Advancement of Bearing Capacity and Settlement Analyses of Piled-Raft Foundation

Krisnanto, S.[1], Sengara, IW.[2], Adelina, F. N.[3]
[1]*Assistant Professor, Bandung Institute of Technology (ITB), Bandung, Indonesia; Indonesian Society for Geotechnical Engineering (ISGE/HATTI)*
[2]*Professor, Bandung Institute of Technology (ITB), Bandung, Indonesia; Indonesian Society for Geotechnical Engineering (ISGE/HATTI).*
[3]*Research Student, Bandung Institute of Technology (ITB), Bandung, Indonesia.*
[1]*E-mail:* sugeng.krisnanto@ftsl.itb.ac.id
[1]*Website:* http://personal.ftsl.itb.ac.id/sugeng/

ABSTRACT: Piled-raft consists of pile group and raft. From the pile group point of view, the presence of raft provides an additional bearing capacity to the pile group. From the raft point of the presence of piles reduces the settlement of the raft. Bearing capacity and settlement of piled-raft foundation involve a complex soil-structure interaction. Since the pile configuration, pile stiffness, raft stiffness, and soil properties may vary, there are several combination of parameters involved in the piled-raft group foundation analysis. Several methods have been proposed in the analysis of piled-raft foundation. The methods vary in the way of treated the piles, raft, and soil. Generally, the methods consist of analytical method, numerical method, small-scale foundation test, and large-scale foundation test. This paper presents a review of the advancement of bearing capacity and settlement analysis of piled-raft foundation. The present as well as the classical methods of analysis are reviewed and discussed. The review shows that numerical method calibrated with small-scale laboratory lest is a promising method to analyse bearing capacity and settlement behaviour of piled-raft group.
Keywords: Piled-raft group, bearing capacity, settlement.

1. INTRODUCTION

Pile is used to sustain load from the upper structure when the ground soil strength is low by transferring the load to a soil layer that has enough strength (e.g. Poulos and Davis, 1980; Bowles, 1996; Tomlinson, 1994). In the practice, the piles are arranged in a group with a pile cap. The pile cap can be located above ground surface or in contact with ground surface.

In the case where the pile cap is in contact with ground surface, actually the cap can be considered as a raft. The pile cap may provide an additional bearing capacity to the pile group. Thus the system can be considered as a piled-raft group.

Piles can also be added to a raft foundation. In this condition, piles work to reduce settlement of a raft foundation that has enough bearing capacity but has an excessive settlement. The system can also be considered as a piled-raft group.

To obtain a general behaviour the bearing capacity and settlement of piled-raft group is difficult for the following reasons: (i) A large number of combination of pile group configuration can occur, (ii) A large number combination of pile group-raft stiffness can occur, (iii) The high load that is required to perform a full-scale load test, (iv) Different stress-strain behaviour between a small-scale and a full-scale tests.

This paper presents a summary of the advancement of bearing capacity and settlement analyses of piled-raft foundation. Several methods of analysis are reviewed and discussed. Finally the prospective method of analysis is recommended.

2. ANALYTICAL METHOD

Several analytical methods have been proposed to design piled-raft. Hain and Lee (1978) analysed the raft as a flexible elastic plate. The piles were modelled as compressible friction piles and the soil were modelled as elastic material. The effect of the piles to reduce settlement was analysed.

Davis and Poulos (1972) introduced an analytical method to calculate settlement of piled-raft group. The calculation of settlement of piled-raft group was based on the calculation of pile group settlement by considering the effect of pile cap. In the calculation of pile group settlement, the effect of settlement of one pile to other piles in the group was considered. The method was developed based on an elastic linear assumption. Thus, the piles, the pile cap, and the soil were in an elastic condition. Davis and Poulos (1972) also proposed a method to generate a simplified load-settlement curve of piled-raft group. In the proposed method, it was assumed that the load was carried by the pile group first and the corresponding settlement was then calculated. After the pile group reach its ultimate capacity, the remaining load was carried by the raft and the corresponding settlement was then computed. The load-settlement curve consisted of two linear sections: (i) The first linear section corresponds to the load-settlement of pile group; (ii) The second linear section corresponds to the load-settlement of raft.

