ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 10, October 2014

A Review on Different Approaches of Piled Raft Analysis

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ABSTRACT: A raft foundation that supported by piles is proved to be an economical foundation system, if the bearing capacity of the raft is adequate to withstand the loads from superstructure. Then the piles located strategically to support the raft can reduce the both overall and differential settlement of the foundation system.

In this paper, different approaches for the analysis of piled raft foundations forwarded by different researchers from time to time are reviewed and their capabilities and limitations are also discussed. Some of the approaches are useful only for preliminary design, while others are useful for detailed design.

KEYWORDS: piled raft, raft, pile, finite element method, stiffness, load-settlement, composite piled raft.

I. INTRODUCTION

In recent decades, recognition of pile supported raft foundation has been increasing that leads to considerable economy without compromising the safety and performance of the foundation. In a pile supported raft or a pile-enhanced raft or a piled raft foundation, the piles are used to reduce raft settlements and differential settlements.

A number of available methods that have been used for analysis of piled raft can be ranged from simplified calculations to more rigorous computer based numerical methods [1]. Apart from all these available methods, a new and innovative approach has been proposed by some researchers like Liang et al. [2]. Despite the recent activity, the concept of piled raft foundation is not new, and has been describe by several researchers, including Zeevaert [3], Butterfield and Banerjee [4], Davis and Poulos [5], Hooper [6], Brown and Wiesner [7], Burland et al [8], Sommer et al [9] and many more. In the early years, because of the limited availability of the computer memory and the processing speed, the use of numerical methods was confined to simple problem. In the last two decades due to rapid development in computer technologies, numerical full three dimensional finite element methods are often used to solve complex problem.

II. WORK RELATED TO PILED RAFT ANALYSIS

From the literature survey it has been found that the analyses of piled raft can be ranged from simplified hand calculation to some innovative approaches. These can be classified into four broad categories.

1. Simplified approaches.
2. Approximate approaches.
3. More rigorous approaches.
4. Some innovative approaches.

Simplified approaches involve the hand calculation using the theoretical solution for a raft and for a pile in elastic continuum. Simplified methods include those of Poulos and Davis [10], Randolph [11, 12], Burland [13], Hemsley [14] and Poulos [15]. All methods involve a number of simplifications while considering the soil domain and applying load on the raft.

The approximate approaches include two main approaches: “strip on spring” approach (by Poulos [16]) and “plate on spring” approach (by Poulos [17], Russo [18], Kitiyodom and Matsumoto [19]).

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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Strip on spring approach: The raft is represented by a series of strip footing and the piles are represented by spring of appropriate stiffness.

Plate on spring approach: The raft is represented by a thin plate and the piles as spring.
The more rigorous approaches include the use of numerical solution, combination of numerical and analytical solution (Clancy and Randolph [20]) and use of commercially available software based on numerical technique (Reul and Randolph [21], Maharaj and Gandhi [22]). A mixed technique based on the finite element method (FEM) and boundary element method (BEM), where FEM is used to model raft and boundary element method is used to model pile-soil and raft-soil (Frank et al [23]; Mendonca and de Paiva [24]) can be treated as more rigorous method.

The innovative approach introduces a new type of foundation named composite piled raft by Liang et al (2003) [2]. In the system of composite piled raft, the short piles made of flexible materials like stone columns are used to strengthen the shallow soft soil, while long piles made of concrete or any other rigid materials are used to reduce settlements and the cushion below the raft is used in order to mobilise shallow soil to participate in the interaction.

III. RESULTS AND DISCUSSION

The results and discussions of different approaches for the analysis of piled raft foundation have been described by several authors, including Poulos and Davis (1980), Randolph (1994), Burland (1995), Hamsley (2000), Poulos (2001) are presented in Section IV. Similarly the results and discussions of approximate approaches, more rigorous approaches and some innovative approaches are presented in Section V, Section VI and Section VII respectively.

IV. SIMPLIFIED APPROACHES

A simplified method for estimating the load settlement behaviour is described by Poulos [25] using the simple method of estimating the load shearing between the raft and the piles, as outlined by Randolph [12]. This is the useful extension of the method that described by Poulos and Davis [10]. The definition of the pile problem considered by Randolph is shown in Fig. 1(a). Using his approach, the stiffness of the piled raft foundation is computed for number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Beyond that point (Point A in Fig. 2), the stiffness of the foundation system is that of the raft alone and this holds until the ultimate load capacity of the piled raft foundation system is reached (Point B in Fig. 2). At this stage, the load-settlement relationship becomes horizontal. Thus, referring to Fig. 2 a tri-linear load-settlement curve of the piled raft system is developed by Poulos [25]. Fig. 1(b) represents the load-settlement curve as presented by Randolph [12].

