Piled Raft Behavior Based on 1-g Model Studies

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ABSTRACT

The results of 1g model tests conducted on piled raft models of square and circular shapes are presented and compared with the results of plain raft and piles tested with raft not touching the ground. The results are analyzed in terms of load-settlement response and established that the piled raft system reduces the settlement of raft significantly. The relationship between the non-dimensional parameters namely load ratio \((P_R)\) and settlement ratio \((d_R)\) is unique and it is independent of pile parameters and density of sand. It follows the relationship of rectangular hyperbola and is useful to determine the load carrying capacity of piled raft for a given settlement and also to determine the resistance offered by the piles of piled raft foundation.

1. INTRODUCTION

The challenge of designing an economical foundation system to support structures sensitive to settlement has led to the advent of a foundation system known as piled raft. This combined foundation system comprising of piles, raft, and the surrounding soil is primarily intended to function as a settlement reducer. The combined foundation system takes advantage of interaction between the constituting elements namely the raft, piles and the soil mass. The pile group in the initial stage shares major part of the load (elastic phase) and at higher load, it adds stiffness to the raft so that the combined system takes higher load compared to the plain raft. As stated, the piles and the raft share the load and in designing the foundation system of piled raft, this aspect namely load sharing behavior gains considerable importance. The economy in the design of piled raft largely depends on the arrangement of piles and pile geometry.

Continuous research based on numerical modeling (Clancy, 1993; Ta and Small, 1996; Gandhi and Maharaj 1996), small scale model studies (Horikoshi and Randolph, 1996; Kim et al., 2002), and data obtained from the monitoring of the proto type piled raft (Katzenbach et al, 2000b; Balakumar and Ilamparuthi, 2007;) have enhanced the confidence level on this foundation system, and the structures supported on this system is on the increase. The present state of knowledge on the behaviour of piled raft is mostly centered on the piled raft seated on deep deposits of over consolidated clay. However it is quite possible that this system can be adopted to support structures sensitive for settlement and are to be supported on loose to medium dense sand. Such a need arises in the case of storage tanks placed on this type deposits exhibiting settlement more than allowable value. Further the permissible settlement for foundations in sand is less than that in clay, hence requires system like piled raft to control the settlement within the permissible value. Further more understanding of load sharing between piles and raft is very much important for the piled raft in medium or loose sand particularly when the piles are driven because the driving of piles improves the state of compaction of the sand. The behavior of piled raft placed predominately on sand has been studied by a few researchers (Turek and Katzenbach 2003; Kim et al., 2002).

Keeping above said points in mind studies were carried out on the behavior of piled raft placed on sand particularly with raft placed directly on the surface of sand bed. This paper presents the load-settlement response of piled raft and a method to predict relation between them so that load carrying capacity of system can be obtains at any given settlement.

2. METHODOLOGY OF STUDY

Although 1g model studies may not reflect the true field conditions, such studies have been found to be very useful in understanding general behavior pattern as well as a guide for further studies. With this view, a series of small scale 1g model tests were conducted on a circular\((D=200\text{mm})\) and square\((B=200\text{mm})\) shape piled rafts placed in three different
bed densities for various length (L), diameter (d) and pile raft area ratio. In the study the effect of raft thickness (t) was found to have negligible effect on the performance of the piled raft. Perspex was used as model material for the pile and the raft. The details of the test set up, the material properties and the testing procedure are well explained elsewhere (Balakumar and Ilamparuthi, 2006).

3. RESULTS AND DISCUSSIONS

The results obtained from the 1g model tests conducted on plain raft, pile group and piled raft are analyzed with a view to bring out the relationship between load and settlement.

