Behavior and performance of piled raft – A comprehensive study

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ABSTRACT

The combined piled raft foundation is unique in the sense that neither the pile group alone nor the raft by itself ensures the safety and the serviceability of the structure it supports; it is the combined system that ensures the safety and serviceability of the structure it supports. Hence a complete knowledge of the contribution of each element namely the pile, raft and the soil on the overall behavior is essential to generate an effective design. Through the results of 1g model tests performed on circular, square and rectangular piled raft the general and the interaction behavior were studied and in this paper typically the essential results of circular piled raft is discussed. A procedure for determining the limiting capacity is also outlined. The effect of any compressible layer present in the soil strata is also outlined. In short, the paper explains the overall behavior of piled raft in a comprehensive manner.

Keywords: Comprehensive, piled raft, types of study.

1 INTRODUCTION

The construction of the foundation system for any high rise buildings takes nearly 30% to 50% of the total construction time, although the cost of the foundation may only be 15% to 20% of the cost of total cost of the facility. This aspect makes the foundation system, the most critical element from the point of view of risk assessment, optimization and assurance of the serviceability requirements. By convention, for tall and heavily loaded structure deep piles are adopted against raft under two conditions namely either there is a risk of bearing capacity failure of the foundation systems or the settlement under the applied load is far in excess of the permissible value.

Traditionally designed pile foundation and pile group does not distinguish between these two problems and is mostly bearing capacity based. When the ground has adequate bearing capacity, but settlement alone is a problem in providing a large group of piles, the number of piles is governed by the geometry of the foundation. This leads to an uneconomical design with a very high factor of safety not justifiable from an engineering point of view to reduce the settlement. So it is evident that ignoring the presence of the raft and its contribution in transferring the load to the competent ground cannot be justified from engineering principles.

2. HISTORY OF PILED RAFT

The concept of reducing the raft settlement by providing piles was introduced by Zeevaert (1957) to support the La Azteca tower. The addition of piles considerably reduced the settlement. Subsequent contribution of various researchers such as Horikoshi and Randolph (1998), Burland et al. (1997), and many others has resulted in the development of piled raft foundations crossing conceptually a number of mile stones. Consequent to this number of tall and heavily loaded structures such as Burge Dubai, (Poulos, 2008) etc. have been supported on piled raft.

3 NEED FOR THE PRESENT STUDY

Different type of studies done so for, deal with specific aspects of piled raft behavior. If the highly sophisticated concepts associated with the analyses of piled-raft are to be put into practice, a clear understanding of the overall behavior of piled raft and the role played by the pile group in the performance of the piled raft is essential. In this presentation an attempt has been made to achieve the above objective by combined analyses of related data from various types of studies made by the above research group as a part of an extensive study on the piled raft behavior.

4 BEHAVIOUR OF PILED-RAFT

In order to understand the above process, the results obtained from 1g model tests (Balakumar, 2008) conducted on small scale models of circular, square and rectangular piled raft placed on poorly graded sand bed have been utilized. In this presentation the results of circular piled raft on medium dense sand has been taken for discussion as a typical case as the trend was identical in the case of square and rectangular piled raft

4.1 General behavior

The characterized load-settlement response obtained from 1g model tests indicate a three phase behavior namely elastic, elasto-plastic and plastic stages as given in Figure 1

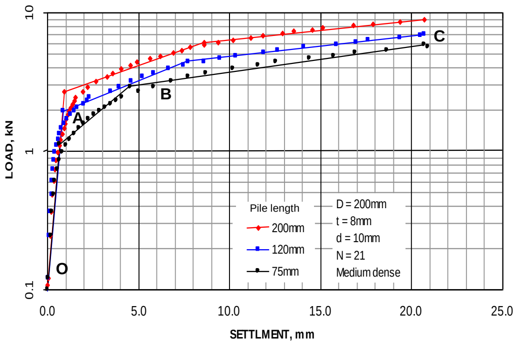


Figure 1. Characteristic response of piled raft for Various pile lengths

At any stage, the load taken by the piled-raft was higher than the un-piled raft, the variation being 40% - 100 %. Table 1 presents the variation of the stiffness of un-piled and piled raft at the end of each phase.

