Optimisation of Piled Raft Foundation Design - A Case Study

D.L.C. Welikala
Department of Transport and Main Roads, Queensland, Australia

ABSTRACT: The piled foundation is a common foundation system which is recognised as an economical method for supporting superstructures by transferring load into the deeper layers of the ground. Piles can be used in a group with a raft, or as a single pile/shaft supporting system. Piled raft foundations have structural redundancy when compared with conventional piled foundations. Many methods exist for estimating the settlement behaviour of a pile cap, ranging from empirical methods, through to commercially available sophisticated computer programs (finite element and finite difference analysis). The challenging problem in the design is the analysis of the interaction between the soil and the foundation structure. Piled raft foundations have proven to be the most viable and economical when compared with the conventional piled or raft foundations. This foundation system has a combined action to support the structure against soil foundation. The modern finite element analysis software programs are capable of assessing the complete performance of soil-structure interaction under the given structural design action.

1 INTRODUCTION

Over the past decade various methods of analysis have been carried out to assess the behaviour of piled raft foundations. As a result, it has been recognised as an optimised foundation system and design concept which improves the bearing capacity to reduces the total and differential settlements of the pile cap. This leads to considerable savings on a project, without compromising the performance and safety of the foundation system. The design of the pile raft foundation system can be optimised to get the best economical foundation by reducing the number of piles, the diameter, thickness and size of the raft, while complying with an adopted design criteria. In the design, design engineers are required to fully understand the mechanism of load transfer from the raft to the pile and to the soil, that is, soil structure interaction needs to be understood. Various methods of analysis of piled raft foundations have been developed over the past decades (Poulos, 2001a; Poulos 2001b; Reul & Randolph 2003; Phung, 2011). The finite element method is used by most of researchers to model the piled raft foundation and it has been found to be the most suitable as the interaction between pile to pile, soil to pile, raft to soil and pile to raft, is a complex problem and very difficult to model using a simplified approach.

This paper describes the optimisation of the combined piled raft foundation system (CPRF) on dense silty sand, based on previous studies carried out for railway projects in large flood plains. Two cases were considered in the analysis. In the first case, the structure was founded on CPRF system, and in the second case, the structure was founded on raft foundations which suffered significant settlement and tilting.

The performance of these foundations under the given load combination is considered, and the results presented in this paper provide an economical foundation system in a simplified manner. Finite element program Plaxis 3D and Piglet were used in the analysis.

2 DESIGN REQUIREMENT

2.1 *Foundation System*

The piled raft system provides pile group support to reduce the settlements under serviceability loads. The raft portion provides additional capacity at ultimate loading if the bearing surface has an adequate strength to take the excess load. Therefore, the combined capacity of the piled raft foundation system, including load sharing capability, should always be considered in geotechnical assessments.

In cases where the raft alone has adequate load capacity, but does not satisfy the settlement criteria of the design, settlement reducing piles may be considered (Burland, 1995; Randolph, 1994). In cases where the piled raft system can provide adequate load capacity from the raft, this situation can be considered as the most economic and effective design application. However, this situation may occur when the piled raft is placed on dense to very dense sand, or stiff to hard clayey soils.

Axial capacity, total settlement and differential settlement are the critical issues considered in this assessment to optimise the design.

2.2 *Design Issues*

The following issues are to be considered in designing piled raft foundation for bridges.

1. Ultimate capacity.
2. Overall settlement.
3. Differential settlement across the pile caps.
4. Structural design action.
5. Possible effect due to external forces.
6. Seismic effect due to earthquake excitation - down drag and liquefaction effects.
7. Wind forces and collision effect.

2.3 *Design Philosophy*

There are three different design concepts defined by Randolph (1994) with respect to piled rafts.

