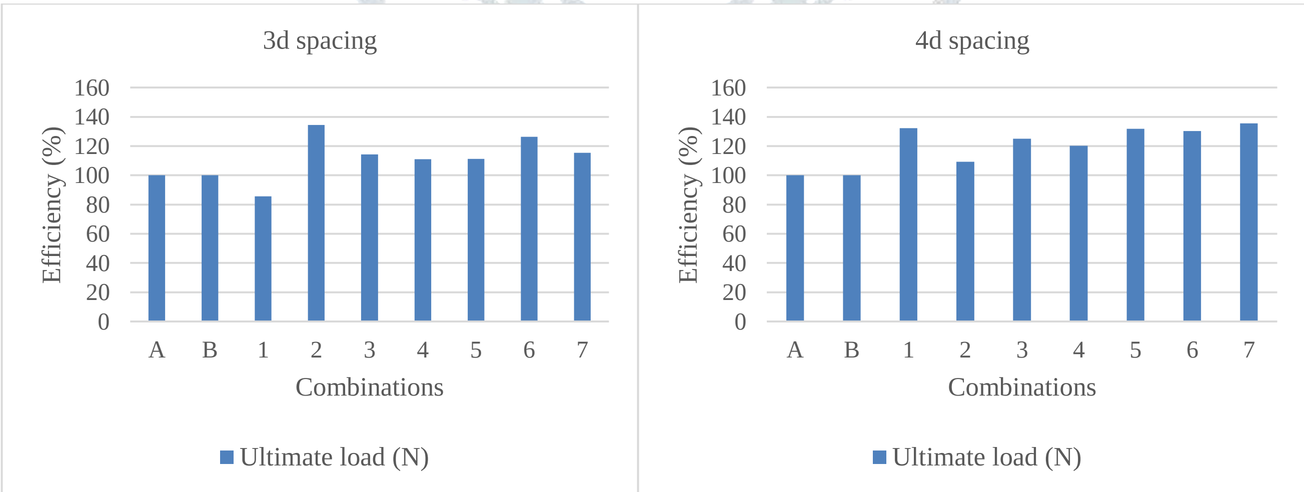


Figure 18: Effect of combinations on the efficiency of pile group ((a)3d spacing and (b)4d spacing) by formula 2

4.3 Analysis of piled raft

Load-settlement characteristics of piled raft

Figure 19(a) and 19(b) shows comparison of load vs settlement characteristics of all combinations having 3d and 4d spacing respectively. combinations 3 and 4 has a higher load carrying capacity compare to other combinations in 3d and 4d spacing respectively in piled raft. The reason is the overlap of the pressure bulb and so that the piled raft acts as a block; when there will be configuration as a Centre concentrated with long piles or when outer peripheral piles are long that time the load carrying capacity will be more.

Figure 20(a) shows the ultimate load of all combinations in 3d spacing. It can be observed that combination 3 has a highest load carrying capacity and combination A has a least load carrying capacity. Combination A has ultimate load 9600 N, combination B has 9840 N. Combination 1,2,3,4,5,6,7 has ultimate load 9950 N, 11700 N, 12000 N, 11250 N, 10900 N, 11500 N, 11300 N respectively. When comparing other combinations to combination 3, Reduction in load carrying capacity in combination A, B, 1, 2, 4, 5, 6, 7 is 20%, 18%, 17.1%, 2.5%, 6.25%, 9.17%, 4.17%, 5.83% respectively.

Figure 20(b) shows the ultimate load of all combinations in 4d spacing. It can be observed that combination 4 has a highest load carrying capacity and combination A has a least load carrying capacity. Combination A has ultimate load 9800 N, combination B has 11800 N. Combination 1,2,3,4,5,6,7 has ultimate load 12000 N, 12255 N, 14200 N, 16300 N, 11900 N, 12800 N, 16000 N respectively. When comparing other combinations to combination 4, Reduction in load carrying capacity in combination A, B, 1, 2, 3, 5, 6, 7 is 39.88%, 27.6%, 26.38%, 24.81%, 12.88%, 27%, 21.47%, 1.84% respectively.

