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An Analytical Study of Piled Raft Foundations: Design and Applications

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Abstract* – *The design concepts given by various researchers on pile-raft foundation is reviewed and described in this paper. It was found out that connected pile raft foundation (CPRF) helps in reducing differential settlement and to some extent overall settlement by locating piles strategically beneath the raft. Unconnected pile raft foundation (UCPRF) as described by Al Ataa et al is also reviewed. He observed that cushion helped in distribution of load beneath the raft. Favorable conditions for UCPRF are similar to that of CPRF. But UCPRF was found relatively less effective (depending on different conditions) foundation system. Author proposes a future scope of combination of CPRF and UCPRF as effective and economical foundation system.

In situations where a raft foundation alone does not satisfy the design requirements, it may be possible to enhance the performance of the raft by the addition of piles. The use of a limited number of piles, strategically located, may improve both the ultimate load capacity and the settlement and differential settlement performance of the raft. This paper discusses the philosophy of using piles as settlement reducers and the conditions under which such an approach may be successful. Some of the characteristics of piled raft behaviour are described. The design process for a piled raft can be considered as a three-stage process. The first is a preliminary stage in which the effects of the number of piles on load capacity and settlement are assessed via an approximate analysis. The second is a more detailed examination to assess where piles are required and to obtain some indication of the piling requirements. The third is a detailed design phase in which a more refined analysis is employed to confirm the optimum number and location of the piles, and to obtain essential information for the structural design of the foundation system. The selection of design geotechnical parameters is an essential component of both design stages, and some of the procedures for estimating the necessary parameters are described. Some typical applications of piled rafts are described, including comparisons between computed and measured foundation behaviour.

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INTRODUCTION

It is common in foundation design to consider first the use of a shallow foundation system, such as a raft, to support a structure, and then if this is not adequate, to design a fully piled foundation in which the entire design loads are resisted by the piles. Despite such design assumptions, it is common for a raft to be part of the foundation system (e.g because of the need to provide a basement below the structure). In the past few years, there has been an increasing recognition that the use of piles to reduce raft settlements and differential settlements can lead to considerable economy without compromising the safety and performance of the foundation. Such a foundation makes use of both the raft and the piles, and is referred to here as a pileenhanced raft or a piled raft. One of the Technical Committees of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) focussed its efforts in the period 1994-7 towards piled raft foundations, collected considerable information on case histories and methods of analysis and design, and produced comprehensive reports on these activities (O'Neill et. al., 1996; van Impe & Lungu, 1996).

This paper describes the philosophy of design of pile-enhanced rafts, and outlines circumstances that are favourable for such a foundation. A three-stage design process is proposed, the first being an approximate preliminary stage to assess feasibility, the second to assess the locations where the piles are required, and the third to obtain detailed design information.

Methods of analysis are described and compared, and some of the key characteristics of piled raft behaviour are described. The assessment of the required geotechnical parameters is then outlined, and finally a number of applications of piled raft foundations are presented.

With the advent of skyscrapers or high rise buildings there was need to study and improve deep foundation system to reduce cost of foundation and make it more reliable Development of Deep foundation system started from bearing piles, skin friction piles, combination of both and eventually pile-raft foundation.. Currently pile raft foundation system is widely used. There are mainly three design philosophies in pile raft foundation proposed by Randolph are as follows.

1) Conventional approach in which piles are designed as group to carry the major load, while making some allowance for the contribution of the raft primarily to ultimate load capacity

2) Creep pilling in which piles are designed to operate at working load at which significant creep start to occur (around three-fourth of the ultimate load capacity). Sufficient piles are included to reduce the net contact pressure between raft and soil.

3) Differential settlement control, in which piles are located strategically to reduce the differential settlement rather than to reduce overall settlement substantially.

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One of the most important aspects of a civil engineering project is the foundation system. Designing the foundation system carefully and properly, will surely lead to a safe, efficient and economic project overall. In other words, foundation system design is one of the most critical and important step when a civil engineering project is considered. Until quite recently, there were some separately used systems like shallow foundations such as rafts and deep foundations such as piles. However, lately the foundation engineers tend to combine these two separate systems. By combining these two systems, the foundation engineer will provide the necessary values for the design, obtain the required safety and also come out with a more economical solution.