1. The piles are to be designed as a group to carry most of the design load with some allowance for the raft to carry.
2. Piles are to be designed to operate at a working load at which significant creep starts to occur, typically 70%-80% of the ultimate load capacity. Sufficient piles are to be included to reduce the net contact pressure between the raft and the soil, to below the pre-consolidation pressure of the soil.
3. A strategic pile layout is required to reduce the differential settlement, rather than reducing the total settlement.

2.4 *Limit State Design*

In engineering design, it is important that a structure has a low probability of collapse, under the worst combinations of load, where the deflections are within the tolerable limits, under normal operating conditions.

The limit state design requires the following expression to satisfy the ultimate loading conditions, as per Australian Piling code AS2159-1995.

$$S^* = \Psi S \geq \Phi_g R = R_{ug}^* \qquad (1)$$

Where S* is the Design action effect, R* is the Design structural strength, Ψ is the Structural reduction factor, Rug* is the Design geotechnical strength, Φg is the Geotechnical strength reduction factor and R_{ug} is the Ultimate geotechnical capacity.

The above criteria will only apply to the foundation system and not to each individual pile within the group. The foundation system with the reduced geotechnical strengths (R_g*) can be used to assess the performance of the CPRF system against structural design action (S*) for the Ultimate Limit State condition. This method can be used effectively to optimise the design of piled raft foundations under the combination of axial, lateral and moment loadings.

If the assessment is carried out under the serviceability limit state, deflection of the foundation system should not exceed the limit specified by the designer.

3 SOIL STRUCTURE INTERACTION

The CPRF act as a composite construction consisting of three major bearing elements Pile, Raft and Subsoil. It is important to understand the difference in load-displacement behaviour between the piles of a CPRF and the piles in a conventionally designed piled foundation. The interaction of a CPRF leads to an increase in the equivalent Young's modulus of subsoil compared to a raft foundation which is stable without piles.

As a result of the interaction mentioned above, the stress state of the subsoil underneath is distinctively different when compared with the stress state of the subsoil of conventional pile foundation.

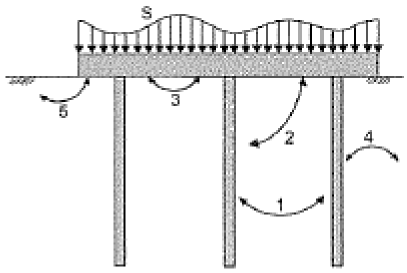

Fig. 1 Soil - structure interactional

A portion of the load transferred from the raft into the subsoil increase the normal stress level ($\Delta\sigma_{compression}$) at the pile shaft. As result, failure shear strength (τ_f) at the pile shaft of CPRF is computed by below modified Mohr-Coulomb failure criteria.

$$\tau_f = \sigma_{cprf}.\tan\phi' + c' = (\sigma_{pile} + \Delta\sigma'_{compresstion}).\tan\phi' + c'$$

This indicates the maximum shear strength at the piles shaft CPRF system is always larger than for a conventionally designed pile foundation and the experimental investigation carried out by Vesic

(1969), Phung Duc Long (1993) has shown this. The interactions within the CPRF system is shown in Figure 1.

4 MODELLING OF PILED RAFT FOUNDATIONS

4.1 *Example*

A simple example of a piled raft foundation consisting of a group of nine circular bored piles, 1.2m diameter in medium dense silty sand, was considered in the analysis. The sandy soil is assumed linearly elastic in the assessment.

The finite element program, PLAXIS 3D was used to assess the stress–strain behaviour of the piled raft in sandy soil using the hardening soil model. The soil parameters adopted are summarised in Table 1. The combined foundation systems were modelled using floor and pile elements.

The following variables were considered:

a) Aspect ratio, pile length(L)/diameter(D)
b) Pile spacing (S) and pile diameter (D) ratio
c) Number of piles (N).

The foundation system was simulated under the load combination of 12000kN vertical and 1200kN horizontal, acting on a pile cap. A raft thickness of 1800 mm is considered in the analysis.