Efficiency analysis of piled raft

Efficiency of piled raft = Q_{pru} / (Q_{ru} + Q_{pgu}), Where, Q_{pru} = ultimate load of piled raft, Q_{ru} = ultimate load of raft alone, Q_{pgu} = ultimate load of pile group.

Figure 21(a) and 21(b) shows the combinations vs efficiency of various combinations having pile diameter 10 mm, differential lengths 10 cm and 25 cm in all the combinations 1, 2, 3, 4, 5, 6, 7 and having 3d and 4d spacing respectively. It is observed that as the spacing increases, efficiency increases in all the cases.

Settlement analysis of piled raft

Figure 22(a) and 22(b) shows % settlement reduction vs load ratio (Q/Q_u) for 3d and 4d spacing respectively. Where, Q = Qu/8, Qu/4, Qu/3 and Qu/2.the combinations A and B are compared in the figures. It can be observed that as the pile length increases, % settlement reduction increases. For combination A, maximum % settlement reduction is 87.93% and for combination B, maximum % settlement reduction is 90.47%. For combination 1, maximum % settlement reduction is 90.50%. For combination 2, maximum % settlement reduction is 87.73%. For combination 3, maximum % settlement reduction is 92.59%. For combination 4, maximum % settlement reduction is 97.73%. For combination 5, maximum % settlement reduction is 90.12%. For combination 6, maximum % settlement reduction is 87.93%. For combination 7, maximum % settlement reduction is 97.51%.

Comparison of load-settlement characteristics of only pile, raft, (pile + raft) and piled raft

Figure 23 and Figure 24 shows comparison of ultimate load of only pile, only raft, pile + raft and piled raft having 3d and 4d spacing. Ultimate load of pile + raft having 4d spacing (combination 4) is 10034 N and ultimate load of piled raft is 16300 N. Difference in load carrying capacity for combination 4 is 62.44%. ultimate load of pile + raft having 4d spacing (combination 7) is 9806 N and ultimate load of piled raft is 16000 N. Difference in load carrying capacity for combination 7 is 63.18%.

