BEHAVIOUR OF PILED RAFT FOUNDATION IN COHESIVE SOIL- AN OVERVIEW

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Abstract: In recent years, an increasing number of structures especially tall buildings have been founded on problematic soil. Raft foundations are widely used in supporting structures when relatively strong layers are present at shallow depth. Sometimes, although the shallow layers of soil have an adequate bearing capacity, a raft foundation can induce excessive settlements. In such cases, piled rafts (raft foundations enhanced with piles) are used. While the loads are assumed to be carried by the raft, piles are included for reducing raft settlement. The piles can be arranged to reduce differential settlement in the raft. The concept of using piles to reduce raft settlement was first proposed by Burland et al. (1977) who placed one pile under each column of a building. The analysis of piled raft foundations embedded in a cohesive soil/layered cohesive soil profile is still a challenge for most of the simplified methods, since they generally model the subsoil as a homogeneous half space. In the design practice, on the contrary, layered soil profiles need often to be modelled and solved. Raft foundations are often subjected to eccentric and inclined loading because of the influence of lateral loads cause as a result of high wind and seismic actions. So that it may create tilt in the structures particularly in case of tall buildings. Cooke (1986) carried out experimental work on unpiled raft, free standing pile group and piled raft of different size in stiff clay and found that piled raft stiffness increases by 30% than that of free standing pile group. Horikoshi (1995) and Randolph (1996) carried out centrifuge test on model piled raft in clay and found that it reduces settlement and differential settlement of raft.

Keywords: *Piled Raft Foundation, Cohesive Soil, Settlement, Experimental Model, Finite Element Modeling.*

1 Introduction

Foundation of tall buildings and bridges are subjected to high lateral loads along with other vertical loads coming from the superstructure. In such case, to increase the load bearing capacity of such foundation system and to decrease the corresponding vertical and lateral deflection piles may be employed along with raft footing. The use of a piled raft as the foundation for buildings has proven to be an effective and economic way to control total and differential settlements as well as improving bearing capacities. The piles are used not only to ensure the stability of the foundation but to act as settlement reducers (Burland et al., 1977). Piled Raft Foundation is an attractive foundation system which allows the load to be shared between the raft and the piles, thereby offering a more economical solution and provides stability on problematic soil. In piled raft foundations, loads are transferred to the soil through the raft and the piles. Unlike the conventional pile foundation design in which the piles are designed to carry the majority of the load, the design of a piled raft foundation allows the load to be shared between the raft and piles and it is necessary to take the complex soil-structure interaction effects into account.

Different techniques have been developed which account for the interactions between the piles, raft and soil (Davis and Poulos, 1972; Hain and Lee, 1978; Kakurai et al., 1987). Most of the research emphasis has been on reducing settlements of the foundation and the relative proportion of the load carried by the piles and the raft. However, the behavior of piles underneath piled rafts is of importance to the performance of the foundations. The settlement of the piled raft foundations as well as the distribution of loads, bending moments, deflections and soil reaction in the pile are important factors in the design to achieve the objective of economic construction with satisfactory performance.

The principle objective of this research paper is to present a brief review of different studies done on piled raft foundation in cohesive soil and layered soil. Their work consists of experimental model and numerical analysis on piled raft foundation in cohesive and layered soil.

2 Literature Review

As compared to a full pile solution, pile assisted raft has a major advantage of substantial reduction in number of piles, which in turn results in savings of cost and time. Poulos (2001) indicated that the 3D numerical modeling is the most reliable and accurate method for the analysis of the piled raft foundation in a clay soils. The maximum settlement, differential settlement, raft bending moments and shear force, pile bending moments are considered as crucial parameter for optimum design of piled raft foundation. Several researchers have been investigated the settlement (Prakoso and Kulhawy, 2001; Cho et al., 2012; Sinha and Hanna, 2016) and bearing behavior (Reul, 2004; Sanctis and Mandolini, 2006; Lee et al., 2010) of a piled raft foundation in clay soils by numerical modeling.