Table 1. Properties of sandy soil

Property	Unit	Value
Unit weight	kN/m3	18
Secant Stiffness (E_{50}^{ref})	kN/m2	20000
Poisson ratio	μ	0.3
Oedometer Stiffness (E_{oed}^{ref})	kN/m2	20000
Unloading - reloading Stiffness (E_{ur}^{ref})	kN/m2	50000
Pre overburden pressure (POP)	kN/m2	100
Power (m)		0.8
Friction Angle	Ø deg	32

5 RESULTS OF THE ANALYSIS

5.1 *Interaction Factor*

Interaction between two piles in a piled raft system is complicated and significantly affects the load-settlement behaviour of the raft. Three dimensional (3D) finite element program, PLAXIS 3D, was used to assess the variation of interaction between two piles at variable distances.

The interaction factor (α) defined by Paulos (1968) is used in the assessment where

α = Sij / Sii

Where Sij is the excess settlement of pile *i* due to a loaded pile j nearby and Sii is the settlement of unloaded pile i under its own weight. The interaction factors of two piles, each 1.2m diameter was determined by PLAXIS 3D analysis by varying pile spacing form 1m to 10m. The results are presented in the form of (α) against s/d ratio in Fig. 2. The results indicates variation of s/d ratio has significant influence in the interaction factor between two piles. The group interaction effect of the piles, which has a significant influence on the carrying capacity of a pile group appears decreasing considerably as the pile spacing increases.

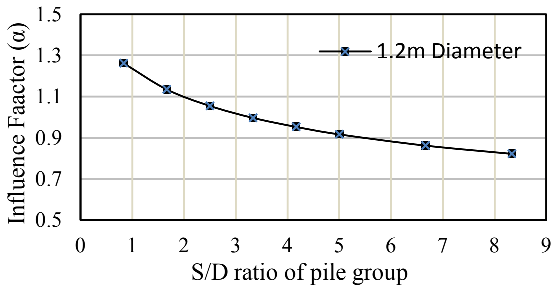

Fig. 2 Influence of s/d ratio on interaction factor

Selection of the optimum value of the s/d ratio for the particular pile group provides the maximum benefit from the group action of the piled raft.

5.2 *Spacing and Diameter Ratio*

The analysis was carried out by varying the s/d ratio by keeping the pile lengths constant. Results were obtained in term of axial capacity of the piled raft under the working loads of 12000kN vertical and 1500kN horizontal, acting on pile cap.

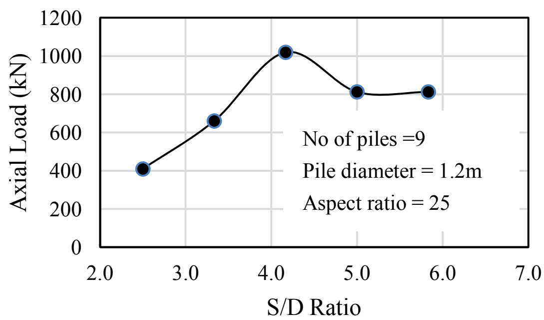

Fig. 3 Axial load vs pile S/D ratio

Figure 3 indicates axial capacity of the piles in the group increases with the s/d ratio up to about 4, irrespective of the pile diameter, and decreases by a relatively low rate.

At the closer spacing, the interaction between piles increases the axial capacity (reducing the carrying capacity) of the piled raft while at larger spacing the raft takes a significant portion of the load.

Further analysis was carried out to check the settlement behaviour of the pile group under the various pile spacing. Fig.4 presents the results of the analysis. Pile spacing of 4D provides minimum settlement of the group.