Figure 1 presents the load-settlement response of a square piled raft tested with 25 piles in medium dense sand and compares its response with plain raft and piles. The physical parameters of the pile, the raft and the bed details are also presented in the figure. The tests were conducted up to a settlement of 20mm (10% of the least lateral dimension of the raft). Comparing the load-settlement response of plain raft and piled raft, it is seen that at any given settlement the load taken by the piled raft is greater than that of plain raft. The load-settlement response of piled raft shows that at initial loads, the rate of increase in the settlement is very small (i.e. within the settlement of 2mm) indicating that the system exhibits a very high stiffness. Subsequent to this as the load increases the rate of change in the settlement increases gradually up to a settlement of 10mm indicating that the stiffness of the piled raft reduces gradually, although it continues to carry more loads. Further to this even for a small increase in the load the piled raft settles rapidly and the additional load taken beyond 10mm settlement is relatively small. This trend establishes the fact that the load-settlement behaviour of the piled raft changes due to interactive response of constituting elements.

Typical characterized load-settlement curve relating to the behaviour of square and circular piled rafts tested in different bed densities are presented in Figures 2 and 3 respectively. The curves show three phase response as reported elsewhere (Balakumar and Ilamparuthi, 2006). This response is due to the load sharing behavior of the pile group. In the phase OA the pile group shares the maximum load and the behaviour is linear; at this stage the stiffness of the piled raft soil system is very high. As the load and the corresponding settlement increases the stiffness of foundation system drops down (Phase AB) and reduces at a rapid rate and approaches the value of the stiffness of the plain raft in the Phase BC. The magnitude of stiffness at various phases namely 0A, AB and BC of the characteristic curve is presented in the Table1 and Table 2 for circular and square piled raft respectively. It is seen from the table that the difference between the stiffness of the plain raft and the piled raft is very high in the initial stage. As the magnitude of settlement increases the stiffness reduces and finally it reaches a value almost equal to the stiffness of the plain raft, although it takes a much higher load.

The behaviour of piled raft in sand due to vertical compression load can be visualized that the load is transferred by the column of sand grains and as it reaches limiting load, more and more columns of sand begin to support the load and each resisting approximately the same magnitude of load. Consequently the confining stress around the pile increases and the piles with ground contacting raft takes higher load at any settlement compared to that of plain raft.
The inter-granular resistance brakes and the piled raft—soil stiffness starts reducing rapidly. This response is seen from the figures 2 and 3. After OA (elastic phase) the stiffness of the piled raft is reduced. In the phase AB of characterization curve the piles function as settlement reducer thereby the system takes higher load compared to that of plain raft at any given settlement. This elasto-plastic response continues up to a settlement level of around 8mm, which is around 4% of the least lateral dimension of the raft. Beyond this settlement, it is seen that the rate of decrease of stiffness is rapid; however the system takes a higher load at any settlement level compared to plain raft.

The load-settlement response of the piled raft was studied by varying pile length, diameter and pile–raft area ratio. In order to generalize the load-settlement behaviour, the load settlement response was plotted in a non-dimensional form by normalizing the load and the settlement. The load corresponding to 20mm settlement was taken as the final load and each load increment was normalized by the final load to get the load ratio (\( P_R \)). Similarly the settlement corresponding to each load increment was divided by 20mm to get the settlement ratio (\( \delta_R \)). In this study the raft settlement of 20mm (i.e. 10% of least lateral dimension of the raft) is considered as failure displacement. The load ratio and the settlement ratio thus obtained are plotted separately for various load-settlement response curves obtained from the experiments.

Typical non-dimensional plots of the load-settlement response for various bed densities in the case of circular piled raft are shown in Figure 4. The response of square shape piled raft with piles at different spacing is also examined and its response is as shown in Figure 5. It is observed from the study the non-dimensional response curves fell in a narrow band irrespective of density of sand, shape of piled raft and spacing between the piles. They show hyperbolic response and is replotted as suggested by Chin (1970 & 1972). The modified hyperbolic plot for circular piled raft that tested in sand bed of three different densities is shown in Figure 6. Similar plot is presented in Figure 7 for piled raft of square shape tested in medium sand with piles placed at different spacing. In these figures (\( \delta_R/P_R \))

### Table 1: Effect of Pile Diameter on Capacity and Stiffness in Medium Dense Sand (\( D = 200mm, t = 8mm N = 21 & L=160mm \))