Several reports were published on the use of piles as settlement reducers by Clancy and Randolph (1993), Randolph (1994), Horikoshi and Randolph (1996), Kim et al. (2001), Prakoso and Kulhawy (2001), Poulos (2001), Cunha et al. (2001), Small and Zhang (2002), Reul and Randolph (2004). So that some literature survey are important to study for finding out some insights and indepth knowledge about Piled Raft Foundation which is discribed below:

Luca de Sanctis and Alessandro Mandolini [28] explained their work based on both experimental evidence and three- dimensional finite element analyses, a simple criterion is proposed to evaluate the ultimate vertical load of a piled raft as a function of its component capacities. The results presented in this paper provides a guide to assess the safety factor of a vertically loaded piled raft. This paper reports the results of recent research based on numerical modeling, and is aimed at studying the factors controlling the interaction between raft, soil, and piles when approaching failure. The investigation reported in this paper is aimed to evaluate the bearing capacity of a vertically loaded piled raft from the separate ultimate capacities of its components (the raft and the pile group). The safety factor of a piled raft is slightly lower than the sum of the two safety factors of the unpiled raft and the uncapped pile group. An important implication for design is following:

For a piled raft loaded by Q, it is possible to define three different factors of safety: For the unpiled raft ($FS_{UR}= Q_{UR,ult} /Q$), for the pile group ($FS_G=Q_{G,ult} /Q$), and for the piled raft ($FS_{PR}=Q_{PR,ult} /Q$). Their ratio $FS_{PR}/ (FS_{UR}+FS_G)$ is always equal to ξ_{PR}, independent of the selected value for Q (or, equivalently, w),

$$\xi_{PR} = \frac{Q_{PR,ult}}{Q_{UR,ult} + Q_{G,ult}} = \frac{FS_{PR}}{FS_{UR} + FS_G} \tag{1}$$

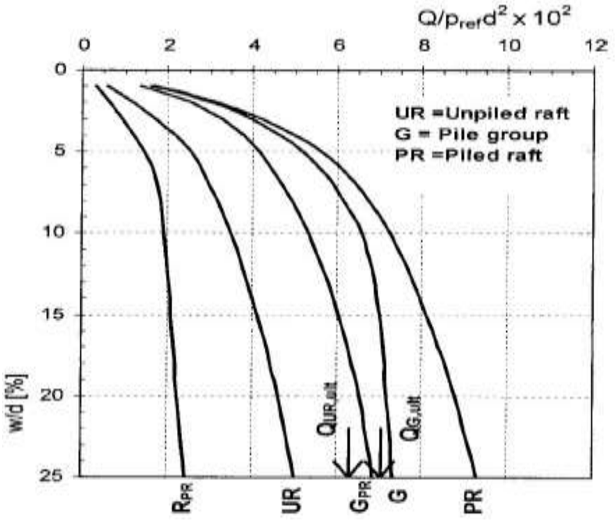

Fig. 1. Normalized Load- Settlement Relationship for the Piled Raft on 25 Piles with *BR/d= 20; L/d= 20; s/d= 4* **[28]**

Donggyu Park and Junhwan Lee [11] investigated various interaction effects and load carrying behavior of piled rafts embedded in clay. For this purpose, a series of centrifuge load tests were conducted using different types of model foundations including single pile, group piles, piled raft and unpiled raft. Different clay conditions were considered to prepare for centrifuge specimens. It was found that the pile group effect in clays is significant within initial loading range showing lower load carrying capacity. As settlement increases, the pile group effect becomes less pronounced. For both soft and stiff conditions, the values of R- P interaction factor varied initially, which became converged to some values around unity with increasing settlement. Similar tendency was observed for the P-R interaction factor. For the stiff condition, the corner and inner piles showed the highest and lowest load carrying capacities, respectively, due to piled raft interaction effects. Correlations to cone resistance were analyzed and presented for the base and shaft resistance of piles for piled rafts.

