Connected Versus Disconnected Piled Raft Systems: A Comparative Experimental Assessment

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Abstract. This article presents a comparative assessment of the behaviors of connected piled raft (CPR) and disconnected piled raft (DPR) systems on the basis of an experimental study. Large-scale physical model tests are performed on 2×2 CPR and 2×2 DPR foundations embedded in sandy soil under static vertical load to understand the fundamental difference in the load transfer process involved in these two geometrically different foundation systems. Test results indicate that the inclusion of granular cushion platform under the raft in case of DPR plays the pivotal role in altering its load transfer mechanism from that of the conventional CPR system. The CPR shows higher load bearing capacity as well as higher settlement efficiency as compared to DPR. However, the DPR, upon loading, exhibits completely opposite pile-raft load sharing phenomenon than conventional CPR system as the raft is observed to take majority of the externally applied load initially and then the pile load share is found to increase gradually with settlement. In CPR, the connected piles reduce the raft stiffness, whereas, in DPR, the piles enhance the raft stiffness and act as soil reinforcements.

Keywords: Connected piled raft, Disconnected piled raft, Settlement efficiency, Stiffness, Experimental study.

1 Introduction and Background

The utilization of connected piled raft (CPR) for the foundation of high-rise buildings [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] is very popular and world-wide. However, due to high shear and bending forces at the raft-pile connection, there lies ample chance of sudden structural failure of piles in the areas of high seismic activities. Therefore, as an alternative solution, Wong et al. [12] proposed to structurally disconnect raft from piles with a cushion which pioneered the concept of disconnected piled raft (DPR) system. Few numbers of research have been conducted in this domain so far [13, 14, 15, 16, 17, 18, 19, 20, 2, 22, 23, 24]. However, very fewer physical experiments have been conducted in this domain and as a result, the load transfer process of DPR is not yet fully understood. Therefore, the present study aims to provide some useful experimental outcomes in order to understand the fundamental deference between CPR and DPR systems in a comprehensive manner.
1.1 Materials for Experiment

Yamuna sand (YS) is used in the model tests as bed material. A graded granular material CM is used as cushion. Table 1 shows the properties of these materials.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>YS</th>
<th>CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean particle size, $d_{50}$ (mm)</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>Min dry unit weight (kN/m$^3$)</td>
<td>13.8</td>
<td>14</td>
</tr>
<tr>
<td>Max dry unit weight (kN/m$^3$)</td>
<td>16.8</td>
<td>17</td>
</tr>
<tr>
<td>Friction angle (Degree)</td>
<td>40.7</td>
<td>47</td>
</tr>
</tbody>
</table>

For model pile, a 1 m long aluminium pipe (25.4 mm diameter and 2 mm thick) is used. To model the raft, a 300 mm × 300 mm × 25 mm aluminium plate is used. The elastic modulus and Poisson’s ratio of the aluminium are obtained as 69230 N/mm$^2$ and 0.33 respectively. Using the scaling law of bending rigidity [25], a prototype pile of 15.5 m length and 600 mm diameter can be represented with this model pile when the scaling factor is 15.5.

1.2 Test Program

All the strain-controlled (0.02 mm/second) model tests are performed in a 2 m × 2 m × 1.8 m steel tank (schematic diagram as Fig. 1) where sand bed having the $R_d$ of 70% is prepared with tamping method. The granular platform is placed over the sand bed covering the pile heads. 350 Ω strain gauges are attached on the pile to measure the axial loads. All the tests are terminated when the raft settles up to 30 mm [3, 11, 26, 29].

As the cost, time and space requirements for a full-scale load test are high, the reduced-scale 1-g model laboratory tests are preferred in geotechnical engineering. Therefore, keeping the limitations (i.e., stress level) of model 1-g tests in mind, an attempt is made to predict the response of DPR under vertical load and have an idea about the load transfer mechanism involving the key effect of granular cushion.
Fig. 1. Schematic of $2 \times 2$ foundation system with loading arrangement: (a) CPR; (b) DPR
2 Results and Discussion

2.1 Load-Settlement Performances of CPR and DPR

Table 2 shows the loads carried by unpiled raft (UR), 2 × 2 CPR and 2 × 2 DPR foundations at 30 mm settlement. The granular cushion is observed to have a decremental impact on the capacity of 2×2 DPR.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UR</td>
<td>15</td>
</tr>
<tr>
<td>2 × 2 CPR</td>
<td>17.8</td>
</tr>
<tr>
<td>2 × 2 DPR (h/d = 3)</td>
<td>15.9</td>
</tr>
</tbody>
</table>

The settlement performance of CPR and DPR is quantified using a non-dimensional quantity termed as ‘Settlement Efficiency’ [13, 27, 28] and it is defined as:

\[
\eta = \frac{W_{UR} - W_{DPR}}{W_{UR}} \times 100 \%
\]

(1)

where, \(W_{UR}\) and \(W_{DPR}\) are the UR and DPR settlements respectively. In case of CPR, \(W_{CPR}\) i.e., CPR settlement has been considered for calculation of settlement efficiency. As, \(W_{UR} > W_{DPR}\) and \(W_{UR} > W_{CPR}\) and \((0 \leq \eta \leq 100\%\), the efficiency of the DPR and CPR at a given load level increases with higher value of ‘\(\eta\)’ [27]. Table 3 highlights the variation of maximum \(\eta\) value for CPR and DPR at 30 mm settlement. The \(\eta\) value of 2 × 2 DPR is observed to have a lower value as compared to that of 2 × 2 CPR.