Table 1. Comparison of stiffness of plain and piled raft for various settlements (D = 200 mm, t = 8 mm, L = 160 mm and d = 10 mm, and N = 21)

Bed	Phase OA (N/mm)		Phase AB (N/mm)		Phase BC (N/mm)	
	Plain	Piled	Plain	Piled	Plain	Piled
Loose	195	380	137	197	98	130
Medium	600	1100	467	633	255	345
Dense	800	1700	617	800	314	410

It seen that at the failure settlement (in the present study 10% of the raft diameter/size) the stiffness of the combined foundation system is close to that of un-piled raft although the combined piled raft foundation takes a load 40% higher than the un-piled raft. This indicates that the pile group at the ultimate stage adds stiffness to the raft which enables the system to take a higher load compared to the unpiled raft.

4.2 Hyperbolic behavior

Figure 2 presents a non-dimensional plot between load ratio against settlement ratio for circular piled raft of three different pile lengths which exhibits a hyperbolic. The plot shows that irrespective of pile length the response is close to rectangular hyperbolic response. The nonlinear part of the curve has been taken and plotted as hyperbolic curve in Figure 3 to get the relationship between the load ratio and the settlement ratio as given in Figure 2. Similar behavior was observed in all the cases studied (Balakumar, 2008)

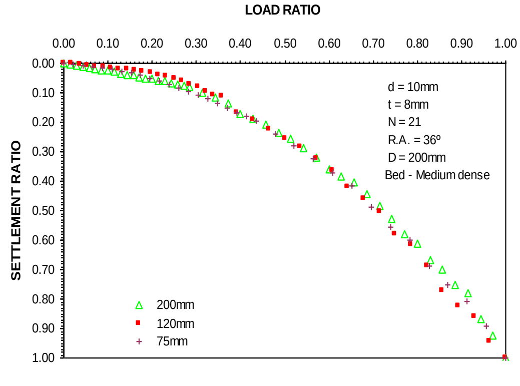


Fig. 2. Load ratio vs Settlement ratio

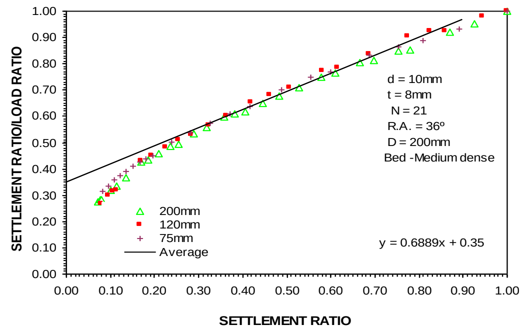


Fig.3 Settlement/ load ratio Vs settlement ratio

4.2 Effect of pile group on behavior of piled raft

The effect of adding the pile group to the raft is explained by comparing the load settlement response of free standing pile group (the raft is not in contact with the ground).and the (the raft is in contact with the ground) the pile group of piled raft wherein the raft is in contact with the bed as given in Figure 4. It is seen that the free-standing pile group exhibits a high stiffness till the total friction is mobilized (2 mm settlement level). Once the friction is overcome the pile group loses its stiffness instantaneously.

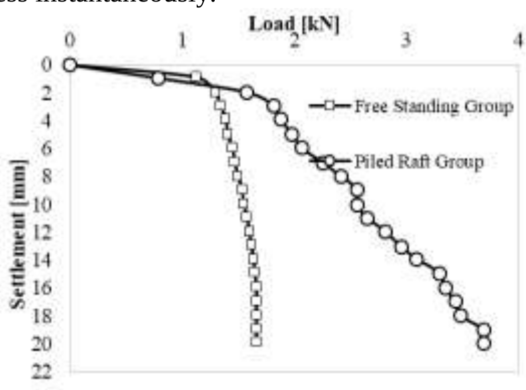


Fig. 4. Comparison of load-settlement response of free standing pile group and pile group of piled raft Non- dimensional plots for various lengths

But the pile group of piled-raft exhibits a higher stiffness till the total friction is mobilized. The settlement level at this stage is around 3 mm which is 1.5% of the raft used in the model test. Thereafter the loss of stiffness is gradual as the settlement increases with the increase in the load. This increase in the capacity of pile group of piled raft is mainly due to raft transferring the applied stress to the pile group and also to the soil. The stress transfer enhances the confining pressure around the piles in the group causing an increase in the frictional capacity of the pile group.

