A Study on Piled Raft Foundation: State of Art

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Abstract

With increasing in urbanisation in last three decades all over the world led to rapid increase in number and height of buildings even on problematic subsoil conditions. Piled raft system proves to be more effective on such problematic subsoil conditions. It takes the high vertical load and used to bring the settlement, differential settlement and tilting of structure within the permissible limit. Piled raft system proves to be cost effective than the conventional pile foundation system. Piled raft foundation accounts for complex soil-structure interaction, which needs interaction between structure engineer and geotechnical engineer for giving most economical and safe design of the system. This paper reveals the performance of piled raft foundation in sandy soil, clayey soil and, layered soil carried through experimental and numerical analysis.

Keywords: Pile raft, settlement, diffential settlement, finite element method.

1. Introduction

In many of the countries which are involved in large projects are constructed or going to be constructed on soft grounds or reclaim soil. For such large projects, initially its is beneficial to check the bearing capacity of shallow foundation, where the shallow foundation does not satisfy the requirement, in that case it is beneficially to go with deep foundation or combination of shallow foundation and deep foundation i.e., piled raft foundation, as it has been proved to be cost effective [48] and also in settlement reduction. Many of the foundations performs poor, which may be in the form of excessive settlement, differential settlement on soft soil [12, 41, 57].Despite of poor performance, piled raft foundation proves to be more efficient [19, 45].In piled raft foundation role of raft foundation is to provide adequate bearing capacity and role of pile foundation is mainly to act as settlement reducers. This system is very complex which involves interaction factors such as pile-to-soil, pile-to-pile, pile-to-raft, and raft-to-soil.

The principle objective of this paper is to present a brief review of different studies on piled raft foundation in sandy soil, clayey soil and layered soil. Their work consists of experimental and analytical studies on piled raft foundation system in sandy soil, clayey soil and layered soil.

2. Experimental Studies

Raft foundation on cohesive soil shows excessive settlement, ultimately causes settlement of the structure. To prevent excessive settlement, use of minimum number of piles below the raft improves the ultimate capacity, settlement and differential settlement of the foundation system. The piles which is to be used as a settlement reducers has been suggested by [3, 59, 30, 12].Piles in piled raft foundation can be used for two reasons: To reduce total settlement in rigid raft and to reduce total and differential settlement in flexible raft [16,29,65,56,78,44,64].

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. He also found that in case of rigid raft load sharing between piles in piled raft foundation depends on number of piles and spacing of piles. Phung (1993) carried out field test in loose to dense sand and found that raft-pile interaction is the governing factor for pile raft behaviour, which causes an increase in skin friction of piles due to contact pressure of raft on soil. 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.Conte et al (2003) extended the work of Horikoshi (1995) and Horikoshi and Randolph (1996) and states that settlement reducing piles at centre of raft can be loaded to full capacity without affecting the foundation stability. Lee and Chung (2005) carried out model test on pile footing in dense sand and found that increase in skin friction is cause due to contact pressure.

