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A Comparative Study of Piled-Raft Foundation by Utilization of Finite Element Techniques: A Review

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Abstract* – *Raft foundation covers the entire area of the structure, transmitting the entire structural load and reduces differential settlements whereas piles are relatively long, slender members that transmit foundation loads through soil strata of low bearing capacity to deeper soil or rock strata having a high bearing capacity. In recent years, a piled-raft foundation which is a composite structure consisting pile and raft has been proved to be an appropriate alternative instead of conventional pile or mat foundations. In this paper, analysis of piled raft foundation has been carried out by using finite element software ANSYS. For understanding the behavior of piled raft foundation, parametric studies has been carried out in medium sand by varying pile diameters and pile lengths in different combinations. It has been found out that Pile diameter has significant influence on the ultimate capacity of piled raft foundation whereas the pile length has not of much significance. It is concluded that an optimum combination of pile diameter of 0.5 m at the center of the raft with 0.4 m at the edges of the raft is giving ultimate load of 4.45 MN with settlement of 26.76 mm which is in acceptable limits.

The design of group piles depends on either the group or single pile capacity of piles. In conventional design method of such foundations, the stiffness of the pile cap is barely taken into account. Such design becomes too conservative if the pile cap is in contact with the ground. Because the pile cap contributes in transferring load to the ground and distributing load over the piles. The design method that considers the contribution of the pile cap and interaction between the different elements of group piles is called piled raft foundation. The concept of piled raft foundation leads to economical design.

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INTRODUCTION

A piled raft foundation is a geotechnical composite construction consisting of three elements: piles, raft, and subsoil.In comparison with conventional foundation design, a piled raft foundation exhibits a totally new dimension for subsoil-structure interaction because of the new design philosophy as to use the piles up to their ultimate bearing capacity regarding the soil-pile interaction. Another difference from traditional foundation design where the load is assumed to be carried either by the raft or by the piles, the total superstructure load is partly taken by the raft through contact with soil and the remaining load is taken by piles through skin friction. The piles in this case do not have to penetrate to fill depth of soil layer, but it can be terminated at lower depths. This lead to an extremely economic foundations.

In this study, piled-raft foundation has been considered which is a combination of advantages of both raft and pile foundation. Piles are provided along with the Raft so that the total load acting is shared partly by the raft and partly by piles. Piled raft foundations utilize piled support for control of settlements with piles providing most of the stiffness at serviceability loads, and the raft element provides additional capacity at the ultimate load.

To study the behavior of piled rafts, numerical method is a reliable and suitable method due to complex soil-structure interaction. Finite Element Method is one of the numerical methods which is a powerful tool to model this complex geometry of piled-raft foundation. ANSYS V11 is one of the sophisticated finite element software which is well suited for foundation analysis because of its flexibility in modeling, meshing and also the field conditions can be incorporated effectively.

In previous literature, it is inferred that the behavior of foundation can be analyzed using methods like finite element method with the help of different software. In some of the studies different diameters of piles and lengths of piles has been considered which affect the performance of the foundation. OH et al. (2008) have carried out analysis on unpiled and piled raft foundation in sandy soil using PLAXIS software. They have varied raft thickness which does not affect significantly the load carrying capacity of the foundation. Rajendra Singh et al. (2012) suggested that pile spacing has much effect on the maximum and differential settlement. Poulos et al. (2011) carried out 3D analysis of piled raft foundation of Incheon tower in South Korea subjected to horizontal and vertical loading using PLAXIS and the same is compared with pile group foundation system. They suggested that piled raft behaves safely in high raised buildings. Luca De Sanctis and Alessandro Mandolini (2006) concluded that piled rafts provide an economical foundation option when an unpiled raft does not satisfy design requirements. Hence, they suggested that addition of limited number of piles will improve the ultimate load capacity and settlement performance of the foundation. They have concluded from their work is that the piled raft foundation is a good option for the future projects.

