Study of piled and disconnected piled raft system with raft foundation in cohesionless soil

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Abstract. In order to deal with the geotechnical problems and with reference to the structural point of view, there arises a concept of combination of shallow and deep foundation i.e. combination of raft and pile foundation where the piles could be both connected and disconnected from the raft known as piled raft foundation (PRF) and disconnected piled raft foundation (DPRF). In this experimental study, analysis was done on raft, piled raft and disconnected piled raft under vertical loading by varying the compactness of cohesionless soil as loose and medium density and the thickness of cushion. The geotechnical parameters such as the bearing capacity and the settlements in foundation were analyzed. It is observed that the bearing capacity in DPRF and PRF was increased 38% in loose; 74% and 75% in medium compactness sand respectively when compared to raft foundation. Settlements were also reduced to 44% in DPRF in medium compactness of soil for raft size 150x150 mm with pile length of 200mm. The optimum cushion thickness in DPRF was achieved where H/B=0.34. Thus, to meet the stability requirements of high-rise buildings, structures built in weak soils and to resist horizontal loading, the DPRF which is effective and economical can be employed.

1. Introduction
Foundation is the vital component of the structure which enables the transfer or transmission of load from the superstructure to the soil to impart greater strength and provide support to the structure. There are various concepts in the area of shallow and deep foundations to improve the bearing capacity and decrease the settlements by the method of implementation of horizontal or vertical reinforcing elements. In order to deal with the geotechnical problems, there arises a concept of union of shallow and deep foundation i.e. the combination of raft footing (shallow) and pile foundation (deep) known as the piled raft system where required number of piles are connected to the raft to improvise the important geotechnical design parameters such as the bearing capacity and settlement. With reference to the structural perspective, the piles and raft can be either connected or disconnected known as piled raft foundation and disconnected piled raft foundation respectively. To meet the stability requirements of high-rise buildings, structures to be built in weak soils and to resist the horizontal loading, the disconnected piled raft system can be employed which is an effective and economical method. The DPRF is the one where the piles are detached from the raft with the cushion
in between them. The piles and the raft are detached by means of cushion which establishes the uniform pressure distribution at the bottom of the raft and the constraint reactions are reduced in the foundation and subsoil effectively.

The detached piles mainly serves for the reinforcing the soil and as a settlement reducer. They can resist heavy loads since the effective size of the foundation is large and helps in reducing the amount of total and differential settlements. The cushion acts as soil reinforcement and mobilizes the load bearing capacity of the soil. It further reduces the skin friction in the joints of the pile and raft and thereby limits the shear forces and bending moments imparted between the superstructure and foundation soil. The load sharing mechanism of DPRF is unique where the loads are resisted by the raft, redistributed by the cushion and the piles acts as a settlement reducer. The bed soil underneath the raft is treated as a reinforced elastic medium which stimulates the reduction in the settlement. A substitute method of the design of foundation is to suggest piles completely as a factor of strengthening the stiffness of base soil by structurally detaching the piles from the raft. The role of reinforcement by piles will not be affected by the small cracks in piles and a low factor of safety can be adopted for structural design.

If the piles and raft are structurally connected, the lateral forces are instantly transferred to the head of the pile and this could generate damage to the connection. Even if disconnected settlement reducing piles are adopted, the lateral forces can be precisely resisted by the adhesion activated along the soil surface interface and by the passive pressures against the basement walls. This united adhesion and passive resistance are sufficient to curb the lateral loads such as earthquake loads. The concept of disconnected foundation was adopted mainly in a bridge which has a bed layer made of gravel that limits the force caused due to shear and bending moments transferred from the superstructure to the basement. In the bridge, the mudline level consisting of cohesionless layer made of sand and gravel to certain height followed by a pier and the soil profile beneath this layer comprised of sand, silty sand and silty clay is present. In such cases, the structural capacity governs the load bearing capacity of the pile rather than geotechnical capacity. The load is carried uniformly throughout the sand bed and then transferred to the pier which gradually decreases the amount of settlement and improves the durability of the structure against heavy seismic forces too.