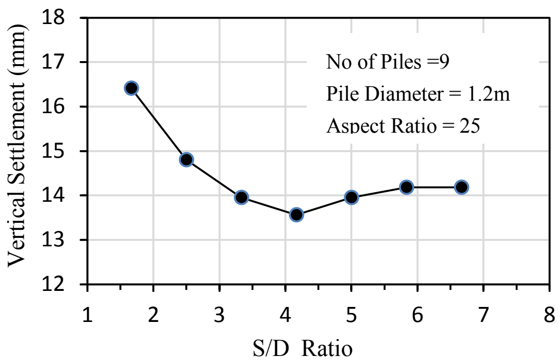

Fig. 4 Vertical settlement vs S/D ratio

5.3 *Pile aspect Ratio*

The analysis was carried out with varied aspect ratios (L/D) by keeping the optimum S/D ratio of 4 under the given working load of 12000kN. The significant influence on the total settlement of the piled raft foundation due to the variation of the aspect ratio is presented in Figure 5. This indicates that the total settlement decreases with the increase in aspect ratio and is less effective beyond the aspect ratio about 30. The settlement decreases more rapidly up to the aspect ratio of 30 and beyond this point the settlement decreases at a lower rate.

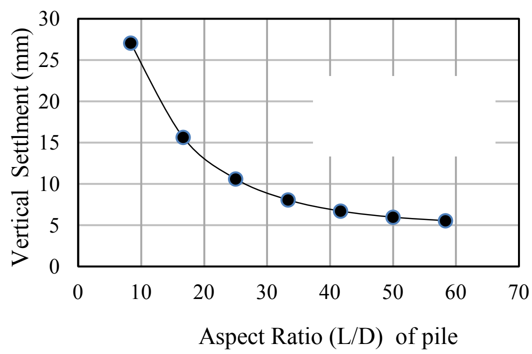

Fig. 5 Vertical settlement vs aspect ratio

The best value of the aspect ratio of the pile group can be considered between 25 and 30 in view of total settlement in this particular case. When comparing Fig. 4 and 5, it clearly indicates that increasing the length of the piles is a more effective design strategy for improving foundation performance than increasing the number of piles.

5.4 *Effect of Raft Thickness*

It is observed that raft thickness plays a vital role in controlling the deferential settlement of the foundation system. The assessment for optimum thickness of the piled raft system is required at the design stage to minimize the differential settlement. However, estimated thickness needs to be factored in to safeguard against punching shear. The study indicates that the proportion of load carried by the piles is not sensitive to raft thickness.

6 CONCLUSIONS

This paper has outlined an optimized piled raft foundation design based on geotechnical parameters adopted for the thick silty sand layer in a major flood plain. The following are the outcomes from the analyses:

1. The maximum settlement of the CPRF depends on the pile spacing and aspect ratio. The Raft thickness does not have a significant effect.
2. Total settlement reduces by 65% up to the aspect ratio of about 30 and further decreases at a slower rate towards the aspect ratio of 60.
3. The axial capacity of the pile increases with the pile S/D ratio and gradually reduces beyond S/D of 4.
4. The interaction between two piles in a CPRF is mainly dependant on the pile spacing and reduces at a relatively low rate beyond S/D ratio of 4.

ACKNOWLEDGMENTS

The Author thanks the Engineering & Technology Branch, Department of Transport and Main Roads, Queensland for their assistance with this paper.

REFERENCES

Poulos, H.G.2001 Method of analysis of piled raft foundations. Coffey Geoscience Pty, Ltd & University of Sydney, Australia.

Phung Duc Long 2010 Piled Raft – A cost effective foundation method for high rises, Geotechnical Journal of the SEAGS & AGSSES, Vol 41,pp.1-12.

Burland,J.B 1995 Piles as settlement reducers Keynote Address,18th Indian Congress on Soil Mechanics, Pavia ,Italy.

Randolph,M.F, 1994 Design method for pile group and pile raft, International Conference on Soil Mechanics and Foundation Engineering ,1994,Vol4,61-82,New Delhi, India.

Vesic,A.S 1969 Expedients with instrumented piles group in sand, Proc. Performance of deep foundation, ASTM,STP 444,s.177-222,1969.