There are different variables which influence the load carrying capacity of piled raft foundation. Initially, the effectiveness of ANSYS is validated with static formula of bearing capacity of unpiled raft and also with existing data on piled raft foundation from available literature before proceeding with parametric study. Then, the parametric study is carried out by considering variables like uniform diameter of piles and uniform length of piles and different diameter of piles and different length of piles under the raft. This parametric study is carried on piled raft foundation in medium sand.

Piles are good solution in site conditions where low bearing capacity and significant settlements are expected. In designing piles as foundation support for structures, it is a common trend to include a pile cap for joining of the pile heads. The pile cap is designed for structural section capacity only. But the pile cap has additional influence on the foundation system besides joining of pile heads and simple load transferring. Recent developments have shown that the stiffness of the pile cap influences the load transferring mechanism of the foundation system. The roll of the pile cap becomes significant if the cap is in direct contact with the foundation soil.

A piled raft is a foundation which acts as a composite construction consisting of three load bearing elements: piles, raft and subsoil. According to its stiffness, the raft distributes the total load of the structure as contact pressure and over the piles in the ground. The piled raft concept needs evaluation of a number of factors in order to come up with analysis/design models that simulate the actual site conditions.

The use of piled raft concept has lead to reduction of total as well as differential settlements. In many cases using raft foundation only induces excessive settlements which are not acceptable due to serviceability requirements. Placing of piles in systematic manner under the raft reduces such settlements to acceptable values. In addition to settlements, the bearing capacity of the whole system of foundation also improves.

The conventional design methods used for pile groups lead to a higher number of piles under the raft. With the concept of piled raft, this number can be reduced. This has proven piled rafts to be economical solution in foundation design for soil conditions where such design is applicable.

LITERATURE REVIEW

Piled raft foundation is assumed to have four kinds of interactions. These interactions are pilepile, pile-raft, pile-soil and raft-soil. A model for full analysis and design of piled raft foundations has to predict these interactions accurately. The model has to be able to simulate the increasing settlement of a single pile under increasing loads, while taking into account the Pile-Soil-Interaction. Therefore, it is necessary to calculate the ultimate skin friction of the pile as a function of depth, in-situ stresses and the strength of soil-layers. The material laws used in the calculation must be explained in detail. It is recommended that a back analysis of a static pile test is carried out, to verify the numerical and material models.

With increasing raft settlement, the vertical and the horizontal stress states change. Due to of a higher stress-state of the soil, the ultimate shear strength of the soil and thus the bearing capacity of the pile increase (Pile-Raft-Interaction). When the pile spacing is small, the Pile-Pile-Interaction additionally has to be taken into account. The requirements of the interactions 1 – 4 can only be satisfied by a three dimensional model of the total structure. Different researchers have conducted analysis, design and performance of piled raft foundation. The researches done range from simple analysis methods by taking a number of assumptions to sophisticated analysis tools like finite element, boundary elements and case studies with site measurements.

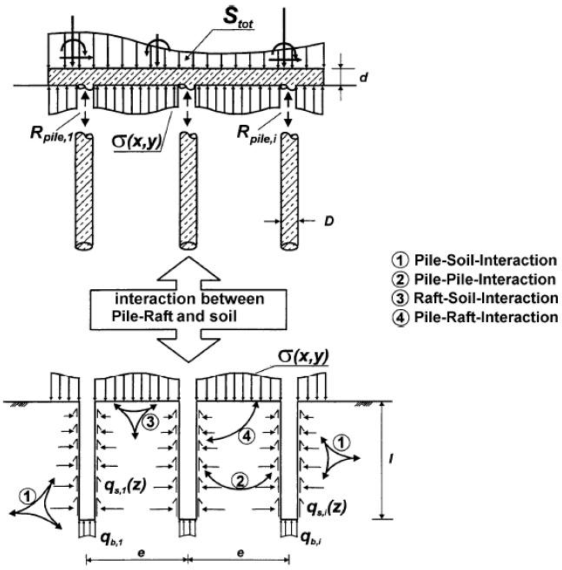

Figure 1 Interactions between pile, raft and soil in a piled raft foundation.