Randolph (1983) proposed an analytical method to analyse the load proportion between the pile group and the raft and the settlement of piled-raft group based on average behaviour. The proportion of load carried by pile group and the raft can be computed incorporating the stiffness of the pile group and the stiffness of the raft.

Randolph (1994) introduced a parameter of the stiffness of piled-raft and an interaction factor. The proportion of load carried by the pile group and the raft can be computed using these factors.

3. NUMERICAL METHOD

Poulos (1991) idealized the raft in a piled-raft group as strip and the piles in a piled-raft group as springs. A computer program GASP (Geotechnical Analysis of Strip with Piles) was developed to accommodate the idealization.

Lee (1993) performed a piled-raft numerical analysis. Lade and Duncan-Chang stress-strain model were used to model the soil. Both piled-raft and raft foundations were analysed. Settlement of piled-raft group and bending moment of raft were obtained in this analysis.

Poulos (1994) performed numerical analyses of interaction among piles and between pile group and raft. The analysis was based on elastic condition. The analysis was incorporated in a computer program GARP (Geotechnical Analysis of Raft with Piles).

Ta and Small (1996) used finite element method to analyse piled-raft group. The analysis was a 2-D analysis incorporating the interaction factor. Therefore, the 3-D condition can be accommodated with lesser computation effort. The method was able to model a piled-raft group in layered soil.

Long, D. C. (2016) performed analysis on a building founded on piled-raft group. The analysis was performed using a commercial 3-D finite element software. In the analysis, it was assumed that the load was carried by the raft first. After the raft reached its ultimate capacity, the remaining load was then carried by the piles.

4. ANALYTICAL-NUMERICAL METHOD

Clancy and Randolph (1993) proposed an analytical-numerical method to calculate load carried by pile group, load carried by raft and settlement of piled-raft group. Piled-raft group was modelled numerically. The interaction factors among piles were calculated analytically. Settlement of piled-raft group can be obtained using this method.

5. SMALL-SCALE LABORATORY MODEL TEST

Sengara et al. (2018) performed a small scale laboratory tests. It was found that the load applied to the piled-raft group was shared between the pile group and the raft. In addition, it was observed that the higher the number of piles, the lower the settlement of piled-raft group. This trend indicated that the presence of piles reduces the settlement of the raft.

6. NUMERICAL METHOD SUPPLEMENTED BY SMALL-SCALE LABORATORY TEST

Long, P. D. (2011) performed laboratory tests of piled-raft small scale model. Based on these result, several buildings on piled-raft group were analysed with a commercial software. In the analysis it was assumed that when a piled-raft group was loaded, the load was carried firstly by the piles until the ultimate bearing capacity was reached. After the piles reach the ultimate bearing capacity, the remaining load was carried by the raft.

7. ANALYTICAL METHOD SUPPLEMENTED BY SMALL-SCALE LABORATORY TEST

Nguyen et al. (2013) proposed an analytical method to design piled-raft group. The interaction factor was proposed to calculate settlement and piles bending moment. The method was then calibrated with small-scale laboratory tests and centrifuge tests.

8. NUMERICAL ANALYSIS ON ACTUAL PILED-RAFT GROUP

Naylor and Hooper (1974) performed numerical analysis to predict the short- and long-term behaviour of piled-raft on London clay.

Sengara (1997) performed analysis on an actual piled-raft group. The load-settlement of single pile was measured in the field. A numerical analysis was then used to simulate the load-settlement curve. The simulated load-settlement curve was close to that obtained from field measurement. Although the analysis was performed on the load-settlement of single pile, the method of obtaining interface parameters for numerical analysis was thorough.