Studies conducted on the variation of load sharing ratio (defined as the ratio of the load taken by the pile group to the total load on the piled raft at any settlement level with settlement as in Figure 5 has indicated that as the settlement increases the load sharing ratio reduces (Balakumar, 2008) gradually till the friction is overcome. As the settlement increases the load sharing ratio reduces at a higher rate up to a settlement level corresponding to 2% to 3% of the pile length and then remains constant indicating that at higher load the pile group acts as settlement reducer without taking any further load indicating that the load sharing ratio is settlement dependent.

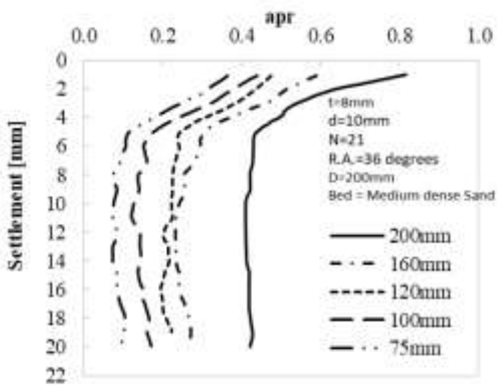


Figure 5 Settlement v/s LS ratio α_{PR} for 10mm dia pile

4.3 Interactive behavior

Considering the effect of installation of the pile on the properties of the soil strata, instead of comparing the response of unpiled raft with that of piled raft, it would be better to study the interaction behaviour of the constituent elements. A study was conducted adopting the expression presented by Horikoshi and Randolph (1995) for the piled-raft stiffness. The stiffness of the piled raft, pile group and the un-piled raft were calculated from the 1g model test results of circular piled raft and the interaction factor α_{rp} was calculated at various settlement levels by varying the pile length and pile raft area ratio. And the variation is presented in Figure 6a and 6b.

It was observed from the study that the interaction factor varies from 0.6 to unity. For a pile length of 0.6 B to 0.8 B (B is the raft diameter or the width) the interaction factor varies from 0.6 to 0.8 and this value matches closely for a pile-raft area ratio of 5.25%. This indicates that when the area ratio is 5.25% and the pile length is 0.8B provides an ideal level of interaction.

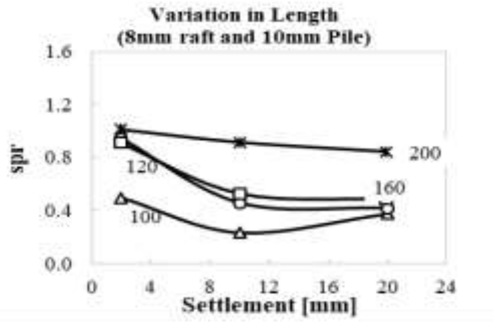


Figure 6a: Effect of pile length on α_{rp}

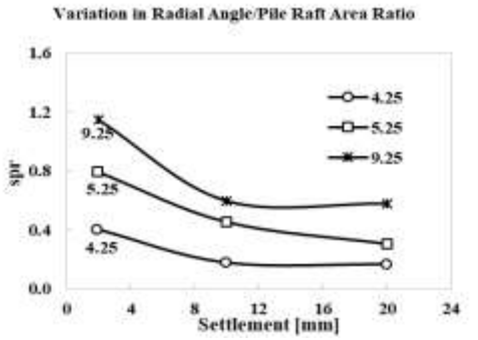
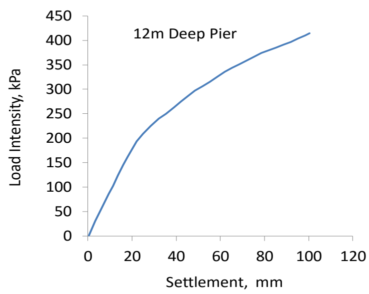