There are various researches were conducted and analysed the effect of raft foundation, piled raft foundation and disconnected piled raft foundation under loading by varying its parameters. For the three density states such as loose, medium and denser soil state conditions, the increment in load resistance capacity was higher with increase in number of pile and reduction in settlement upto 50% in denser condition comparatively to the loose condition [1]. The parameters such as the stiffness of raft, pile length, pile arrangement and number of piles were varied; derived the conclusion that there was reduction in differential settlement and bending moment. The increment in pile length enhanced the stiffness of the foundation system and the increasing the number of piles was found to be ineffective in improving the bearing capacity of the foundation [2-5]. The adoption of reduced factor of safety for the pile design was derived and the characteristics of pile acting as a soil reinforcing member was studied [6,7]. In 3x3 unconnected piled raft system, the settlement in concrete slab was noticed to be decreased by 22% when compared to the field values for a span of 6 months of time. The settlements of piled raft system were lowered about 13% to 68% in slab and 20% to 65% in pile heads when compared with the unconnected piled raft system without the consideration of configuration of piles for a span of one year [8,9].

The load transferring mechanism of piles was investigated using a finite element analysis software ABAQUS in the disconnected piled raft separated by a cushion and the maximum settlement has decreased by 78% [10]. The comparative study on load sharing mechanism of connected piled raft and disconnected piled raft was done wherein the effects of negative skin friction and the relative stiffness of pile and raft were analysed. If the stiffness of the granular material is not higher, then the connected piled raft will be more efficient than the disconnected one [11,12]. In order to effectively design the settlement reducer piles, the bearing ability of the piles should be designed 80% of the service load which can cater to the seismic loads [13]. When the number of piles connected to the raft increases,
then the load capacity ratio and settlement degradation ratio improves efficiently and also the effect of load on the raft decreases. There will also be a slight effect on load capacity ratio and settlement degradation ratio when the thickness of raft increases though it has only significant effect on the load carrying capacity of the raft [14-16].

In this experimental study, analysis was done on unpiled raft, piled and the disconnected piled raft foundation under vertical loading by varying the compactness of soil (loose and medium dense) and the thickness of cushion. The geotechnical parameters such as the bearing capacity and the settlements in the foundation were analysed and compared.

2. Material Properties

2.1. Sand

The soil medium chosen for the experimental work was river sand. Laboratory tests were conducted on the sand samples for the determination of index properties such as the gradation of the soil by sieve analysis, specific gravity by pycnometer method, maximum and minimum density by Relative density apparatus and sand replacement method as per the IS codal provisions. The test soil medium comprises of 0% gravel, 0% clay, 12% coarse sand, 61% medium sand and 27% fine sand. From the grain size distribution curve shown in figure 1 and test results tabulated in table 1, the soil is classified as poorly graded sand.

![Grain size distribution curve for sand](image)

*Figure 1. Grain size distribution curve for sand.*

2.2. Gravel

The gravel is used as the cushion which is laid between the raft and piled embedded sand bed. The tests were carried out in the laboratory and determined its properties such as specific gravity by Pycnometer method, Particle size distribution and relative density test. From the test results, it was found that it is poor graded gravel (GP). The preliminary test results of gravel are tabulated in table 1 and grain size distribution curve is presented in figure 2.
Table 1. Properties of sand and gravel.

| Soil parameters                        | Test results         |
|----------------------------------------|----------------------|
|                                        | Sand | Gravel |
| Specific Gravity, G                    | 2.7  | 2.6    |
| Maximum dry density, g/cc              | 1.84 | 1.56   |
| Minimum dry density, g/cc              | 1.58 | 1.42   |
| Coefficient of uniformity, Cu          | 4.6  | 2.542  |
| Coefficient of curvature, Cc            | 0.73 | 1.49   |
| Classification of Soil Sample          | Poorly graded sand (SP) | Poorly graded gravel (GP) |

Figure 2. Grain size distribution curve for gravel.

From the comparison of grain size distribution of sand and aggregate chips presented in Figure 3, it is evident that most of the gravel particles are of the size 6.3mm. The particles which is coarser than the sand bed particles are more desirable to use in the cushion. Thus, the particles which retained in the 4.75mm sieve was used to prepare the cushion layer.
Figure 3. Comparison of grain size distribution curve of sand and gravel.