Analysis/Design Methods-

On July 2001, A Report Prepared on Behalf of Technical Committee TC18 on Piled Foundations by International Society of Soil Mechanics and Geotechnical Engineering illustrated methods of analysis of piled raft foundations. The well-known author perhaps the most quoted author, H.G. Poulos, on a number of research papers has tried to list and explain methods of analysis for piled raft foundation. (Mekbib, 2004) and (Chow H. S., 2007) have also given enough outlines in their paper. The methods mentioned/explained by (Poulos, 2001) are presented in a number of other papers as well.

From the point of view of overall performance of piled raft foundation, it is desirable that a method be capable of predicting the entire load-settlement behavior of the system. As illustrated in (Fig 1), there are essentially three portions to the load settlement curve:

1. A more or less linear portion, representing the situation where both the piles and raft are behaving in an essentially linear manner.

2. A less stiff portion, in which the piles may have reached their full capacity, but the raft continues to carry increasing load.

3. A final portion, representing overall failure of the foundation system.

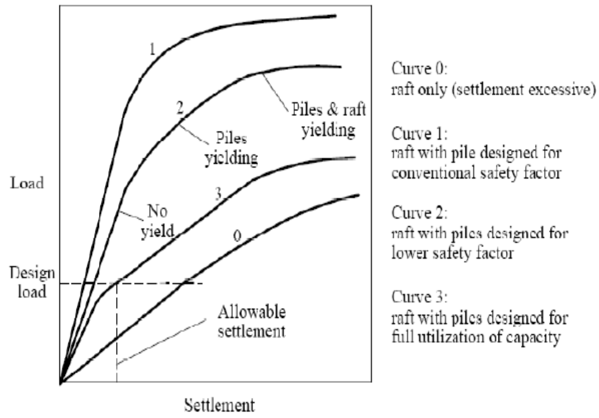

Figure 2 Load settlement curves for piled rafts according to various design philosophies.

(Randolph, 2004) has defined clearly three different design philosophies with respect to piled rafts.

(i) The "conventional approach" in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft primarily to ultimate load capacity. In (Fig 2), Curve 1 represents this design philosophy in which the piles take the majority of load.

(ii) "Creep piling" in which the piles are 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 included to reduce the net contact pressure between the raft and the soil to below the reconsolidation pressure of the soil. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than (i).

(iii) Differential settlement control, in which the piles are located under the raft where high settlement is expected. This will make the settling area of the raft more stiff which ultimately reduce the differential settlement.

A number of methods can be cited in terms of their ability to predict load-settlement behavior of a piled raft foundation. But three broad classes of analysis methods are identified according to the assumptions, complexity and numerical methods employed.

a. Simplified calculation methods

b. Approximate computer-based methods

c. More rigorous computer-based methods.

PILE GROUP

A solution to the problem of pile-soil-pile interaction in the analysis of pile groups has been suggested by Chow (1986,1987), and a computer coding of this method has been presented by Smith and Griffiths (1988). Figure 3 shows the main points of the analysis, namely the pile stiffness, the soil stiff- ness in the form of t-z springs, and the interactions between the piles through the soil.

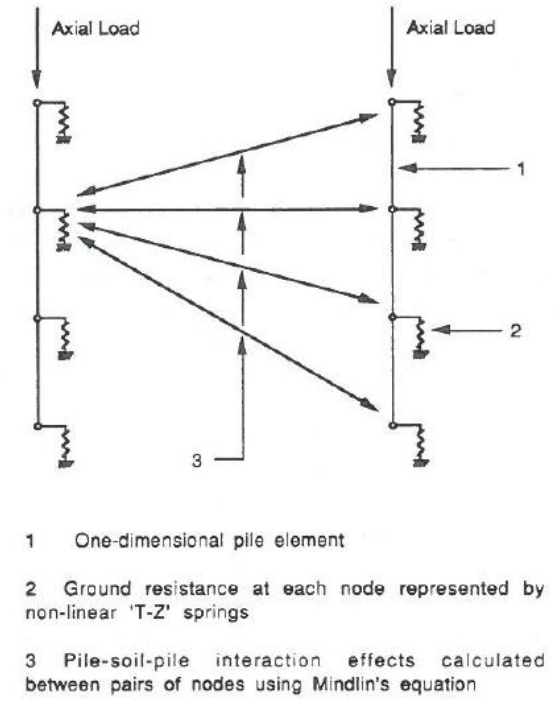

Figure 3. Representation of piles and soil.