Considering the interaction effects, the load capacities of unpiled raft and group piles as follows:

$$Q_{pr} = \eta_r \cdot Q_{ur} + \eta_p \cdot Q_{gp} = \eta_r \cdot Q_{ur} + \eta_p \, \chi_g \sum Q_{sp} \tag{2}$$

Where, Q_{ur} and Q_{gp} = load capacities of unpiled raft and group piles; η_r and η_p = pile-to-raft (P-R) and raft-to-pile (R-P) interaction factors; and χ_g = pile-to-pile (P-P) interaction factor; and Q_{sp} = load capacity of single pile. It should be noted that all load components given in Eq. (2) are specified at the same settlement level. The pile-to-pile interaction factor, χ_g, is also referred to as the pile group effect factor that is often adopted to estimate the load capacity of group piles. The P-R and R-P interaction factors *(*η_r *and* η_p*)* represent changes in load capacities of raft and piles in comparison to those of unpiled raft and group piles.

$$\eta_r = 1 - 3\left\{\frac{\left(\frac{A_g}{A}\right)}{\left(\frac{s_p}{B_p}\right)}\right\} \tag{3}$$

where A_g = area defined by perimeter line of piles; A = raft area; s_p = center-to-center pile spacing distance; and B_p = pile diameter.

Ali-Asghar Zekavati and Alireza Khodaverdian [5] investigated the behavior of micropiled raft in power transmission line tower foundations in cohesive soil, concentrating on their uplift performance whether due to the tower position along the line or under wind loading conditions. In this regard, first a number of micropiles were driven into the ground of a project site at the Parehsar power plant, Gilan, Iran. Compression and uplift loading tests were conducted according to relevant standards.

On the basis of the field data, a 3D finite element model was developed and subsequently calibrated and verified. The behavior of micropiled rafts subjected to uplift, which is a typical type of loading in foundations of 230 kV four- circuit lattice towers, was then studied by means of this model in terms of a wide- ranging parametric study. In the sensitivity analyses, the impacts of various parameters, such as micropile spacing to diameter *(s/d)* and length to diameter *(l/d)* ratios along with undrained shear strength of the soil have been investigated on the uplift capacity of an individual micropile within and out of the group. Furthermore, interaction factors were computed based on diverse values for undrained shear strength of the soil, *s/d* ratio, *l/d* ratio, and grout-soil adhesion.

From design and analysis perspectives, the FEM outputs revealed that the efficiency coefficient of micropiled raft during uplift can be considered equal to one. Moreover, it was found that not only does the behavior of micropiles affect the neighboring micropiles immediately adjacent to the loaded one, it also influences those in further rows, the result of which would be considering their significance as well.

Francesco Basile [13] proposed 3D boundary element solution for computing the non-linear response of piled rafts to vertical loads. The validity of the analysis is demonstrated through comparison with alternative numerical solutions and field measurements. The key feature of the proposed approach of this paper lies in its computational efficiency which makes the analysis economically viable not only for the design of piled rafts supporting high rise buildings (generally based on complex and expensive 3D FEM or FDM analyses) but also for that of bridges, viaducts and normal buildings.

In this paper, it has been shown that the concept of piled raft, generally adopted for ‘‘large’’ flexible piled rafts, can also be applied effectively to ‘‘small’’ rigid piled rafts (and to any larger piled raft in which the assumption of rigid raft is valid), making PGROUPN- software ideally suitable to a wide range of foundations such as bridges, viaducts, wind turbines and ordinary buildings (where use of 3D FEM or FDM analyses would be uneconomical). Non- linear soil behaviour is modelled, in an approximate manner, by assuming that the tangent soil Young’s modulus (E_{tan}) varies with the raft- soil interface stress (t) according to the common hyperbolic stress- strain law:

$$E_{tan} = E_i \, (1 - R_f \, t/t_{lim})^2 \tag{4}$$

Shivanand Mali and Baleshwar Singh [45] presented numerical simulation of large piled raft foundation through 3D finite element modeling by means of PLAXIS-3D software. The objective of this research work is to investigate the effect of pile spacing, pile length, pile diameter and raft- soil stiffness ratio on the settlement, load-sharing, bending moments, and shear force behavior of large piled raft foundation subjected to vertical load on a clay soil.