between cap and soil, also found that lesser load is taken by raft at initial load stage. Fioravante et al (2008) carried out centrifuge test on circular raft in over consolidated clay and found that distribution of load between the piles underneath the raft is not uniform and load transfer mechanism differed from isolated pile. He also observed that as number of piles increase, raft settlement decreases and also postulates that displacement piles are more effective than non displacement piles in reducing raft settlement. He stated that when the piles reach the ultimate capacity, after that contribution of raft starts and also found that stiffness of foundation system increases as number of piles underneath the raft increases. Hakam (2004) performed model test on piled raft in soft clay and postulates that pile raft system increases the ultimate load of pile raft more than 100%. V.A.Barvashov and G.G.Boldyrev (2009) carried out research experimental and theoretically on pile raft system postulates that the settlement of soil at a depth 2d under the pile tip is 1.5 to 2.0 times more than the inter pile-soil and it remain constant up to depth of 6d.It states that soil layer under tip of pile is divided in two layers: deformation depends on distinct effect of individual piles and lower layer,deforamaion depends on action of piles and interpiles soil as a distributed load. Balakumar.V and Ilamparuthi. K (2009) performed a 1g model test of circular piled raft system on sand and found that the stiffness of piled raft system is very closed to raft-soil stiffness, which implies that piles performs as settlement reducers rather than load sharing member. Balakumar.V and Ilamparuthi. K (2010) performed a 1g model test of square and circular shape piled raft foundation and proved that the nonlinearity of piled raft behaviour is very near to hyperbolic relation and also proved that asymptotic load ratio and initial stiffness ratio remains same, irrespective the physical properties of piles and soil.EI Sawwaf (2010) carried an experimental work on short piles under a raft either connected or disconnected which was loaded eccentrically and found that it improves raft bearing pressure, reduces raft settlement and tilting, which leads to an economical design.Fioravante and Giretti (2010) performed a centrifuge test on piled raft foundation in sandy soil and found that piles transfers the load from raft to wider and deeper volume of soil, hence proves piles act as settlement reducer and also observed that sharing of load between pile and raft is related to stiffness of pile-soil system.Matsumoto et al. (2010) performed an experimental study subjected to horizontal and vertical load on piled raft foundation model to study the effect of pile head connected on raft performance. They found that when the vertical load is applied, pile head connection condition has little effect on its behaviour and when the connection is less rigid, the horizontal load taken by raft decreases. Singh.A.K and Singh.A.N (2011) performed experiment on piled raft foundation in sand and postulate that numbers and location of piles plays an important role in improving the capacity of piled raft system.

2. Theoretical Studies

The development of computer technology and high speed processor provides greater and quicker for computing numerical methods in structural and geotechnical engineering. It helps the researchers to to solve the complex interaction taking place between soil and structure in more convenient way. Brown P.T (1969) introduces numerical method in geotechnical engineering of circular raft on elastic layer of finite depth.Banarjee and Butterfiled (1971) developed numerical analysis for pile cap interaction. Hooper (1973) was the first user of finite element method for understanding complex interaction of piled raft foundation. Important contributions to understand the Behaviour was made by [25 ,4 , 38 , 61 , 64 , 62 , 34 , 65 , 58 , 13 , 63 , 80 , 7 , 8 , 70 , 71]