Chow's work is based on the popular method of single pile analysis where one-dimensional beam-column finite elements are used to model the pile. The soil response is modelled by a discrete spring at each node, based on load transfer curves suggested by Seed and Reese (1957), (referred to as t-z or p-y curves, depending on whether axial or lateral response is being considered).

In the present work, only linear t-z response has been considered, with the gradient of the t-z curve linked to the elastic soil modulus using the relationships proposed by Randolph and Wroth (1978).

To model a pile group, Mindlin's (1936) elastic continuum solution, for displacements due to a point load, is used to provide interaction effects between pile nodes.

Although only axially-loaded vertical piles have been considered here, the method can be extended to look at more general pile groups with lateral loading and raked piles, and is*capable of modelling a soil in which the stiffness increases linearly with depth.

Unlike the boundary element method, consideration of non-homogeneous soil and soil non-linearity do not increase the size of the system of equations to be solved.

METHODOLOGY

Two dimensional plane strain nonlinear analysis under vertical load is carried out using finite element software ANSYS to determine ultimate load carrying capacity and settlement of foundation. Here, pile and raft are treated as linear, soil-raft and soil-pile interface as non-linear and Drucker-Prager constitute model is used for soil.

Here, pile and raft were modeled as linear isotropic and the properties considered for analysis are Young's modulus (E), Poisson's ratio(μ) and density for pile and raft. Soil is modeled as an elasto plastic and in addition to linear material properties, properties like material cohesion strength (c), friction angle) and flow angle is given. For pile, raft and soil, PLANE82 was used as an element type and the element behavior is specified as plane strain. The interface behavior is nonlinear. Contact elements CONTA172 (for soil) and TARGET169 (for pile and raft) at soil-pile and soil-raft interface are considered. Regarding boundary conditions, nodes constituting bottom of the soil zone is fixed against both vertical and horizontal directions whereas the zone away from pile raft, i.e., the vertical surface of soil at the boundary is restricted against horizontal movements. The horizontal boundary (H) was placed at 5 times the piled raft cluster diameter (5D) and the vertical boundary (V) is placed at 3 times the piled raft cluster diameter (3D) as shown in Figure 4.

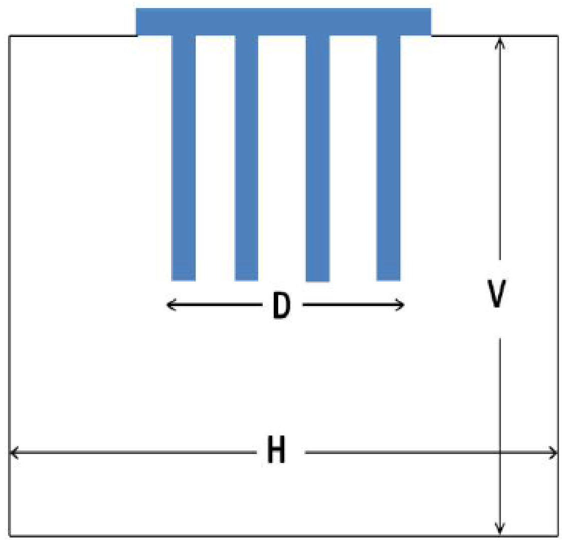

Figure 4: Piled Raft Foundation.

For validation of ANSYS, immediate settlement in medium sand is calculated using static formula and the same is compared with the results obtained from ANSYS. Here, the results obtained from ANSYS are compatible with the calculated theoretical results.