Fig. 6b. Effect of piled raft area ratio

5 LIMITING CAPACITY AND DESIGN METHOD

The capacity of the piled raft is settlement dependent and is limited to the value corresponding to the settlement reduction required. Hence the pile group capacity gains more importance than the individual pile capacity. If the pile group can be considered as a short stubby pier, the pier capacity can be determined by normal analytical procedure. On these lines a numerical study was carried out considering a hypothetical pile group of 9 piles with 5d spacing (d is the diameter) was considered. The diameters of the piles were 800mm and 16m long. The soil profile was taken from the general soil profile prevailing in Gold Coast and Surfers paradise area (Oh et al., 2008). The pier model and the geotechnical parameters used in the analyses are given in the earlier publications of the above Geotechnical research group (Balakumar et al., 2013).

Figure 7 below presents the load settlement response of a typical 12m deep pier which exhibits a hyperbolic behavior which can be expressed in terms of Chin – Kondtner type functions (Balakumar et al., 2013).



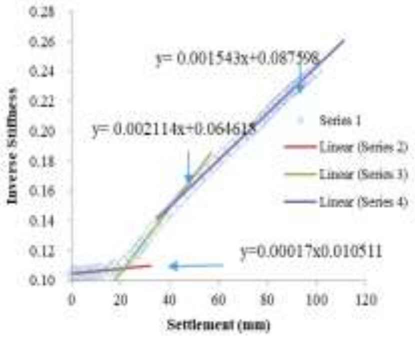


Fig. 8. Load settlement response PLAXIS (b) Chin's graph (12m pier)

Accordingly, the inverse of the stiffness is plotted against the settlement and the linear plot was obtained as in Figure 8. The inverse of the slope gives the asymptotic ultimate capacity of the pile group. A typical case was analyzed, and it was found that the asymptotic ultimate capacity is three times the capacity corresponding to the elastic limit and 1.5 times the load corresponding to elastic plastic limit. Hence the limiting capacity is limited to the load corresponding to elasto plastic stage corresponding to 10% of the pile diameter.

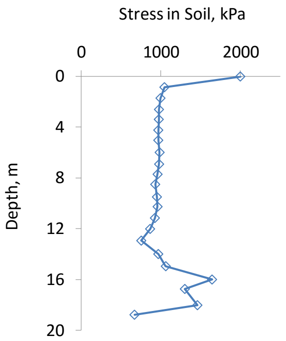


Fig. 9. Stress in soil

5.1 Effect of intermediary compressible layer

It is very rare to find natural deposits with ideal isotropic and homogeneous condition. Many uncertainties arise concerning the use of mechanical properties of the subsoil materials in calculations of a single pile and pile groups even considering ideal conditions. It was observed that the general soil profile of Gold Coast and Surfers Paradise area has an intermediary peat layer (Min. J. Huang, 2006)) which further complicates the analyses. Due to this the shaft stress distribution shows an increase in the stress over the length of the pile group passing through this layer as in Figure 9. This increase in the stress has to be accounted for in the pile group design. In doing the numerical analyses the most difficult part is the evaluation of in-situ parameters particularly in situ elastic modulus. To cater for this, the trend in the evaluation of essential parameters has also changed from laboratory-based testing to in situ testing. Frank et al., (1991) have shown that the pressure meter can effectively be used for the prediction of the load settlement response of the pile and hence pile group.

6 CONCLUSIONS

The load settlement response of piled raft has three phases. The load sharing behavior is settlement dependant. The variation in the stiffness with settlement and the load sharing response indicate that an optimum performance of piled raft can be achieved up to the end of phase AB. The limiting capacity of the piled raft can be obtained by considering the pile group as apier using Chin's method. Presence of any intermediary compressible layered not become a constraint as it will be enough if the increased stress in the pile section passing through the compressible layer is properly accounted for.

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