The conventional pile design philosophy is based on that piles carry all the load and they are accepted as a group, no contribution is made by the raft to the ultimate load capacity. The new trend in the foundation engineering is combining raft foundations and pile foundations. The combined system can be based on different design philosophies which can be classified as follows:

1) Settlement reducing pile concept: In this philosophy, piles are only located to reduce the total settlement and they are designed to work at limiting equilibrium, in other words, for the piles, factor of safety values against bearing capacity is taken as unity.

2) Piled raft concept: This philosophy is one of the newly adopted concepts in which a significant portion of total load is carried by the raft contrarily to the conventional design. Piles are designed to work at 70-80% of the ultimate load capacity.

3) Differential settlement control: Placing piles under the raft strategically and of course in a limited number will enhance the ultimate load capacity of the foundation and decrease both the settlement and the differential settlement.

CONNECTED PILE RAFT FOUNDATION

Zhuang and Lee used finite element method to study the load sharing between pile and raft. They observed that load sharing between piles in pile raft system was affected by pile stiffness, raft rigidity and pile length to diameter ratio. They also observed that as the pile length increases the pile rigidity decreases and the load distribution becomes more uniform. Ta and Small, developed a method which was based on finite layer method, for the analysis of pile raft foundation in layered soil. They found that load sharing between piles in the pile raft system was influenced by thickness and stiffness of soil layer. Load shared by piles increases as the bearing strata becomes stiffer. Russo developed a numerical method for piled raft system, which takes into consideration non-linearity of the uni-lateral contact at the raft–soil interface and the nonlinear load–settlement relationship. They stated that non-linear analysis should be considered for the piled raft system because piles act as settlement reducers and their ultimate load capacity may be reached. Reul and Randolph observed that pile raft interaction leads to an increase in the pile friction with an increase of the load or increase of the settlement.

Figure 1 clarifies the different approaches for pile design. Curve 0 represents the case where only raft is used as foundation leading to excessive settlement at design load. Curve 1 shows conventional approach of design in which all the loads imposed on foundation from superstructure is considered to be taken only by piles. Apart from this if the hard stratum is at a considerable depth use of longer length of a pile contributes to twisting moment on foundation and results in uneconomical practice.

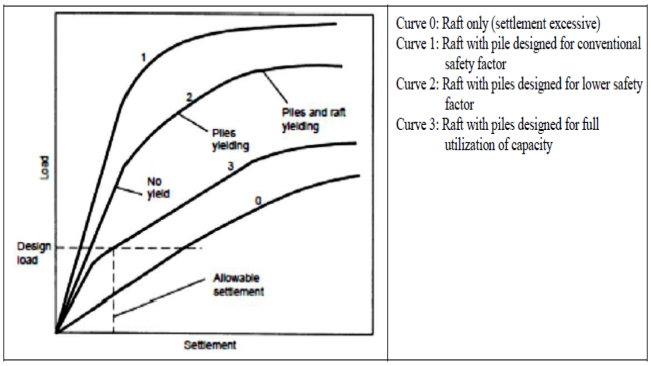

Figure 1: Load-settlement curves for piled rafts according to various design philosophies.

In curve 2 lower safety factor is considered for design and as there are fewer number of piles are used, raft carries a considerable load. Curve 3 represents the case in which piles are positioned in such a way to act as a settlement reducers. Even though there is more settlement at design load compared to first two cases, it is acceptable and method is economical.

Soil strata consisting of relatively stiff clay or dense sand is the favorable condition for pile raft foundation. On the other hand soft clay, loose sand, soil strata which consist of soft compressible layers at comparatively shallow depth, soil strata which will undergo consolidation settlement (resulting in soil shrinkage) and soil profile which is likely to undergo swelling due to external causes are unfavorable for pile raft.

The three design processes considered by him are as follows:-

(a) Preliminary stage to assess the feasibility of using a piled raft, and the required number of piles to satisfy design requirements

(b) Second stage to assess where piles are required and the general characteristics of the piles

(c) Final detailed design stage to obtain the optimum number, location and configuration of the piles, and to compute the detailed distributions of settlement, bending moment and shear in the raft, and the pile loads and moments.