Similarly, validation is done using literature is compared with the results obtained from ANSYS. The outcome of this analysis is that the results obtained from ANSYS are compatible with the literature. The model meshed is shown in Figure 5. The resultant model from the analysis showing displacement contours is shown in Figure 6.

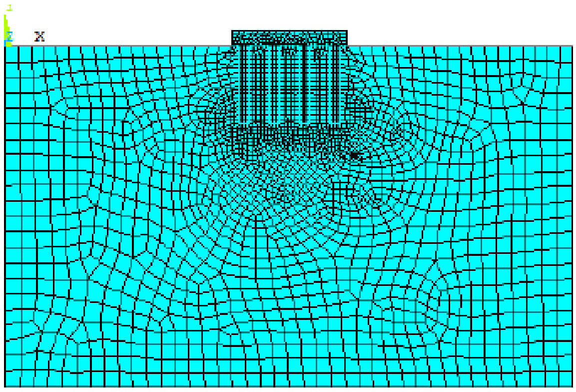

Figure 5: Meshed Model.

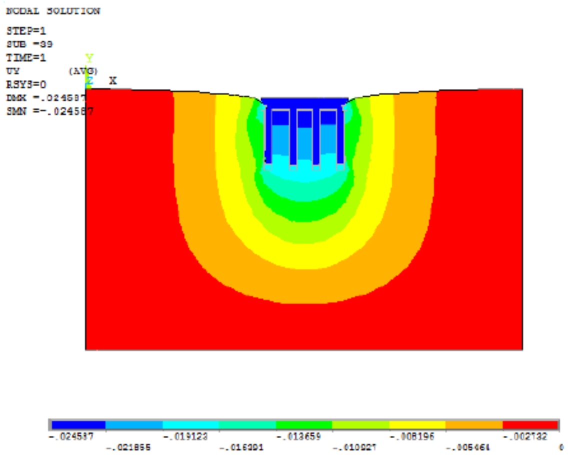

Figure 6: Displacement Contours Along y-Direction.

RESULTS

Effect of Pile Diameter -

Initially, the influence of pile diameter on the behavior of piled raft foundation is analyzed. The number of piles (16 in no.), pile length (all are of 3 m), thickness of raft (0.6 m), spacing of piles (3 d) are kept constant. The material properties considered are shown in Table 1.

Properties	Piled Raft	Soil (Medium Sand)
E	$2.5*10^7$ kPa	$4*10^4$ kPa
μ	0.15	0.3
ρ	2500 kg/m³	1900 kg/m³
C	-	5kPa
Φ	-	35°
ψ	-	10.5°

Table 1: Material Properties.

From the analysis, the ultimate load capacity and corresponding settlement is obtained for all the combinations are given in Table 2.

Pile Diameter(m)		Ultimate load P (MN)	Settlement δ (mm)
Centre of the raft	Edges of raft		
0.3	0.3	2.12	19.57
0.4	0.4	3.388	24.59
0.5	0.5	4.808	26.903

Table 2: Values of Ultimate Load and Settlement.

The ultimate load carrying capacity increases significantly with the increase in pile diameter. From this study, it can be concluded that even though relatively it is difficult for casting different diameters, but it is giving relatively higher values of ultimate load which is cost effective also.

CONCLUSION

The paper has demonstrated the major concept of piled raft foundation that piles can be utilized to reduce differential settlements with an eventual increase of total settlement which is acceptable in prevailing codes.

A method of analysis for pile-raft systems has been developed using finite elements. The three kinds of interactions, namely pile-soil-pile, pile-soi 1-raft and raft-soil-raft are accounted for using the elastic theory of Mindlin.

Hence, the piled raft foundation has a better scope for both research and applications in the field. This paper will give an idea for designers and practitioners about benefits of using different diameters under raft.

Further work will be performed in order to validate the program against field performance, but the early indications are that the method represents an improved yet efficient method of analysis for piled raft foundations.

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