2.3. Pile and Raft Model

The steel piles of length 200mm with diameter (D) 12mm are chosen for the work which will be embedded in the sand bed. The raft of dimension 150x150mm and thickness 12mm were also fabricated with steel. Pile length is classified based on a criterion on the width of the raft. They are of two types such as the pile length shorter than raft width are short piles and the pile length larger than the raft width are long piles. The short piles are 0.8 times the breadth of the raft (0.8B) which is 120mm and the long piles are 1.25 times of the breadth of the raft (1.25B) which is 200mm. A set of four number of long piles were adopted for this experimental study with the centre to centre spacing (S) between the piles for raft dimension 150mm x 150mm and for 4 number of piles is 120mm i.e. 10 times the diameter of the pile. The dimensional specifications of the disconnected piled raft model are illustrated in table 2. The raft model and long piles are shown in figure 4 and 5 respectively.

| Description                      | Specification          |
|----------------------------------|------------------------|
| Raft dimension                   | 150mm x 150mm          |
| Raft thickness                   | 12mm                   |
| Pile diameter (D)                | 12mm                   |
| Pile Length (L)                  | 200mm                  |
| Pile arrangement                 | 2x2 pile group         |
| Centre to centre spacing (S)     | 120mm                  |
3. Experimental Setup

3.1. Test Tank

The settlement analysis tests were carried out in a steel fabricated tank with inner dimensions 0.9m*0.9m*1m with the hydraulic jack of capacity 700kg/cm² at the top and the load was applied using a hand pump. Two steel angles were used to fix the dial gauges. Proving ring of 50 kN capacity was fixed in such a way it lies in contact with the hydraulic jack. The test tank was properly rested on the machine foundation. The tank should be fabricated in proper dimensions such that it should not be vulnerable for any deflection errors during the application of loading through the frames. The test tank for the settlement analysis testing in the laboratory is shown in Figure 6.
3.2. Experimental Programme

The hand pump which is present adjacent to the test tank was used to give loading to the load frame which was transferred through the hydraulic jack to the foundation model. The proving ring in contact with the hydraulic jack records the values of loading given to the foundation model and the corresponding values of settlement was noted in the dial gauges. Two dial gauges were used and each of two dial gauges were fixed at the L angles on both the sides. The L angles were fixed firmly with the frame of the tank using screws so that there should be no undesirable deflections caused to the dial gauges due to external movements.

The experimental programme was planned for vertical loading test with raft, piled raft and disconnected raft piled cases in cohesionless soil. The raft of dimension 150x150mm was tested under vertical loading condition in loose and medium compactness of soil. The piled raft and disconnected piled raft case comprise of tests with raft 150x150mm, piles of length 200mm and diameter in the loose and medium compactness of sand. The thickness of cushion layer (H/B = 0.17, 0.34 and 0.5) where B is the width of the raft and H is the height of the gravel cushion was varied and its effects were studied. The soil sample was made ready after all its preliminary testing in the laboratory. The test tank was filled with sand after proper calibration. The calibration of sand bed was done by sand pouring method to achieve the desired density of sand. The sand was filled layer by layer, keeping interval of 50mm. For every 50mm, calculated quantity of sand was poured to achieve the desired density and then it was cross checked. The desired densities of sand were 1.71 g/cc for medium state of soil and 1.58 g/cc for loose state of soil. The schematic diagram of piled raft and disconnected piled raft test tank is shown in figure 7 and 8 respectively.

![Figure 7](image1.png) **Figure 7.** Schematic diagram of the piled raft test tank.

![Figure 8](image2.png) **Figure 8.** Schematic diagram of the disconnected piled raft test tank.

After preparation of sand bed to the desired height, the raft was placed over the sand bed for testing. In piled raft tests, the piles were connected to the raft and embedded in the sand such a way that raft alone lies above the sand. While in disconnected piled raft system, the piles were embedded in to the sand and then the gravel cushion layer was filled with desired density over which the raft is placed. Then the angles were placed and the dial gauges were fixed with its support. The proving ring was placed over the raft and hydraulic jack was moved down; fixed in such a way that it is in contact with the ball bearing between the proving ring and the hydraulic jack. The tests were conducted by applying loads and corresponding settlements values were noted down from dial gauges. After each test, load Vs settlement graph was plotted to analyse the performance of the foundation system.
4. Results and Discussion

The test results are shown in comparison of piled raft and disconnected piled raft footing with the raft footing; effect of cushion thickness in DPRF. Load bearing capacity versus the settlements of raft, PRF and DPRF in two different compactness of sand, compactness of sand versus maximum settlement and compactness versus load bearing capacity. Figure 9 shows the disconnected piled raft foundation subjected to vertical loading in the loose compactness of sand where the punching shear failure can be observed.