9. NUMERICAL METHOD SUPPLEMENTED BY LARGE-SCALE FIELD TEST

Hussein (2018) performed a large-scale field loading test on piled-raft group. The large-scale piled-raft group was then simulated in a 3-D numerical model. The numerical model was calibrated to obtain close results to the large-scale model.

10. DISCUSSION

The comparison of the previous analysis method is shown in Table 1. Generally the method of analysis of piled-raft group can be categorized as: (i) Analytical method; (ii) Numerical method; (iii) Small-scale laboratory model test method; (iv) Large-scale field model test or instrumentation on an actual piled-raft group. Several methods of analysis consist of more than one method.

Analytical method provides a strong theoretical basis. However, a closed form solution is not always available to accommodate a complex pile group configuration. In addition, it is not easy to vary pile group configuration in an analysis of piled-raft group using this method.

Table 1 Comparison of the previous methods of analysis

Method	Basis in Development of the Method			
	Analytic	**Numeric**	**Small-scale Lab. Model Test**	**Large-scale Field Model Test / Instrumentation on Actual Piled-Raft Group**
Naylor and Hooper (1974)		√		
Hain and Lee (1978)	√			
Davis and Poulos (1972)	√			
Randolph (1983)	√			
Poulos (1991)	√	√		
Clancy and Randolph (1993)	√	√		
Lee (1993)		√		
Poulos (1994a)		√		
Poulos (1994b)				
Randolph (1994)	√			
Ta and Small (1996)		√		
Long, P. D. (2011)		√	√	
Nguyen et al. (2013)	√		√	
Long, D. C. (2016)		√		
Hussein et al. (2018)				√
Sengara et al. (2018)			√	

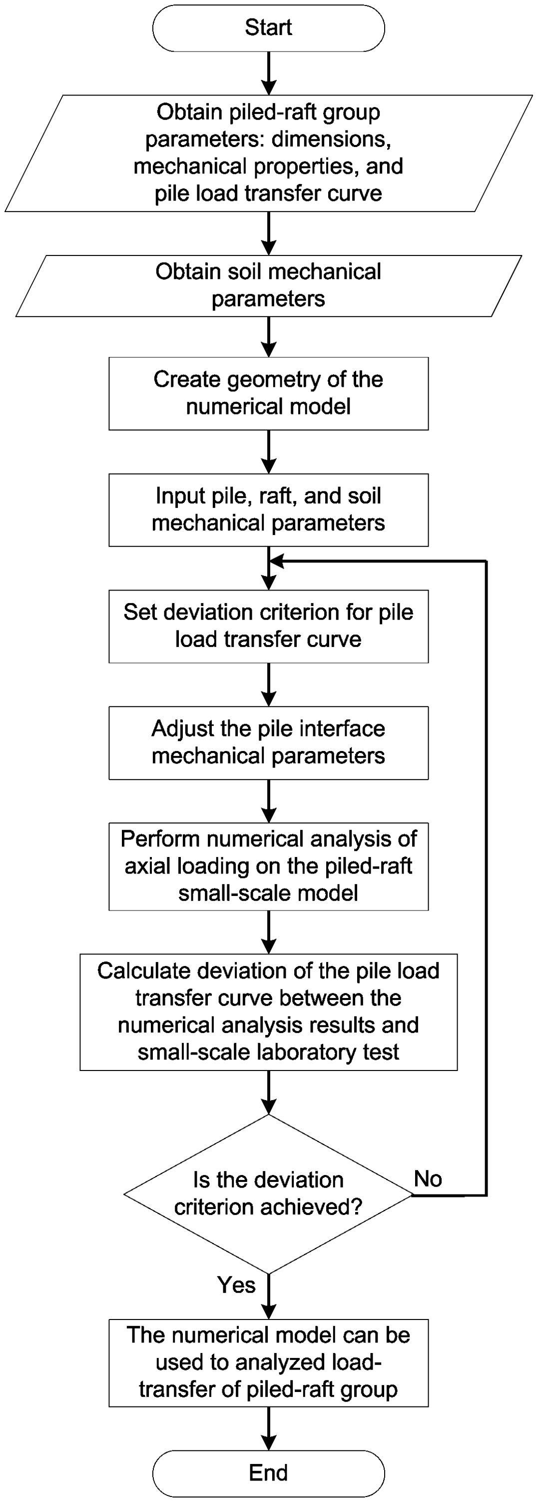

Figure 1 Preliminary flow diagram for the analysis using numerical method calibrated with small-scale laboratory test