Butterfield and Banerjee (1971) studied the behaviour of piled group embedded in elastic half space continuum with rigid cap. Mindlins solution was used to understand the soil structure interaction response. Based on elastic continuum theory, Wiesner and Brown (1980) developed an analysis method of piled raft foundation. He represent raft as a thin elastic plate supported on piles and soil. Elastic continuum theory can provide satisfactory results of piled raft foundation when compared with experimental studies. Randolph (1983) used a flexibility matrix method to compute the interaction between single piles and circular raft and overall stiffness of piled raft system. Burland J.B (1986) performed two dimensional finite element analyses on London clay in which raft was modelled as rectangular plate 8 noded isoparametric element, subjected to uniformly distributed load on elastic half space. The computed results of heave and settlement were compared. Kuwabara F. (1989) used a boundary element method which was based on elastic theory, on piled raft foundation in homogenous soil and subjected to vertical loading. He states that this method which was developed by him does not consider the slip between pile and soil, non homogeneity of soil and end bearing piles. Clancy P. and Griffits D.V (1991) used a finite element technique for piled raft foundation, where raft was taken as 4 node quadrilateral plate bending element and pile as an axial element. Clancy P. and Randolph M.F (1993) developed a numerical method which was based on method on hybrid model that combines the finite element modelling for the structural elements of piled raft foundation and analytical solutions for modelling the response of soil. Zhuang G.M and Lee I.K (1994) used a finite element method to understand the load sharing between the piles in piled raft system. They observed that load sharing between the piles in piled raft system was affected by pile stiffness, raft rigidity and pile length to width ratio. They also observed that as pile length increases and raft and pile rigidity decreases, the load distribution become more uniform.Ta L.D and Small J.C (1996) developed a method, which was based on finite layer method for the analysis of soil and finite element method for the analysis of raft, for piled raft foundation on layered soil. They found that load sharing between the piles in piled raft system was influence by thickness and stiffness of soil layer.Ta and Small (1997) observed that load shared by piles increases and that by raft decreases as bearing strata becomes stiffer. Russo (1998) developed a numerical method for piled raft system analysis, which considers non-linearity of the unilateral contact at the raft-soil interface and the non-linear load-settlement relationship. He 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. Mendonca A.V and de Paiva J.B (2000) developed a boundary element method for analysis of piled raft foundation system, in which soil was modelled as an elastic linear homogeneous half space, pile as single element and raft as a thin plate, which accounts for the interaction between raft, soil and pile. This method can be used for rigid and flexible caps. Prakoso W.A and Kulhawy F.H (2001) used PLAXIS software, which is based on finite element method and states that satisfactory results are obtained from 2D plane strain analysis without excessive time for modelling and computing.De-Sanctis et al (2001) discussed the limitations of 2D plane strain finite element analysis and stated that only 3D finite element analysis provides the optimum design methodology. Poulos H. (2001) developed a simplified analysis method as a tool for preliminary design of piled raft foundation system. Small J.C and Zhang H.H (2002) used a finite layer theory for the analysis of piled foundation system on layered soil subjected to vertical load, lateral load and moment. El-Mossallamy (2002) developed a numerical tool, which considers mix technique of boundary element and finite element method, which accounts raft stiffenss, nonlinear behaviour of settlement reducer piles and slip along pile shaft for the analysis of piled raft foundation system. Mendonca A.V and de Paiva J.B (2003) used combination of finite element and boundary element for the analysis of piled raft foundation system, in which interaction between piles, soil and raft was considered. Kitiyodam P. and Mastumoto T. (2003) presented simple analytical method for piled raft foundation embedded in non homogenous soil subjected to vertical and lateral load, by using hybrid model.Maharaj (2003) performed 3D nonlinear finite element analysis to understand the behaviour of piled raft foundation in stiff clay. The elastic raft and piles was modelled by hexahedron 8 noded brick element which was subjected to uniform loading. He focused on load settlement behaviour of piled raft due to effect of raft and pile stiffness. The output of all these analysis was compared with results of freestanding piles or pair of square piles without any raft or cap [75].Reul (2004) used a finite element method to model piled raft foundation in over consolidated clay and stated that with increase in load, piled raft interaction leads to increase in skin friction of piles. Wong and Poulos (2005) presented a simplified method using computer program GEPAN, based on boundary element method to estimate the pile-to-pile interaction factor between two dissimilar piles of pile group and piled raft foundation. Garcia et al (2005) used visco-hypoplastic constitutive law in three dimensional finite element analysis to study the piled raft foundation system on clay soil.Novac et al (2005) studied load settlement behaviour of piled raft foundation system by performing three dimensional finite element analysis and found that results obtained from finite element analysis match with the measured value of two case studies (Westebd I if Frankfurt, Germany and Urawa, Japan) on over consolidated stiff clay. The piled raft was modelled as reinforced concrete was embedded in soil media. Vasquez et al (2006) studied the three dimensional non linear finite element analyses to understand the behaviour of piled raft foundation system considering non linear behaviour of soil and linear elastic behaviour of raft and pile.Hassen G. et al (2006) developed 2D plane strain elasto-plastic multiphase model to simulate the behaviour of piled raft foundation system subjected to combined loading. Six nodded triangular finite element were used to represents surrounded soil mass and pile reinforced zone. Vasquez et al (2006) replaced