![Disconnected piled raft before and after failure under vertical loading condition.](image)

4.1. Optimum Cushion Thickness / Effect of thickness of cushion in DPRF

Figure 10 shows the variation of cushion thickness and its corresponding load bearing capacities with the settlements in cases of $H/B=0.17$, 0.34 and 0.5 at loose compactness of sand. With the increasing $H/B$, there shows the elevation in bearing capacity. The high stresses are transferred from the raft to the cushion layer made of gravel with density of 1.58g/cc and lower stresses were transmitted to the sand bed which has the density same as sand bed during the distribution of load which caters to the increment in the load carrying capacity of the DPRF. The optimum cushion thickness was found at $H/B=0.34$ where $H$ is the height of the cushion and $B$ is the width of the raft.

Figure 11 shows the variation of cushion thickness and its corresponding load bearing capacities with the settlements in cases of $H/B=0.17$, 0.34 and 0.5 at medium compactness of sand. With the increasing $H/B$, there is an elevation in bearing capacity of foundation. The high stresses are transferred from the raft to the cushion layer and then lower stresses were transmitted to the sand bed due to the distribution of load which plays a role in incrementing the load carrying capacity of the DPRF. The optimum cushion thickness in medium compactness of sand under vertical loading conditions was at $H/B=0.34$. 
4.2. Comparison of raft, piled and disconnected piled raft

Figure 12 and 13 shows the comparison of piled raft and disconnected piled raft system with the raft footing under vertical loading conditions in loose and medium compactness of sand respectively. This show that the ultimate load bearing capacity of foundation has incremented in disconnected piled raft foundation and piled raft foundation when compared to the raft foundation. It is evident that the settlements were decreased in disconnected piled raft system when comparing with piled raft and raft
foundation. The load sharing mechanism in DPRF where the initial forces due to loads were transmitted to the cushion and uniformly distributed over there; the further forces are transmitted to the piles which acts as settlement reducers plays a vital role in decreasing the settlement and increasing the bearing capacity.

**Figure 12.** Comparison of Load-Settlement values in Raft, PRF and DPRF in the loose compactness sand.

**Figure 13.** Comparison of Load-Settlement values in Raft, PRF and DPRF in the medium compactness sand.
4.3. Effect of Compactness of Sand

**Figure 14.** Effect of compaction in ultimate load bearing capacity of the foundations.

**Figure 15.** Effect of compaction in Settlements of the foundations.
The effect of compactness of sand in controlling the geotechnical parameters were studied in raft, PRF and DPRF at loose and medium compactness of soil having densities 1.58g/cc and 1.71g/cc respectively. From the Figure 14 and 15, the ultimate load bearing capacity increment was observed 18%, 65% and 67% in raft, PRF and DPRF respectively; the settlements have also decreased with the increase in compactness of sand due to the uniform load carrying mechanism between the grains of the sand which are tightly packed without the voids.

5. Conclusion
Analysis of Raft footing, Piled Raft Foundation and Disconnected Piled Raft Foundation of raft dimension 150x150mm with piles of length 200mm and diameter 12mm under the application of vertical compression loads by varying the cushion thickness and compactness of sand were done. It was analyzed that in DPRF, the highest bearing capacity was noticed in a particular cushion thickness even with the further incrementation in thickness. The optimum cushion thickness was observed at H/B=0.34 in both loose and medium compactness of sand.

In comparison of PRF and DPRF with raft in loose compactness of sand, the ultimate load bearing capacity has incremented 38% in both the cases; settlements have decreased 0% in PRF and 33% in DPRF. In comparison of PRF and DPRF with raft in medium compactness of sand, the ultimate load bearing capacity has incrementd 74% in PRF and 75% in DPRF; settlements have decreased 13% in PRF and 42% in DPRF. It is evident that DPRF is much efficient than PRF and Raft footing in load sharing mechanism and reducing the settlements of footing. It is also observed that with the increase in compactness of sand, the bearing capacities have elevated with the decrease in settlements due to the removal of voids by the process of compaction which aligns the sand grains closer facilitating the uniform pressure distribution throughout the sand bed.

6. References
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