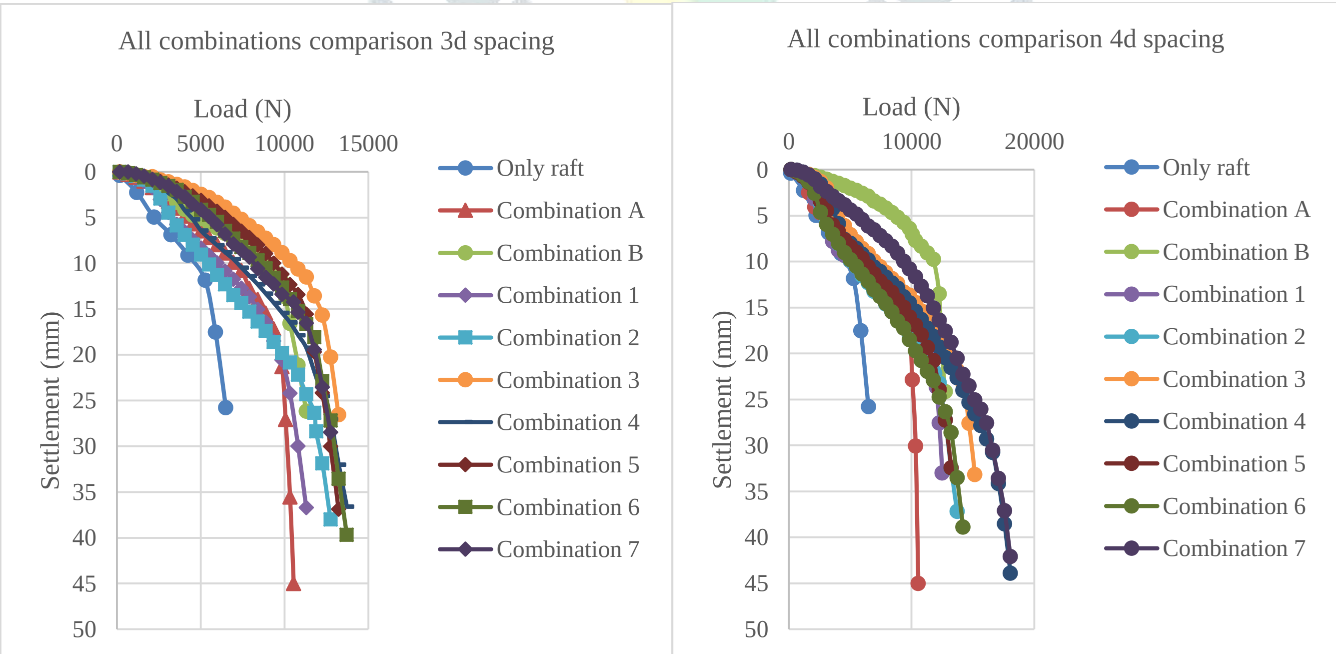


Figure 19: Comparison of Load-settlement characteristics of all combinations in piled raft ((a)3d spacing and (b)4d spacing)

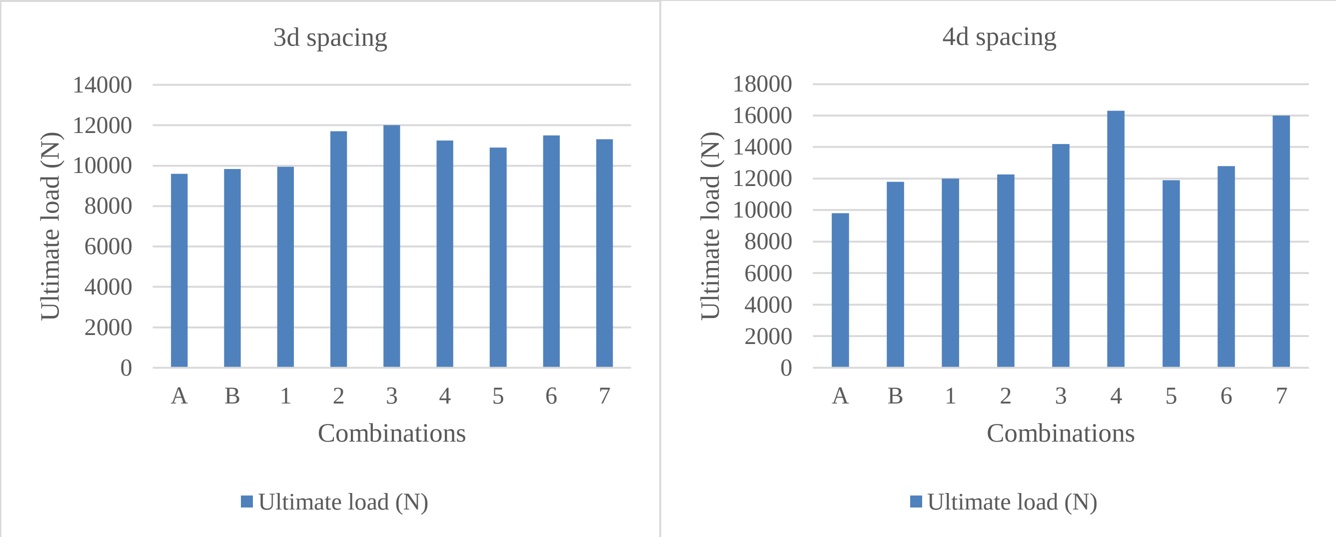


Figure 20: Ultimate load of all combinations in piled raft ((a)3d spacing (b)4d spacing)