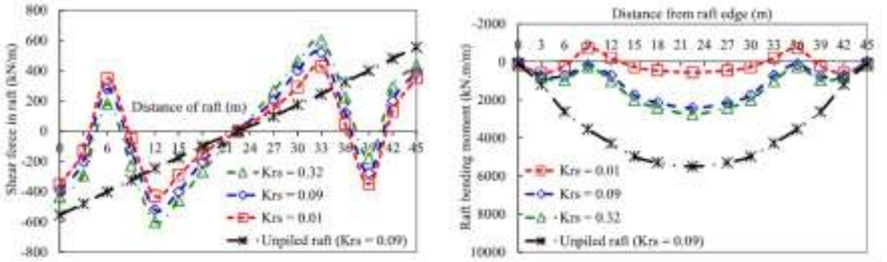

Fig. 2. Effect of Raft- Soil Stiffness Ratio on (a) Bending Moment and (b) Shear Force Along the Width of the Raft $(N_p = 49, S_p = 4.5\ m, B_g/B_r = 0.6)$ **[45]**

The results indicated that with increase in pile spacing up to the 5 to 6 times of the pile diameter, both average settlement ratio and differential settlement ratio decreased effectively and thereafter it increased gradually. Raft with smaller raft- soil stiffness ratio and larger pile group to raft width ratio observed to be effective in decreasing the average settlement ratio. The load- sharing ratio decreased with increase in pile spacing whereas; it increased with increase in pile length. With increase in pile spacing, bending moment ratio increased and as the length of pile increased bending moment ratio decreased up to pile group to raft width ratio of 0.6 and thereafter it increased. In unpiled- raft and piled- raft, maximum bending moment and minimum shear force is obtained at the center of the raft. The bending moment was affected marginally when raft- soil stiffness increases more than 0.09. The shear force increase as the raft- soil stiffness ratio increase. At any raft- soil stiffness ratio, shear force at the edge pile is noted to be minimal as compared to inside piles. Also, shear force changes its sign in the vicinity of edge pile. As the raft- soil stiffness ratio increases, the maximum bending moment and maximum shear force in the raft increases.

A. Ambarish Ghosh and B. Rituparna Dey [2] presented the behaviour of the piled raft foundation system considering the influence of the factors like raft thickness, pile length, diameter and number of piles. An experimental program in laboratory has been conducted on model piled rafts in cohesive soil. The experimental program includes the model test on raft supported by (2×2), (3×3) pile groups. In the laboratory test, model mild steel piles of diameter 5 mm, 10 mm and length 150 mm and 200 mm has been used. The raft has been made of polypropylene plate with plan dimensions of 100 mm×100 mm with different thicknesses of 10 mm and 15 mm. The objective of the experimental program is to study the behaviour of piled raft foundation system subjected to vertical load. A numerical analysis has been carried out by using geotechnical finite element software, PLAXIS 2D, to study the influence of the above mentioned parameters on the behaviour of the piled raft foundation in cohesive soil deposit.

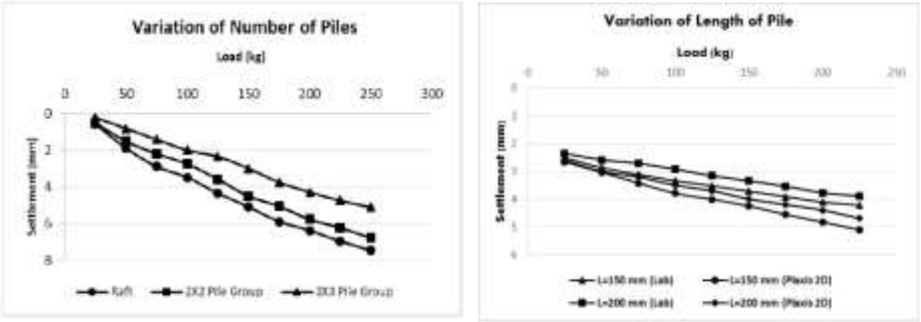

Fig. 3. (a) Load Settlement Curve for Raft and Piled Raft and (b) Load Settlement Curve for Pile Length of 150 mm and 200 mm **[2]**

The results indicated that settlement of pile is decreased when they are placed beneath the raft which clearly states that for a combined piled raft foundation system, piles act as settlement reducers and as the number of piles beneath the raft is increased, overall settlement of the foundation is decreased. This is because load shared by the soil is less compared to that of the raft without piles resulting in less settlement. The overall settlement for a 200 mm long pile was found to be less compared to a 150 mm long pile from figure 3(b). Length of the pile is directly related to its load carrying capacity. Mobilized load carrying capacity of pile per unit length will be less while increasing the pile length. Thus results in decrease in settlement.