In the numerical methods, the pile group configuration can be varied and analysed easily. Thus, this method can accommodate the weakness of the analytical method. However, to obtain representative input parameters in the numerical analysis is not easy. A calibration process between the numerical analysis and full-scale or small-scale model tests is required to obtain the representative parameters.

Full-scale model test is the technically best among the methods considered in this paper. This method can simulate the stress-strain condition in the actual foundation. However, the method costs the most among the methods considered in this paper. The amount of material and the instrumentations require high cost.

Considering both the technical performance of analysis and the cost of analysis, numerical method calibrated with small-scale laboratory tests is a promising method to analyse bearing capacity and settlement behaviour of piled-raft group. A laboratory small-scale test can be used to calibrate the numerical model. The numerical analysis can then be used to analysis several pile group configurations as well as the pile group and raft stiffness's in a piled-raft group. A scaling analysis (e.g. Altaee and Fellenius, 1994) can be performed to convert the small-scale stress-strain condition to the full-scale stress-strain condition.

A preliminary flow diagram for the analysis using numerical method calibrated with small-scale laboratory test is shown in Figure 1. The piled-raft group parameters and soil mechanical parameters are first obtained. The load-settlement curve and the load distribution along the piles are then obtained. The numerical model is then created incorporating the piled-raft group, soil, and soil-pile interface parameters. The numerical analysis is then performed and the soil-pile interface parameters are then adjusted so that the deviation between the load-transfer and load distribution along piles between the laboratory test results and numerical analysis results are within the deviation criteria. Once the deviation criteria are satisfied, the soil strength and interface parameters can be used to analyse piled-raft group model with different configurations and dimensions.

Laboratory test is one important key in the proposed method of analysis shown in Figure 1. How far the piled-raft group configurations and dimensions in the numerical model can be extended from the calibrated numerical model need to be investigated. Further research is still required related to these matters.

11. CONCLUSIONS AND RECOMMENDATIONS

1. In general, the methods of analysis of piled-raft groups consist of four categories: (i) Analytical method; (ii) Numerical method; (iii) Small-scale laboratory model test; (iv) Full-scale field model test or actual instrumentation on actual piled-raft group.
2. A method of analysis of piled-raft group can be consisted of one category or combination from two or more categories.
3. Considering both the performance of analysis and the cost of analysis, numerical method calibrated with small-scale laboratory tests is a promising method to analyse bearing capacity and settlement behaviour of piled-raft group.
4. A flow diagram for the analysis using numerical method calibrated with small-scale laboratory test is proposed from this study. The analysis start with obtain the piled raft group parameters (dimension, mechanical properties, and pile load transfer curve) and soil mechanical parameters (shear strength and stress-strain relationship), followed by create a numerical model. The pile interface mechanical parameters are then adjusted to fit with the results of small-scale laboratory test.
5. Further research is still required to obtain more laboratory small-scale data as well as to investigate how far the piled-raft group dimensions in the numerical model can be extended from the calibrated numerical model.

12. REFERENCES

Altaee, A. and Fellenius, B. H. (1994) "Physical modeling in sand", Canadian Geotechnical Journal, Vol. 31, No. 3, pp. 420-431.

Bowles, J. E. (1996) Foundation Analysis and Design, Fifth Edition, McGraw Hill, New York, 1175 p.

Clancy, P. and Randolph, M. F. (1993) "An approximate analysis procedure for piled raft foundations", Int. Journal for Numerical and Analytical Methods in Geomechanics, Vol. 17, pp. 849-869, DOI: https://doi.org/10.1002/nag.1610171203.

