PILED RAFT BEHAVIOUR – MODEL STUDIES AND FIELD PERFORMANCE

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ABSTRACT: In order to establish the general applicability of piled raft foundation, the data obtained from hydro testing of a typical ammonia tank was compared with the results of independent small scale model studies. The pile supported raft of the tank and the model piled raft had a pile - raft area ratio of 9% and 9.25%. It was found that, the load settlement and the load sharing response of the tank foundation and the model were identical. The study established that even when the system was not designed as a piled raft, under favourable conditions, the ground supported raft together with the pile group would have a tendency to behave as piled raft.

INTRODUCTION
The settlement requirement for the storage structures is often very stringent and depends upon the nature of the storage material and the permissible deflection of the pipeline. The design of foundation system for such storage tanks and structures has always been a challenge for the geotechnical designers. Traditionally designed deep piles, had been the automatic choice of the foundation system in such cases. By convention, deep piles were designed to take the entire applied load to eliminate the settlement and the presence of raft and its capacity to share the load was being completely ignored. The urge for economising the foundation design has led to the conviction among the designers to believe that reducing the settlement to a permissible level rather than completely eliminating it can produce considerable economy. This has led to the recognition of the load sharing behaviour of the raft and the pile. The load sharing behaviour of the raft and the piles was brought out three decades before by researchers [1, 2], and others. The foundation system with this load sharing concept is addressed as piled raft wherein the piles are added as settlement reducers. The piled raft system has a lot of advantages [3] under the favourable circumstances particularly when the raft rests on strata with adequate bearing capacity.

Recognising the advantages and the economy that can be achieved by reducing the settlement to a permissible level continued research work has been carried out adopting analytical and numerical modelling [4,5,6,7,8,9], small scale model studies with centrifuge models [10], 1g models [11,12] and by monitoring the prototype piled raft [6,11,3].These extensive studies have made the piled raft foundation a viable alternative to deep piles and many structures have now been supported on piled raft [3,13] successfully. However the development of piled raft appears to have been directed more towards specific conditions as given below.

1. In majority of the cases the supporting soil has been deep deposits of overconsolidated clay.
2. They have been supporting predominantly tall buildings (with very high column loadings) with deep basements, wherein very thick rafts are placed at deeper depths. In such cases the raft gets the advantage of relief in the overburden pressure from settlement point of view.

However there are various other conditions where the concept of piled rafts can be considered. For example, when storage tanks are to be placed on loose or loose to medium dense sand, deep piles are resorted to, as the permissible settlement for foundation placed on sand is less than that for the foundation placed on clay. Also the tank pad namely the combined raft is placed very close to the ground level or at ground level itself. One more important aspect is that the driving of piles in sand improves the state of compaction. Although this has not been quantitatively established, but qualitatively accepted. If the above conditions apply, then the pile supported raft of the storage structures will behave as piled raft even if they have not been designed as piled raft. In order to understand the above behaviour, the load settlement response obtained from the results from hydro tests conducted on a tank farm was examined in more detail based on published results of [14]. Typically the result of hydro test conducted on a 33m diameter ammonia tank is discussed.

STUDY OF THE FIELD DATA
A tank farm comprising of 33m diameter ammonia tanks, 28m diameter phosphoric acid tanks and some small storage structures were constructed as a part of a huge manufacturing facility. The soil profile at the site had alternate seams of soft clay, medium dense to dense sand and stiff clay as presented through the results of cone penetration tests in Figure 1. The tanks were supported on closely spaced (3D, D being the diameter of the pile) 450mm dia driven cast in situ piles terminated at 10m from ground level of which 6m length of the pile was passing through sand. The capacity of the pile was 65 tonnes and this was established by individual pile load tests. The ammonia tank had 437 piles and the pile-raft area ratio was close to 9%. The raft was 400 mm thick, being a flexible tank. On completion, the tank was subjected to hydro test with 17.90 m of standing water. The water was pumped in...
at a slow rate in stages. The rate of loading for the hydro test was designed considering the mobilization & dissipation of pore pressure based on the principles of critical state soil mechanics. The settlement was recorded in the centre and eight symmetrically placed points along the periphery.

Table 1 Comparison of Settlement of pile supported raft and unpiled raft for Ammonia Tank

<table>
<thead>
<tr>
<th>Load in kN</th>
<th>Unpiled Raft Settlement, in mm</th>
<th>Pile Supported raft Settlement, in mm</th>
</tr>
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<tbody>
<tr>
<td>5129</td>
<td>104</td>
<td>6.0</td>
</tr>
<tr>
<td>8549</td>
<td>163</td>
<td>19.0</td>
</tr>
<tr>
<td>11968</td>
<td>209</td>
<td>47.0</td>
</tr>
<tr>
<td>15302</td>
<td>252</td>
<td>65.0</td>
</tr>
</tbody>
</table>

It is seen that at any load level the settlement of the pile supported raft was much lower than the unpiled raft. The load settlement response of the piled raft was characterised by plotting the load on the log-scale (y-axis) and settlement in normal scale (x-axis). This helps in identifying the various stages in load settlement response. This is presented in Fig. 4.