CLASSIFICATION OF METHODS OF ANALYSIS

Several methods of analyzing piled rafts have been developed, and some of these have been summarized by Poulos et al (1997). Three broad classes of analysis method have been identified:

- Simplified calculation methods
- Approximate computer-based methods
- More rigorous computer-based methods.

Simplified methods include those of Poulos and Davis (1980), Randolph (1983,1994), van Impe and Clerq (1995), and Burland (1995). All involve a number of simplifications in relation to the modelling of the soil profile and the loading conditions on the raft.

The approximate computer-based methods include the following broad approaches:

- Methods employing a “strip on springs” approach, in which the raft is represented by a series of strip footings, and the piles are represented by springs of appropriate stiffness (e.g. Poulos, 1991)
- Methods employing a “plate on springs” approach, in which the raft is represented by a plate and the piles as springs (e.g. Clancy and Randolph, 1993; Poulos, 1994; Viggiani, 1998; Anagnastopoulos and Georgiadis, 1998).

The more rigorous methods include:

- Boundary element methods, in which both the raft and the piles within the system are discretized, and use is made of elastic theory (e.g. Butterfield and Banerjee, 1971; Brown and Wiesner, 1975; Kuwabara, 1989; Sinha, 1997)
- Methods combining boundary element for the piles and finite element analysis for the raft (e.g. Hain and Lee, 1978; Ta and Small,

1996; Franke et al, 1994; Russo and Viggiani, 1998)

- Simplified finite element analyses, usually involving the representation of the foundation system as a plane strain problem (Desai,1974) or an axi-symmetric problem (Hooper, 1974), and corresponding finite difference analyses via the commercial program FLAC (e.g. Hewitt and Gue, 1994)

- Three-dimensional finite element analyses (e.g. Zhuang et al, 1991; Lee, 1993; Wang, 1995; Katzenbach et al, 1998) and finite difference analyses via the commercial program FLAC 3D.

3-D MODELING OF PILED RAFT FOUNDATION

The function of any foundation is to transmit the load to the soil in order to provide safety, reliability and serviceability to the structure. Current practice is to provide a deep foundation, when the shallow foundation is not sufficient to provide adequate safety and reliability. However, a combination of the shallow and deep foundation can be a cost effective design approach. The pile raft foundation is such a combination of a deep pile group and a shallow raft foundation, which has gained increasing recognition in very recent years.

It is evident from the available literature that the piled raft foundation was constructed about fifty years ago and the attempt to capture its behavior was started in the early eighties, which has intensified in the last few years, but no appropriate design strategy has been formulated yet. This is because of the complex interactions among the raft, pile and soil, which is three dimensional in nature and cannot be captured by any analytical method so far developed. With the advancement of computer technology and numerical code, the researchers are now trying to model the complex behavior of pile raft foundation.

COMBINED PILE-RAFT FOUNDATION (CPRF)

Combined Pile-Raft Foundation (CPRF) has been widely recognized as economic and rational foundation for high rise buildings when subjected to vertical loading due to its effectiveness in load sharing by both raft and pile components. Adequate design of CPRF subjected to vertical load considering raft resistance reduces number, length or diameter of piles without compromising the safety of the foundation. This concept have been extensively used in Germany, Japan, UK and many other countries for its overwhelming performance under unfavorable ground condition (Yamashita 2012). International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) published international guideline for CPRF design, construction and practice (Katzenbach and Choudhury (2013)). For seismically vulnerable areas, it is important to secure the safety of foundations during expected earthquake in the design process. One of the practical and conventional design techniques is the application of equivalent static horizontal loads at the top of CPRF to analyze the load sharing response and checking connection sensitivity by using different connection conditions between raft and piles. In the last decade, centrifuge modelling of CPRF subjected to static lateral loading and shaking, shaking table tests of small sized piled raft with and without superstructure, static lateral or cyclic loading test or large scale test (Sawada and Takemura, 2014) and analytical studies (Choudhury et al. 2015) have been carried out. These experiments and analyses results are available for various pile head connection conditions ranging from fully hinged to fully rigid and it has been observed that connection condition is one of the key factors affecting the behavior of CPRF during static, horizontal loading and shaking. However, design and analysis of CPRF having different connection condition when subjected to horizontal and seismic loading in addition to vertical load is not well understood till now due to complexities involved in the interaction of pile, soil and raft under such loading and connection considerations.