<table>
<thead>
<tr>
<th>Cases</th>
<th>(\eta_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × 2 CPR</td>
<td>30 %</td>
</tr>
<tr>
<td>2 × 2 DPR (h/d = 3)</td>
<td>11 %</td>
</tr>
</tbody>
</table>

2.2 Foundation Stiffness

Table 4 shows the variation of foundation stiffness for 2 × 2 CPR and 2 × 2 DPR under vertical load. Here, the representation has been made in terms of the ratio of the stiffness of 2 × 2 CPR or, 2 × 2 DPR to the stiffness of UR. From Table 4, it can be seen that the ratio of the stiffness of 2 × 2 CPR to UR is 1.42 as the piles attract the higher load at the beginning. Interestingly, this ratio is found to achieve an average value of 1.2 due to the introduction of structurally connected piles beneath the raft. However, the ratio
of the stiffness of the raft in $2 \times 2$ CPR to UR is observed to increase non-linearly from an initial value of 0.6, indicating the non-uniform raft-soil contact, to an average value of 0.95 as the settlement progresses. So, the piles are found to lessen the stress under the raft in CPR system.

Table 4 also depicts that the ratio of the stiffness of $2 \times 2$ DPR to UR attains an initial value of 1.25 and then decreases to an average value of 1.03 with increasing settlement highlighting the higher load bearing ability of $2 \times 2$ DPR than UR. Due to large overburden stress under the raft owing to granular cushion platform, the average value of the stiffness ratio of the raft in $2 \times 2$ CPR to UR is found 1.06. Therefore, it can be concluded that, in DPR, the piles enhance the raft stiffness and act as soil reinforce-
ments.

<table>
<thead>
<tr>
<th>Foundation stiffness ratio</th>
<th>Initial value</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness ratio of $2 \times 2$ CPR to UR</td>
<td>1.42</td>
<td>1.2</td>
</tr>
<tr>
<td>Stiffness ratio of raft in $2 \times 2$ CPR to UR</td>
<td>0.6</td>
<td>0.95</td>
</tr>
<tr>
<td>Stiffness ratio of $2 \times 2$ DPR to UR</td>
<td>1.25</td>
<td>1.03</td>
</tr>
<tr>
<td>Stiffness ratio of raft in $2 \times 2$ DPR to UR</td>
<td>1.2</td>
<td>1.06</td>
</tr>
</tbody>
</table>

2.3 Pile-Raft Load Sharing

Fig. 2 shows the gradual distribution of load between raft and piles with normalized settlement ($w/B$), where $B$ is the raft width.

![Fig. 2. Variation of pile-raft load proportions with settlement](image)
From the Fig, it is clear that in $2 \times 2$ CPR, the piles attract the load initially due to higher stiffness and then the raft share enhances with settlement. However, in DPR, the raft attracts the load initially and then the piles take part in load sharing.

In Fig. 2, the raft in DPR shares 90% of the total load when the settlement reaches 30 mm. The pile load share is very small. This happens because of the less no of the piles used in this study. However, with higher piles beneath the raft, the pile load share would increase up to 35 to 40%. However, this pile load sharing percentage in DPR would be lesser than the pile load share in case of a conventional CPR system. It is noteworthy that the relative compaction of the cushion layer must be around 90 to 95% for better result of the whole DPR system.

3 Limitations and Future Scope of the Present Study

The followings are some of the limitations and future scopes of the present study:

- This study entirely focuses to understand how a granular cushion layer beneath the raft alters the load transfer process of a vertically loaded disconnected piled raft system from that of the conventional connected piled raft system. To establish the relationship between raft thickness and cushion thickness, further detailed parametric studies need to be done by varying raft thickness and cushion thickness. However, this aspect does not fall in the scope of the present study.
- Under seismic condition the piles would be subjected to base shear, bending as well as axial force. However, this present study is done under static vertical loading condition only. The seismic assessment of DPR system and the related design aspects are in the future scope of this study.
- With the introduction of the granular cushion between raft and piles for a disconnected piled raft, the interaction between piles, cushion and raft becomes complex and dependent on settlement. This particular interaction study needs a thorough research and extended experimental works which are in the future scope of this study.

4 Concluding Remarks

From the experimental outcomes, the followings can be concluded:

- The inclusion of granular cushion platform under the raft in case of DPR plays a key role in altering its load transfer mechanism from that of a CPR system.
- The $2 \times 2$ CPR shows higher load bearing capacity as well as higher settlement efficiency as compared to $2 \times 2$ DPR.
- In CPR, the connected piles are found to act by reducing the raft stress on the soil, however, in DPR, the piles enhance the raft stiffness and act as soil reinforcements.
- The piles attract the load initially in CPR, however, in DPR, the raft shares the load at the beginning.
References