The figure 4 clearly shows a three phased behaviour of the pile supported raft foundation (piled raft) which is identical to that of model piled raft as shown in Fig 5. This behaviour confirms that although the pile group was designed to carry the entire structural load, in reality there appears to be a load sharing process between the raft and the pile group. In the first phase maximum load was taken by the pile group as seen by the high stiffness. Thereafter the stiffness reduces gradually up to an extent and then rapidly. Also the pile group has functioned as settlement reducer. This is evident from the fact that the settlement of the pile supported raft is far less than the computed unpiled raft settlement. To represent the settlement reduction and the load shared by the pile group quantitatively, the settlement reduction ratio $S_R$, which is the ratio of difference in the settlement between the unpiled raft and piled raft at any load level divided by the unpiled raft settlement for a given loading and the load sharing ratio $\alpha_{sr}$, ratio of the load taken by the pile group to that of piled raft for a given settlement were computed from the settlement of the unpiled raft and the load settlement results of hydro tests. The values are presented below in Table 2. From the table 2 it is seen that the load sharing ratio reduces with the settlement and at the final stages the load sharing ratio remains more or less constant. However it is seen that the pile group has taken 72% of the load and the raft has shared 28% of the load.
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Table 2 SR and αpr at different of load from hydro test for typical Ammonia Tank.

<table>
<thead>
<tr>
<th>% of Loading</th>
<th>SR (%)</th>
<th>αpr (%)</th>
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<tbody>
<tr>
<td>25</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>84</td>
</tr>
<tr>
<td>75</td>
<td>82</td>
<td>77</td>
</tr>
<tr>
<td>100</td>
<td>73</td>
<td>72</td>
</tr>
</tbody>
</table>

1g MODEL STUDIES

In order to validate the behaviour of the pile supported raft, the results of the hydro test were compared with the results of the 1g model tests conducted on circular piled raft. These tests were part of the elaborate and well planned research programme that was carried out to study the behaviour of piled raft on sand keeping in mind that the piles would be relatively smaller diameter for representing driven piles with moderate capacity and the raft placed close to the ground level. Rafts typical of storage tanks (circular) and structures like buildings (non circular) were taken up for the study. Among the various methods available it was decided to study the behaviour of piled raft on sand adopting 1g model studies. Primarily 1g model study was preferred mainly because it easier to conduct parametric studies and represents more or less field conditions. Although the results cannot be used directly for field problems, the results do give good idea of the performance of the system.

The details of the test setup and the model piled raft are presented in earlier publications. The bed was prepared by sand raining process and recalibrated compaction procedure in layers. The variation of angle of internal friction with bed density is presented in Figure 6.

Fig. 6 Variation of angle of internal friction with unit weight

This confirms that the pile group at higher load adds the required capacity for the raft to take a higher load compared to the unpiled raft. Comparing the progression of SR and αpr values estimated in table 2 and 3 it is seen that the behaviour of model piled rafts and the pile supported raft are more or less identical.

Table 3 Settlement reduction and load sharing at different settlement levels.

<table>
<thead>
<tr>
<th>% of Loading</th>
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<th>αpr (%)</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>72</td>
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<td>75</td>
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<td>100</td>
<td>50</td>
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The characteristic load settlement response obtained from the 1g model tests for 3 different area ratio is presented in Fig.6. Comparing Fig.6 with Fig.4 it is seen that the behaviour is identical in both the cases. In the three phased response stage OA represents the elastic stage, AB represents the elasto plastic stage and BC represents plastic stage wherein even for small increase in the load the piled raft loses its stiffness rapidly. Fig.7 presents the load sharing behaviour wherein the load sharing ratio αpr is plotted against the settlement. It can be seen that up to a settlement level of 2mm the load sharing ratio is very high and then gradually decreases and beyond 10mm settlement which corresponds to nearly 50% of the final load applied. The SR and αpr value at different % of loading is given in αpr table 3.

Fig. 7 Settlement v/s LS ratio αpr for different area

Fig. 5 Characterization curves – 1g model circular raft - various area ratios

The model piles were installed with a specially made template and a guide. The sequence of installation by driving was done in similar way as in the field. The raft was connected to the piles with countersunk stainless steel screws. The loading was applied in small increments and for each increment the time versus settlement was also recorded. The tests were carried out by varying the parameters relating to the pile namely pile-raft area ratio, pile diameter and pile length.
Comparing the behaviour, it is seen that the pile group acted as settlement reducer and also exhibited ductile behaviour. In the initial stage of both the cases, the pile group takes a higher proportion of the load and at the final stages the load shared by the pile group reduces, to about 70% in the case of storage tank under study. Very similar to the model behaviour, the load shared by the pile group reduces with the settlement and tends to remain constant suggesting that, even though the tank foundation was not designed as a piled raft system, it behaved like piled raft.

But in the case of storage tank foundation under study, the pile group shared much higher proportion of the applied load under large settlements also, perhaps due to the fact that the soft clay layers immediately below the raft and the thin fill has very limited stiffness. It is also possible that the installation procedure of very closely spaced driven piles enhanced the density of the supporting sand layers below the soft clay, thereby increasing the individual pile capacities. However, the soft clay does not achieve higher stiffness by the pile driving process.

CONCLUSION
The study has clearly established that the principles of piled raft can be applied in general under favourable conditions, when the raft is seated on a layer with reasonable bearing capacity. It is evident from the fact that even when the system was not designed on principles of load sharing by interaction the load sharing has taken place leading to the foundation system behaving as a piled raft.

In case of tank foundation the pile group appear to have shared much higher load mainly because driving of closely spaced piles has densified the sand layer enhancing the confining stress of the soil around the pile and this has resulted in the pile group taking much higher proportion of the applied load compared to that of the model piled raft.

The study has established the general applicability of the principles of piled raft when the settlement alone governs the design.

REFERENCES