CONCLUSION

This paper demonstrates that the design of piled raft foundation systems can be carried out as a three-stage process, involving a preliminary design phase to obtain an approximate assessment of the required number of piles, a second phase to assess where piles may be required, and a detailed design phase to refine piling requirements and locations and provide information for the structural design of the foundation.

Piled raft foundations have the potential to provide economical foundation systems, under the appropriate geotechnical conditions. Further analysis may be carried out to investigate whether a combination of UCPRF and CPRF proves to be economical. By providing connected pile system at a critical location (critical location is to be identified through modeling or other appropriate method), the differential settlement can be reduced. To reduce overall settlement, cushion of higher thickness with relatively higher modulus of elasticity shall be provided. But if we opt for higher elastic modular cushion the section tends to be uneconomical. So combination of two or more different materials (thus different elastic modulus) shall be used.

REFERENCES

Ahner, C., and Soukhov, D., (1999). “Safety Concept in Codified Design of piled raft foundation (CPRF)”, LACER 4, pp. 403 - 412. Universität Leipzig

Anagnostopoulos, C. & Georgiadis, M. (1998). A simple analysis of piles in raft foundations. Geotech. Engng 29, No. 1, pp. 71-83.

Anagnostopoulos, C. and Georgiadis, M. (1998). A Simple Analysis of Piles in Raft Foundations". Geot. Eng., Vol. 29 (1), pp. 71-83.

Castelli, F., and Di Mauro, F., (2003). Numerical analysis of piled raft foundations, BGA International Conference on Foundations, Thomas Telford Publishing, UK, pp.187-196

Choudhury D, Phanikanth VS, Mhaske SY, Phule RR, Chatterjee K. (2015). Seismic liquefaction hazard and site response for design of piles in Mumbai city. Indian Geotechnical Journal; 45(1): pp. 62-78.

Chow H.S.W., Small J.C (2006). "Analysis of Piled Raft Foundation with Piles of Different Lengths Subjected to Horizontal and Vertical Loading", NIMGE, Porc.6th European Conf. on NUMGE, Graz, Austria, 6-8 September, 2006, pp. 583 – 588.

Chow H.S.W., Yong K.Y. (2001). "Analysis of Pile Raft Foundation Using a Variational Approach", ASCE, International Journal of Geomechanics, vol. 1 no.2, pp. 129-147.

Clancy, P. & Randolph, M. F. (1993). Analysis and design of piled raft foundations. Int. J. NAM Geomech.

Hamada J, Tsuchiya T, Tanikawa T, Yamashita K. (2011). Lateral loading test on piled raft foundation at large scale and their analyses. International Conference on Advances in Geotechnical Engineering, Nov. 7-9; pp. 1059-1064.

Katzenbach K, Choudhury D. (2013). ISSMGE Combined Pile-Raft Foundation Guideline. International Society for Soil Mechanics and Geotechnical Engineering, ISSN: 1436-6517, ISBN: 978-3-942068-06-2: pp. 1-28.

Katzenbach K., Choudhury D. (2013). ISSMGE Combined Pile-Raft Foundation Guideline. International Society for Soil Mechanics and Geotechnical Engineering, ISSN: 1436-6517, ISBN: 978-3-942068-06-2: pp. 1-28.

Poulos H. G. (2001). Pile raft foundations: design and applications. Geotechnique, 51 (2): pp. 95-113.

Poulos, H.G. (2001). Piled Raft Foundations – Design and Applications. Geotechnique, Vol. 50, (2): pp. 95-113.

Poulos, H.G., (2001). Piled raft foundations: design and applications, Géotechnique, Vol.51, No.2, pp. 95-113

Sawada K, Takemura J. (2014). Centrifuge model test on piled raft foundation in sand subjected to lateral and moment loads. Soils and Foundations, 54(2): pp. 126-140.

Solanki C. H., Vasanvala S.A., Patil J. D. (2013). A study of piled raft foundation: state of art. Int J Eng Res Technol (IJERT) 2013 ;2(8); pp. 1464-70.

Yamashita K. Field measurements on piled raft foundation in Japan. Proc. Of 9th Conf. on Testing and Design method of Deep foundation: IS-Kanazawa 2012, pp. 79-94.

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