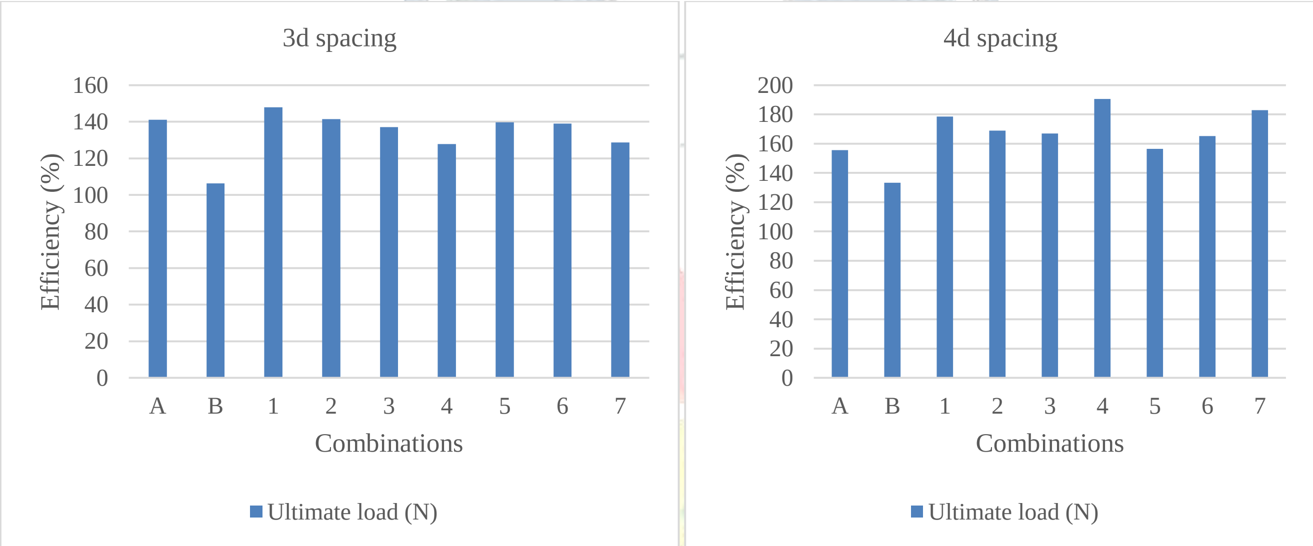


Figure 21: Effect of combinations on the efficiency of piled raft ((a)3d spacing (b)4d spacing)

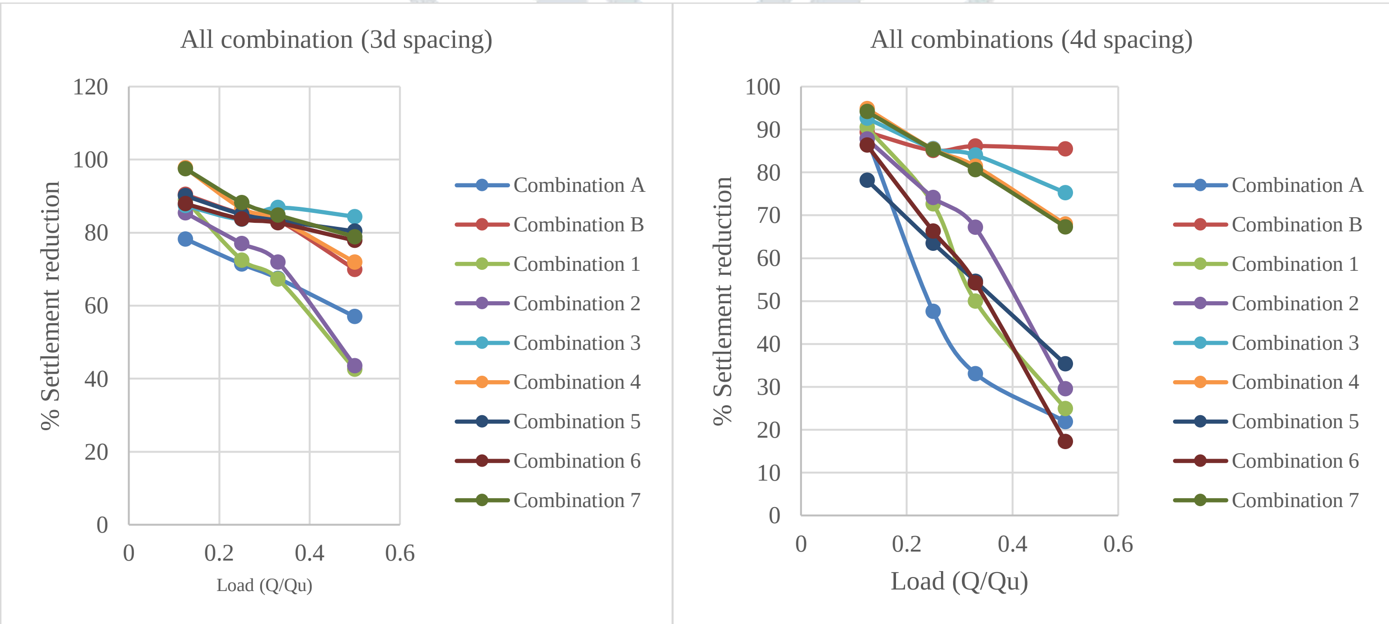


Figure 22: Effect of combinations on settlement of piled raft ((a)3d spacing (b)4d spacing)