the linear elastic soil constitutive law by non linear soil constitutive equation of Mohr coulomb model.Novac et al (2005) studied the same case and findings of both of them are settlement of central pile assuming a dish shape settlement of the raft.Der Guey Lin et al 2006. used two dimensional finite difference numerical tool to discuss pile-raft- soil interaction in case of piled raft foundation system resting on layered soil subjected to vertical load. The soil is modelled as linear elastic material and raft as beam element. He found that high bending moment may be induce in raft and pile due to lateral displacement of soil for vertical uniform loading. Ningombam Thoiba singh et al (2008) used finite element software ANSYS to study the interaction analysis for piled raft in cohesive soil. The pile and raft considered to be linearly elastic. He found that in reducing overall settlement of piled raft is not influence by thickness of raft. He also stated that in piled raft foundation piles reach their ultimate capacity earlier than raft.E.Y.N.Oh et al (2009) performed numerical analysis of piled raft foundation in sandy and clayey soil on PLAXIS and FLAC software. He found that maximum settlement of foundation depends on number of piles and pile spacing and with increasing raft thickness, differential settlement reduces.H.K Engin et al (2009) performed a finite element analyses on PLAXIS 3D software to investigate the behaviour of pile in piled raft system. The beam was modelled by beam element. He compared the load settlement behaviour of Mesee-Torhaus building using FE model with measured value and found that result obtained from FE model was in good agreement with measured value.JinHyung Lee et al (2009) carried out numerical analysis using 3D finite element method to describe the behaviour of piled raft on soft clay subjected to vertical loading. The slip interface model between pile-soil was used in analysis. The load sharing between raft and pile at ultimate state was evaluated. He found that use of limited number of pile underneath the raft improves the bearing capacity and settlement behaviour of raft.Meisam Rabiei (2009) carried out a parametric study on piled raft foundation using computer program ELPLA.He studied pile configuration, pile lenth,pile number and raft thickness on behaviour of piled raft foundation. He found that with increasing raft thickness, decrease in pile number and pile length maximum bending moment in raft increases [56, 47, 72, 52].He also stated that with increase in raft thickness and uniform increase of pile length reduces central and differential settlement. R.Ziaie Moayed et al (2010) studied the effect with different pile diameter on behaviour of piled raft foundation by 3D finite element method. If the bottom soil layer is dense than the piled raft foundation with different pile diameter proves to reduce total and differential settlement, but it is not so in case where bottom soil layer is soft.Sandeep rai et al (2010) studied to understand the effect of piles on response of raft foundation. He stated that by providing the piles in central portion of raft, settlement of pile raft reduce system reduces. He also stated that load sharing between piles is high initially and decreases as settlement reached to a constant value.Karim H H et al 2012. studied the percentage of load shared by pile and piled raft by performing a experimental work and the same is compared with PLAXIS 3D and ANSYS software. They stated that the total carried by piles depends on piles number in group and interaction between the piles is affected by pile spacing. Sangseom Jeong (2012) carried out numerical analysis using FE package ABAQUS to study the behaviour of square piled raft in clay soil. The pile soil slip interface model were performed to study the behaviour of piled raft .He stated that variation of reduction ratio of stiff clay was smaller than soft clay, whereas reduction ratio of stiff clay was greater than soft clay. He also stated that pile group area ratio for stiff clay was slightly lesser than soft clay.Henok F.Gebregziabher and Rolf Katzenbach (2012) carried out parametric studies on piled raft foundation on layered soil by three dimensional non linear finite element analyses. The pile and soil are modelled as 20 nodded second order solid element of brick shape and raft is modelled as 8 nodded second order shell element. They postulated that critical spacing between piles, pile length and their arrangement is important in reducing settlement and load sharing behaviour of combine piled raft foundation. They also stated that load sharing of raft foundation increases, when the piles are widely space and applied load are higher. Dang Dinh Chung Nguyen (2013) carried out a centrifuge test on piled raft foundation and same is compared with PLAXIS 3D software results, to calculate central and differential settlement with different arrangement of piles. He found that model with concentrated pile arrangement reduces central and differential settlement than pile raft model with uniform arrangement

3. Summary

This review paper on piled raft foundation postulates that considerable research, either experimentally or theoretically has been conducted on the behaviour of piled raft foundation. Significant contributions have been made to learn the different aspects of piled raft foundation. Most of these models reckon on arduous analytical and numerical methods.

The plate on spring, 2D finite element analyses and hybrid approach are incompetent of analyzing the torsional behaviour and material alteration in third axis.Therfore 3D finite element method is the most competent to replicate the complex behaviour of piled raft foundation.

It was found from literature review that finite research has been committed to evolve simple analysis models and design methods. A number of 3D numerical models have been developed but no effort is found to evolve analytical method based on numerical methods. Analytical methods were stated only to access the settlement of the piled raft foundation but the forecasting of differential settlement and ultimate bearing capacity is yet to be done. Therefore further studies are required to evolve simple analysis and design methods. Prediction of load sharing between piles and raft in piled raft system are required at preliminary design stage. The need for developing simple analysis and design models for piled raft foundations has been recognized by many workers in this field such as [56,13,16,18] and others.

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