Shiladitya Mandal and Siddhartha Sengupta [44] presented the performance of eccentrically loaded square rafts connected with short piles and resting on soft cohesive soil. The load was applied with varying eccentricity (e) to raft width (B) ratios of 0.05, 0.1 and 0.2. Experiments were conducted with two different raft sizes of 180 mm*180 mm and 220 mm*220 mm connected to 0, 2, 3, 4 and 5 numbers of piles in different cases.

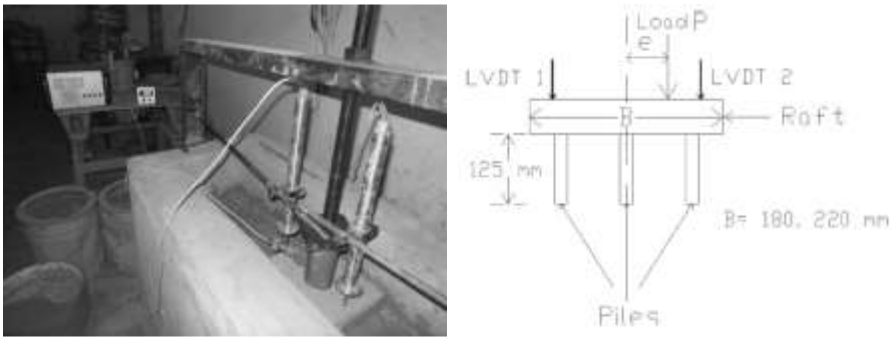

Fig. 4. (a) Model Test Tank and Load Frame and (b) Raft with Reinforcing Piles and Applied Load **[44]**

The results showed that in general as compared to unpiled rafts, the average bearing pressure increased almost two times for piled rafts having 5 piles corresponding to *e/B = 0.2*. For rafts with 5 numbers of piles the average settlement reduced to almost one- third in most cases as compared to rafts without pile corresponding to identical *e/B* ratio. The foundations were also proved to be greatly effective in reducing the tilt. For *e/B = 0.05*, on increasing the number of connected piles from 0 to 5, the tilt reduced from 2.00^o to 0.19^o in case of 180 mm*180 mm raft, and from 2.15^o to 0.10^o corresponding to 220 mm*220 mm raft respectively.

R. Radhika and S.P. Jeyapriya [42] have done parametric study and numerical analysis of piled raft foundation on soft clay. Laboratory model tests were conducted on both unpiled and piled raft on soft clay. The model tests include the use of unpiled raft and piled raft of three configurations namely 1x1, 2x2 and 3x3 with varying Slenderness Ratio of 23, 27 and 30. The results proved that ultimate load has increased and the settlement has reduced which is expressed by Load Improvement Ratio (LIR) and Settlement Ratio (SR). Parametric study showed that reduction in settlement takes place due to increase in pile length as well as with increase in number of piles. Among the tested footing models, the maximum length of pile of 180 mm with piled raft of 3x3 group showed 67% increase in ultimate load and 83% reduction in settlement compared to that of same pile configuration with pile length of 140 mm. The observed settlement values from experimental study was compared with numerical modeling using PLAXIS 2D and found that the results are in good agreement. Settlement reduces with increase in length and number of piles. The percentage reduction in settlement was found to be significant when the number of piles increased from 1 to 9 in each piled raft configuration.

3 Summary

The analysis of piled raft foundations embedded in a cohesive soil/layered cohesive soil profile is challenge for most of the simplified methods, since they generally model the subsoil as a homogeneous half space. In the design practice, on the contrary, layered soil profiles need often to be modelled and solved. However, the efficiency of the piled raft system depends on the load eccentricity ratio and pile arrangement. Raft foundations are often subjected to eccentric inclined loading because of the influence of lateral loads cause as a result of high wind and seismic actions and that may result in tilt of the structures particularly in case of high rise buildings.

Using the settlement reducing piles beneath the raft in such cases may increase the soundness of the structure and may reduce the tilt of the raft. However, the piled raft subjected to eccentric and inclined loads has not been fully studied. Most of the research work was done on parametric numerical study for uniformly distributed load or concentrated column loads on piled raft. So that the study is necessary to gain more understanding of behaviour of piled raft foundation for eccentric inclined load over cohesive soil/layered cohesive soil mass that creates overturning of the structure, which is commonly found in practice.

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