Table 3: ultimate load of circular raft with different methods

Raft diameter	Ultimate load (N)		
180 mm	IS code	Terzaghi	Exxperimental
	1877.4	1815	5700

Table 4: ultimate load of single pile with different methods

Pile parameters	Ultimate load (N)			
D (mm)	L (cm)	IS code	Meyerhof	Experomental
10	10	20.33	25.23	75
	25	107.93	120.43	295

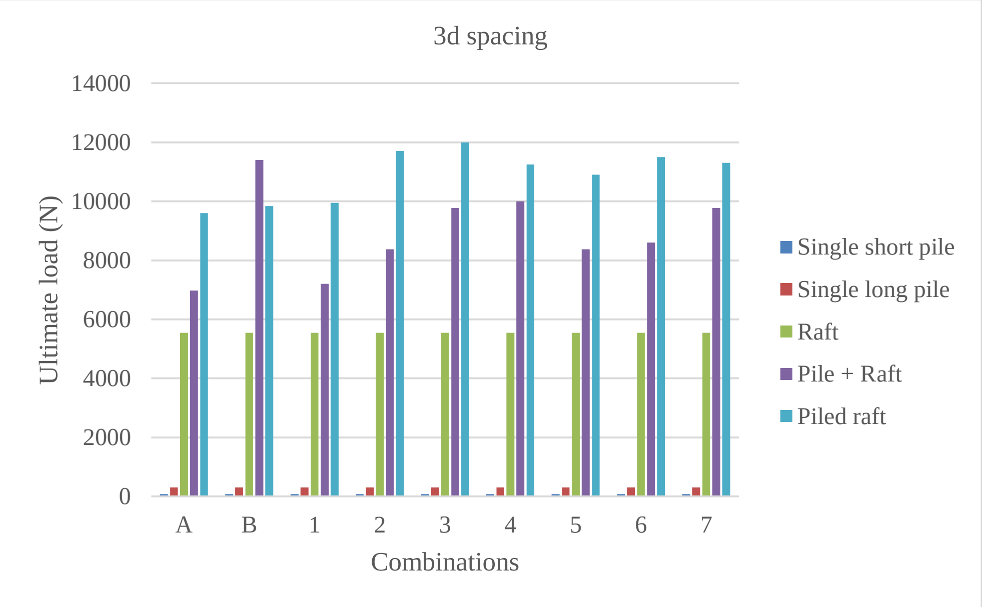


Figure 23: Comparison of ultimate load of pile only, raft only, pile + raft and piled raft for 3d spacing

