PILED RAFT ANALYSIS AND DESIGN METHODOLOGY

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ABSTRACT: In the present investigation, model tests and numerical simulation of piled raft were carried out on medium dense sand bed to understand the influence of area ratio of piled raft on load-settlement behavior and load sharing mechanism. The pile in 1% and 3% area ratio piled rafts take load predominantly up to settlement of 0.004D but for 5% area ratio piled raft it is 0.01D. From the parametric study, reduction in settlement takes place due to increase in pile length as well as with increase in area ratio of piled raft system. It is sufficient to reduce the differential settlement in piled raft foundation when the ratio of diameter of raft to length of pile is four.

INTRODUCTION
Raft foundation is normally adopted where sum of the area of all individual footings exceeds one half of the total building area. It is designed as rigid, in order to reduce differential settlement and to resist high moments. However, rafts exhibit differential settlement more than permissible limit particularly when rafts of large size subjected to non-uniform column loads. In case of pile foundation, the number of piles required in a pile group is higher for heavier loads and cost of foundation increases proportionately. Whereas in the recent years, the combination of raft and piles are adopted to overcome some of these difficulties, which are termed as piled rafts. The piled raft system effectively reduces total and differential settlements apart from offering higher bearing resistance compared to the rafts. The addition of a limited number of piles reduces the total settlement as well as differential settlement. Further piled raft foundation is an economical foundation option where the performance of the raft foundation is not satisfactory. Numerous researchers have worked on piled raft and their concentration was on piled raft for heavily loaded structures. The study on the applicability of piled raft for buildings of moderate loading is very limited. Further, a unique method for the design of piled raft is yet to be established. Therefore, it is proposed to investigate the load sharing mechanism between raft and pile through model test and numerical simulation.

LITERATURES

Table 1 Sizes of model piled raft

<table>
<thead>
<tr>
<th>Area ratio</th>
<th>Dia. of single pile (mm)</th>
<th>Dia. of pile in group (mm)</th>
<th>Length (mm)</th>
<th>No. of piles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>20</td>
<td>9</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>3%</td>
<td>35</td>
<td>15</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>5%</td>
<td>45</td>
<td>20</td>
<td>200</td>
<td>5</td>
</tr>
</tbody>
</table>

METHODOLOGY
A rectangular steel tank of inner dimension of 0.74m X 0.74m X 0.6 m was used to conduct the model tests. Sand is placed in layers of 50 mm thick by means of controlled pouring to achieve the desired density of 1.55 g/cm$^3$. A model circular plate having holes marginally bigger in diameter than pile was placed on the sand bed such that its center coincides with the centre of the load transferring plate and also the center of the tank. Piles of the piled raft foundation were driven with the help of guide pipe if the diameter is less than 15mm. Piles of larger diameter (> 15 mm) were placed in position before filling the final 20 cm of sand bed and sand was poured around the piles. The model raft was connected with the piles by stainless steel screws. The applied load was measured by a pre-calibrated proving ring of capacity 20 kN and each division of proving equal to a load of 0.03 kN. Two displacement dial gauges having a travel of 50 mm and least count of 0.01 mm was used to measure the settlement of piled raft. Each load increment was retained till the settlement measured remained constant. 1g model tests were conducted on circular piled raft of 200 mm diameter and thickness 8 mm made of Perspex material to require the model scale of 1:100. Table 1 presents the details of piles used in the laboratory model tests.

RESULTS AND DISCUSSIONS
Laboratory tests were carried out on circular piled raft of diameter 200 mm and pile length 200 mm with varying
diameter corresponding to area ratio of 1%, 3% and 5% with circular raft of 200 mm diameter. Tests were conducted by providing single pile at centre and five pile group distributed as shown in Fig 1 but both having same area ratio. Fig 2 shows the load-settlement response of pile, raft and piled raft of area ratio 3%. It can be seen from the Fig 2 that at any particular settlement level, the resistance offered by the piled raft is higher than the resistance offered by the pile and plain raft and for a given settlement the resistance of piled raft is marginally higher than the sum of resistance of raft and pile.

![Fig 1](image1.png)

(a) Centre pile  (b) Five pile group

**Fig. 1** Arrangement of pile in piled raft for a given area ratio

As it can be seen from Table 2, the stiffness of the system decreases with the increase in settlement irrespective of the area ratio. In the initial stages the stiffness reduction is proportional to the diameter of pile but if the settlement increases the proportionality breaks and the reduction becomes higher. In case of 3% area ratio piled raft, the increase in stiffness is 8.25% more than that of 1% area ratio piled raft and for 5% area ratio piled raft, it is 18.9% more than 1% area ratio piled raft at 20 mm settlement.