Davis, E. H. and Poulos, H. G. (1972) "The Analysis of pile-raft systems", Australian Geomechanics Journal, Vol. G2, No. 1, pp. 21-27.

Hain, S. J. and Lee, I. K. (1978) "The analysis of flexible raft-pile systems", Géotechnique, Vol. 28, No. 1, pp. 65-83, DOI: https://doi.org/10.1680/geot.1978.28.1.65.

Hussein H. H., Karim H. H., Shlash K. T. (2018) "Theoretical verification for full-scale tests of piled raft foundation", Advances in Analysis and Design of Deep Foundations, GeoMEast 2017, Sustainable Civil Infrastructures Abu-Farsakh M., Alshibli K., Puppala A. (Eds). Springer, Cham, pp. 200-212, DOI: https://doi.org/10.1007/978-3-319-61642-1_16.

Lee, I. K. (1993) "Analysis and performance of raft and raft-pile systems", Proc. 3rd Int. Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, pp. 1331-1345.

Long, D. C. (2016) "Prediction of piled raft foundation settlement – a case study", Geotechnical Engineering Journal SEAGS & AGSSEA, Vol. 47, No. 1, pp. 1-6.

Long, P. D. (2011) "Piled raft - A new foundation philosophy for high rise buildings", Proc. 1st International Conference Geotechnics for Sustainable Development - Geotec, Phung (Eds.), Construction Publishing House, Hanoi, pp. 267-276.

Naylor, D. J., Hooper, J. A. (1974) "An effective stress finite element analysis to predict short and long-term behavior of a piled-raft foundation on London clay", Proc. Conference on Settlements of Structures, Cambridge, pp. 394-402.

Nguyen, D. D. C., Jo, S-B., and Kim, D. S. (2013) "Design method of piled-raft foundations under vertical load considering interaction effects", Computers and Geotechnics, Vol. 47, pp. 16-27, DOI: http://dx.doi.org/10.1016/j.compgeo.2012.06.007.

Poulos, H. G. (1991) "Analysis of piled strip foundation", Computer Methods and Advances in Geomechanics: Proceedings of the Seventh International Conference on Beer et al. (Eds.), Balkema, Rotterdam, Vol. 1, pp. 183-191.

Poulos, H. G. (1994) "An approximate numerical analysis of pile-raft interaction", Int. Journal for Numerical and Analytical Methods in Geomechanics, Vol. 18, Issue 2, pp. 73-92, DOI: https://doi.org/10.1002/nag.1610180202.

Poulos, H. G. and Davis, E. H. (1980) Pile Foundation Analysis and Design, John Wiley & Sons, New York, 397 p.

Randolph, M. F. (1983) Design of Piled Raft Foundations, Dept. of Engineering Cambridge Univ, 34 p.

Randolph, M. F. (1994) "Design and Performance of a Piled Raft Foundation", Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, Vol. 5, pp. 61-82.

Sengara, I. W., Roesyanto, Krisnanto, S., Jayaputra, A. A., and Irsyam, M. (2018) "Settlement and bearing capacity study on small-scale piled-raft foundation in sand," accepted for publication in 2018 in Geotechnical Engineering, South East Asian Geotechnical Society (SEAGS) & Association of Geotechnical Societies in South East Asia (AGSSEA), Bangkok, Thailand.

Sengara, IW. (1997) "FE analysis and field load test performance of drilled shaft for 52-story tower foundation design", Proc. Third Asian Young Geotechnical Conference, Singapore, pp. 295-304.

Ta, L. D. and Small, J. C. (1996) "Analysis of piled raft systems in layered soils", International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 20, No. 1, pp. 57-72,DOI:https://doi.org/10.1002/(SICI)1096-9853(199601)20:1<57::AID-NAG807>3.0.CO;2-0.

Tomlinson, M. J. (1994) Pile Design and Construction Practice, Fourth Edition, E & F N Spon, London, 411 p.