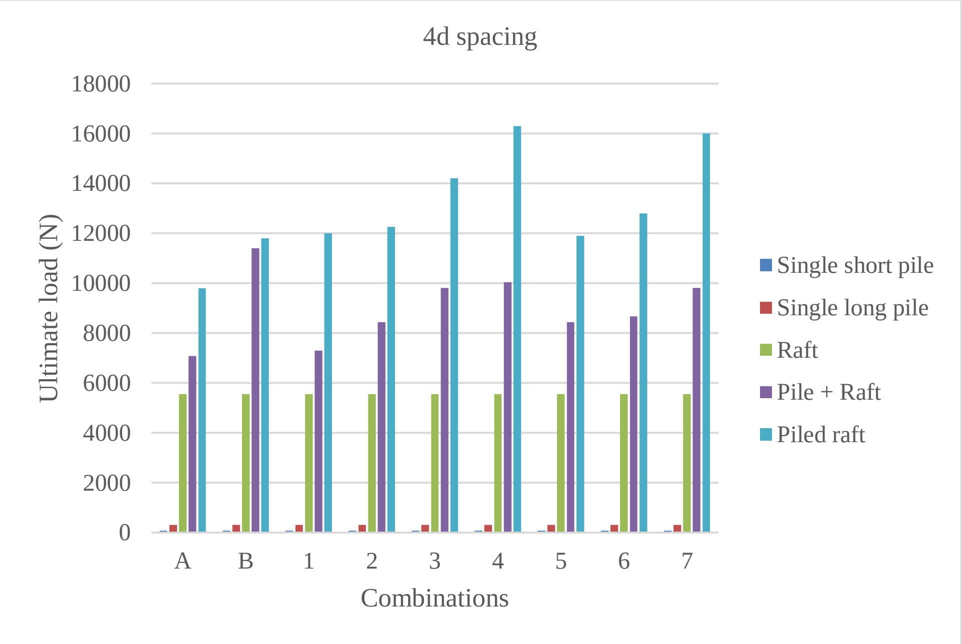


Figure 24: Comparison of ultimate load of pile only, raft only, pile + raft and piled raft for 4d spacing

V. CONCLUSION

Main conclusions from this experimental study are as follows:

The load vs settlement characteristics are typically non-linear in nature. Initially this increase in settlement is very slow, with progress of loading which is curvilinear with convex downward. With further progress of loading turns into straight line having higher progressive settlement in single pile, raft, pile group of all combinations and piled raft of all combinations.

As per theoretical analysis the ultimate load on raft using IS code and other methods seems inappropriate according to present investigation in single pile and circular raft.

Conclusion from pile group

As the number of pile increases, the load carrying capacity and ultimate load increases and settlement decreases in combination A and B. As the pile length increases, the load carrying capacity and ultimate load increases and settlement decreases in combination A and B. As the spacing of pile increases, the load carrying capacity and ultimate load decreases and settlement increases in all combinations.

When comparing combinations which has differential pile length, it is observed that the combinations which has the long piles which is Centre concentrated (combination 4) or which has long piles more on outer periphery (combination3) or outer side (combination 7) has the higher load carrying capacity compare to other combinations which has differential pile lengths.

As the number of pile increases, the load carrying capacity and ultimate load increases. (combinations A and B)

Comparing to combinations with differential length of piles with combination with all long piles, reduction in load carrying capacity in the combinations which has the long piles which have Centre concentrated (combination 4) or which has long piles more on outer periphery (combination3) or in bulk (combination 7) is least. As the short piles in the combinations increases, the load carrying capacity decreases.

As the number of pile increases, the efficiency of pile group is decreases in the circular pile group. As the spacing of pile increases, the efficiency of pile group decreases in the combination A and B. In the combinations of differential lengths, combination 2 and 7 has more efficiency than all other combinations in 3d and 4d spacing respectively.

Conclusion from piled raft

As the number of pile increases, the load carrying capacity and ultimate load of circular piled raft increases and settlement decreases. As the length of pile increases, the load carrying capacity and ultimate load of circular piled raft increases and settlement decrease in all the combinations. As the spacing increases, the load carrying capacity and ultimate load of circular piled raft of all the combinations increases and settlement decreases.

Comparing combinations with differential length of piles, the load carrying capacity in the combinations which has the long piles in bulk (combination 7) or which has long length piles at Centre concentrated (combination 4) or on outer periphery (combination3) is higher. As the short piles in the combinations increases, the load carrying capacity decreases.

The improvement in load carrying capacity combination which has long length piles at Centre concentrated (combination 4) has the highest improvement in load carrying capacity with the increase in spacing.

Efficiency increase with increase in the spacing of the pile in the circular piled raft in all the combinations.

Load ratio (Q/Q_u) vs % settlement reduction characteristics is curvilinear in nature. As the length of pile increases, higher % settlement reduction is observed, settlement reduction is generally increases with spacing of piles in all the cases and % settlement reduction is more in the combination 7 and 4 compare to other combinations.

Circular Piled raft of all the combinations have more load carrying capacity and less settlement than the pile and the pile group only and raft only.

Ultimate load of the all the combinations of piled raft are more than that of the ultimate load of summation of only pile and only raft due to interaction between pile and raft. Piled raft has much higher load carrying capacity due to block action of a pile group in it. At last, it can be concluded that combination 7, combination 4 and combination 3 can be used for carrying more load and for less settlement compare to other combinations. These combinations can be useful where there is differential loading requirement at different places. so rather going for same length of piles these combinations should give the economical and safe design.

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