![Fig 2](image2.png)

**Fig. 2** Load-settlement responses of pile, raft and piled raft of area ratio 3%

<table>
<thead>
<tr>
<th>Area Ratio</th>
<th>Stiffness @ 2 mm (N/mm)</th>
<th>Stiffness @ 6 mm (N/mm)</th>
<th>Stiffness @ 20 mm (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>500</td>
<td>433</td>
<td>286</td>
</tr>
<tr>
<td>3%</td>
<td>600</td>
<td>467</td>
<td>295</td>
</tr>
<tr>
<td>5%</td>
<td>700</td>
<td>533</td>
<td>324</td>
</tr>
</tbody>
</table>

**Table 2** Stiffness at different settlement level.

In Fig 4 the load share between the raft and pile is presented for different settlements as a width ratio of raft. The Fig depicts the share of load between the pile and raft of piled raft. It shows piles share major part of applied load in the initial stage of loading and the share reduces rapidly and remains almost constant beyond the settlement of 0.04D (D = 200 mm). Further the share becomes insignificant beyond the settlement of 0.04D particularly for the area ratio of 1% and 3%. This shows that the resistance of pile is fully mobilized at lower settlement and at higher settlement the resistance of pile is the residual resistance. In case of 1% and 3% area ratio piled rafts, the pile shares major part of applied load up to settlement of 0.004D but for 5% area ratio, the pile is active in sharing the load up to the settlement of 0.01D.

![Fig 3](image3.png)

**Fig. 3** Load-settlement response of piled raft with central pile and piled raft with group pile of A_r = 3%.

![Fig 4](image4.png)

**Fig. 4** Load share of pile and raft at different settlement / raft width for A_r = 3%
NUMERICAL ANALYSIS
The software used for the study needs validation with available results and previous research works. PLAXIS 2D was chosen for the study. It is commercially available FEM software, wholly dedicated to analysis pertaining to soil-structure interaction and foundation related geotechnical problems. MOHR-COULOUMB model was adopted for the soil medium and LINEAR ELASTIC MODEL was adopted for the raft and pile. For modelling the soil and raft various parameters are required. The parameters required for modelling the soil such as, Young's modulus and dilatancy angle were obtained through experiments conducted on the sand medium. The $E_s$ of the sand was determined as 3.5 N/mm² and the Poisson’s ratio was taken as 0.3. The angle of internal friction and dilatancy angle was computed to be 38° and 10° respectively. Input for the analysis can be given by way of prescribed loads or prescribed displacements. In this analysis, input was given via a prescribed displacement of 20 mm corresponding to 10% of the raft diameter. Standard plaxis fixities were given as the boundary condition. PLAXIS has the option of having either a plane-strain model or an axi-symmetric model. Since the model is symmetric about its central axis and the loading is also symmetric, axi-symmetric analysis was carried out and the load-settlement graph corresponding to piled raft was then plotted and compared with the test results. The results obtained using PLAXIS compared well with the experimental results within a variation of about 10%.

The load share between the pile and the raft is the most critical parameter in the design of a piled raft foundation. Further studies involving the load-sharing between the raft and the pile and the load transferred through bearing is done through numerical analysis. The load shared by the pile in piled raft system increases with increase in area ratio of piled raft. The major portion of the pile load is predominantly transferred through friction of the piles and very less is transferred through bearing. In all the cases, nearly 75% of the load coming to the pile is resisted through friction only.

PARAMETRIC STUDY
The model chosen for study consists of a circular water tank resting on cohesionless, medium dense sand. The tank has a radius of 20 m and the height of the tank is about 15 m. The entire load of the structure needs to be transferred to the underlying soil by means of a suitable foundation system. The total load acting on the foundation has been calculated to be 200 kN/m². The young’s modulus of soil was taken to be 35000 kN/m² and the Poisson ratio as 0.3. The angle of internal friction for medium dense sand varies between 34° and 39°. In this case, it is taken to be 37°. Dilatancy angle has been assumed to be 10°. To comfortably transfer the load, the thickness of slab was calculated to be 1 m and the same has been employed. Three parameters have been chosen i.e. area-ratio of the piled-raft, and the length and diameter of the pile, for the parametric study. The number of piles was chosen to be 25 numbers, with one central pile and two rings of piles at an angle of 30°. The two rings were spaced at a distance of 8m c/c from each other so that the influence of one pile over the other can be avoided. Table 3 shows the settlement reduction with increase in length of pile and increase in area ratio.

<table>
<thead>
<tr>
<th>Area ratio</th>
<th>Settlement (mm)</th>
<th>Area ratio</th>
<th>Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>113</td>
<td>1%</td>
<td>112</td>
</tr>
<tr>
<td>1%</td>
<td>109</td>
<td>3%</td>
<td>104</td>
</tr>
<tr>
<td>5%</td>
<td>104</td>
<td>5%</td>
<td>103</td>
</tr>
</tbody>
</table>

Fig 5 gives the variation of differential settlement with respect to area ratio and diameter of raft (D) / length of pile (L). Differential settlement here corresponds to the difference between the settlement at the centre and the edge of raft. The graph clearly shows that with increase in area-ratio there is a marked decrease in the differential settlement. But for the same area-ratio, variation of D/L ratio does not seem to produce much difference. Hence, a D/L ratio of 4 is sufficient to reduce the differential settlement in piled raft foundation.

CONCLUSIONS
From the 1g model tests, the settlement reduction increases with increase in area ratio of the piled raft system. The load share of pile increases with increase in area ratio of the piled raft foundation.

The stiffness of the piled raft system increases with increase in area ratio of the piled raft foundation and decreases with increase in settlement.

In view of load share, the pile in 1% and 3% area ratio piled rafts shares major part of applied load up to settlement of
0.004D but for 5% area ratio, the pile is active in sharing the load up to the settlement of 0.01D.

Reduction in settlement takes place due to increase in pile length as well as with increase in area ratio. The ratio of diameter of raft to length of pile = 4 is sufficient to reduce the differential settlement in piled raft foundation.

REFERENCES