<table>
<thead>
<tr>
<th>Pile Dia. (mm)</th>
<th>( d/t ) ratio</th>
<th>Load (kN)</th>
<th>Stiffness (N/mm)</th>
<th>Load (kN)</th>
<th>Stiffness (N/mm)</th>
<th>Load (kN)</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 mm</td>
<td>0.75</td>
<td>1.40</td>
<td>700</td>
<td>3.00</td>
<td>233</td>
<td>5.70</td>
<td>285</td>
</tr>
<tr>
<td>8 mm</td>
<td>1.00</td>
<td>1.80</td>
<td>900</td>
<td>2.80</td>
<td>667</td>
<td>6.30</td>
<td>315</td>
</tr>
<tr>
<td>10 mm</td>
<td>1.25</td>
<td>2.20</td>
<td>1100</td>
<td>3.80</td>
<td>900</td>
<td>6.40</td>
<td>320</td>
</tr>
</tbody>
</table>

### Table 2: Effect of Bed Density on Load Taken and Stiffness 6d Spacing (\( L = 160mm, t = 6mm & d = 10mm \))

<table>
<thead>
<tr>
<th>Bed Density</th>
<th>( @ 2mm ) Settlement</th>
<th>( @ 6mm ) Settlement</th>
<th>( @ 20mm ) Settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load (kN)</td>
<td>Stiffness (N/mm)</td>
<td>Load (kN)</td>
</tr>
<tr>
<td>Loose</td>
<td>0.8</td>
<td>400</td>
<td>1.6</td>
</tr>
<tr>
<td>Medium</td>
<td>1.7</td>
<td>850</td>
<td>3.85</td>
</tr>
<tr>
<td>Dense</td>
<td>2.1</td>
<td>1050</td>
<td>4.6</td>
</tr>
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</table>

**Fig. 4:** Non-dimensional Plots of Circular Piled Raft for Various Bed Densities

**Fig. 5:** Non-dimensional Plots for Piled Raft of Square Shape with Different Pile Spacing
values are presented against settlement ratio $\delta_R$. The relationship thus obtained between $P_R$ and $\delta_R$ is as given in equation (1).

$$\frac{\delta_R}{P_R} = m \delta_R + C \quad (1)$$

where $\delta_R$ is the settlement ratio and $P_R$ is the load ratio; $m$ is the slope of the line and inverse of this in this case gives the asymptotic limiting load ratio. The value of $C$ gives the inverse of the initial stiffness ratio. The Tables 3 presents the values of $m$ and $C$ for variation of the pile length, the diameter, the pile raft area ratio and the bed density in the case of circular piled raft.

Similarly for the square shape the $m$ and $c$ values for variation of spacing, diameter and the length of the piles are presented in Table 4. From the Tables 3 and 4, it is seen that irrespective of the shape of the piled raft and the physical parameters of the pile the value of $m$ and $c$ remains almost constant indicating that the asymptotic limiting load ratio is constant. If the pile group and the continuum is considered as equivalent pier as proposed by Poulos and Davis (1980), then the hyperbolic relation established in this study can be used to predict the asymptotic limiting load ratio, which will be the ultimate capacity of the pile group.

Table 3: Variation of $m$ and $C$ for Circular Piled Raft

<table>
<thead>
<tr>
<th>Constants</th>
<th>Length</th>
<th>Diameter</th>
<th>Area Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>0.689</td>
<td>0.674</td>
<td>0.672</td>
</tr>
<tr>
<td>$C$</td>
<td>0.35</td>
<td>0.36</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 4: Variation of $m$ and $C$ for Square Piled Raft

<table>
<thead>
<tr>
<th>Constants</th>
<th>Spacing</th>
<th>Diameter</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$C$</td>
<td>0.42</td>
<td>0.4</td>
<td>0.4</td>
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</table>

4. CONCLUSIONS

The characterized load-settlement response has proved that the nonlinear behavior of piled raft is close to hyperbolic relation. The non-dimensional plot of load ratio versus settlement ratio has proved that irrespective of the shape of the raft, physical parameters of the pile and the bed density the response of the piled raft is identical and the asymptotic load ratio and the corresponding initial stiffness ratio remains same.

REFERENCES