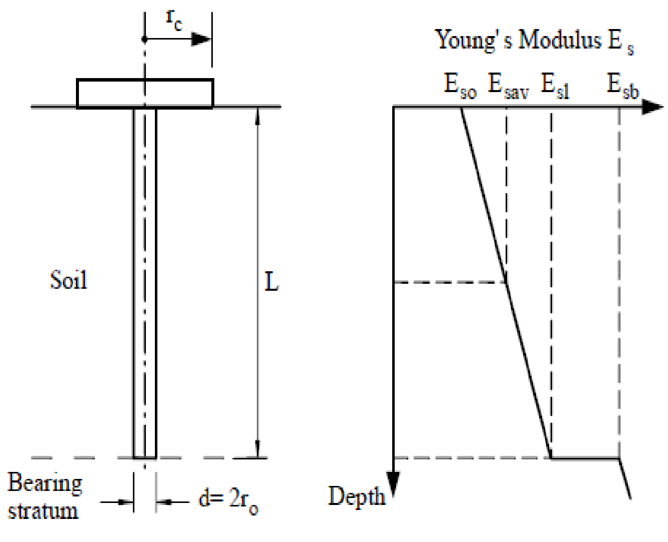

Fig. 1 (a) Simplified representation of pile-raft unit (Randolph, 1994)

DOI: 10.15680/IJIRSET.2014.0310037

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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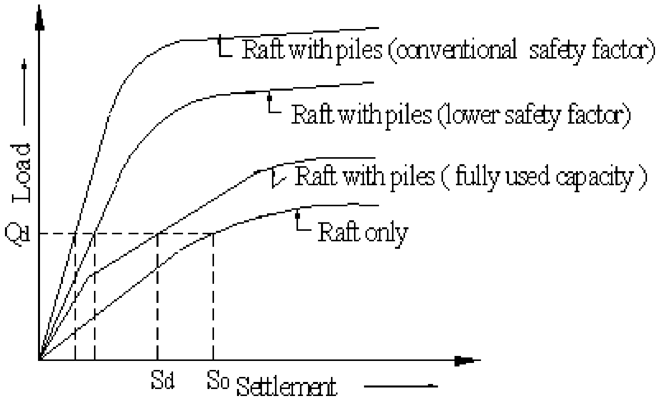

Fig. 1 (b) Load-settlement curve for piled rafts according to various design philosophies (Randolph, 1994)

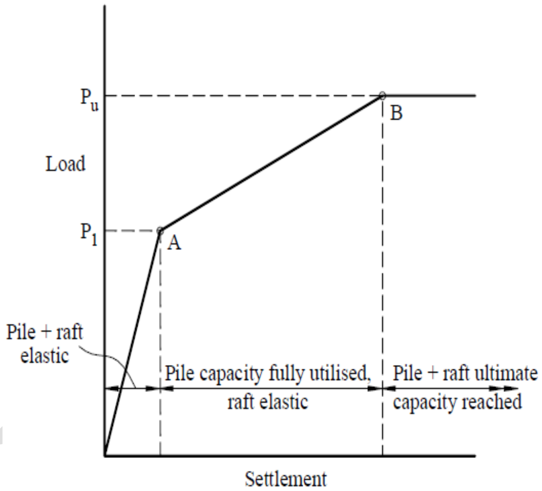

Fig. 2 Simplified load-settlement curve for preliminary analysis (Poulos, 2001)

Burland [13] has developed some simplified process of design when piles are designed to act as settlement reducer and to develop their full capacity at the design load.

- Estimate the total long-term load-settlement relationship for the raft without piles (Fig. 3 & 4). The design load P_0 gives a total settlement S_0.
- Assess an acceptable design settlement S_a, which should include a margin of safety.
- P_1 is the load carried by the raft corresponding to S_a.
- The load excess $P_0 - P_1$ is assumed to be carried by settlement-reducing piles. The shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. However, Burland suggests that a "mobilization factor" of about 0.9 be applied to the 'conservative best estimate' of ultimate shaft capacity, P_{su}.
- If the piles are located below columns which carry load in excess of P_{su}, the piled raft may be analyzed as a raft (Fig. 3) on which reduced column loads act. At such columns, the reduced load Q_r is:

$$Q_r = Q - 0.9P_{su} \qquad (1)$$

- The bending moment in the raft can be obtained by analyzing the piled raft as a raft subjected to the reduced loads Q_r. The process of estimating the settlement of the piled raft is not explicitly set out by Burland, but it would appear reasonable to adopt the approximate approach of Randolph.

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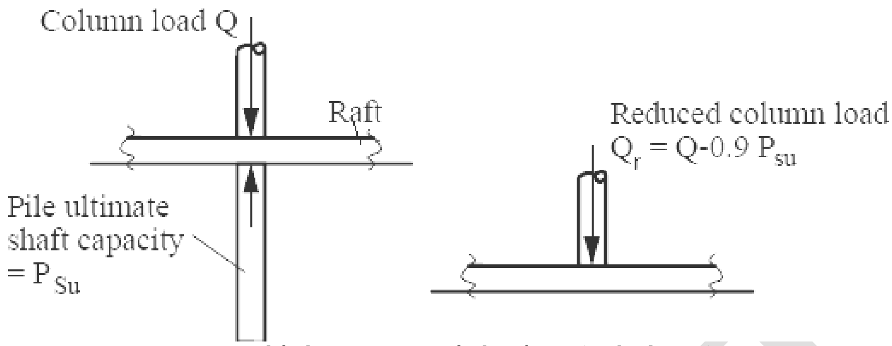

Fig. 3 Simplified representation of pile-raft unit (Burland, 1995).

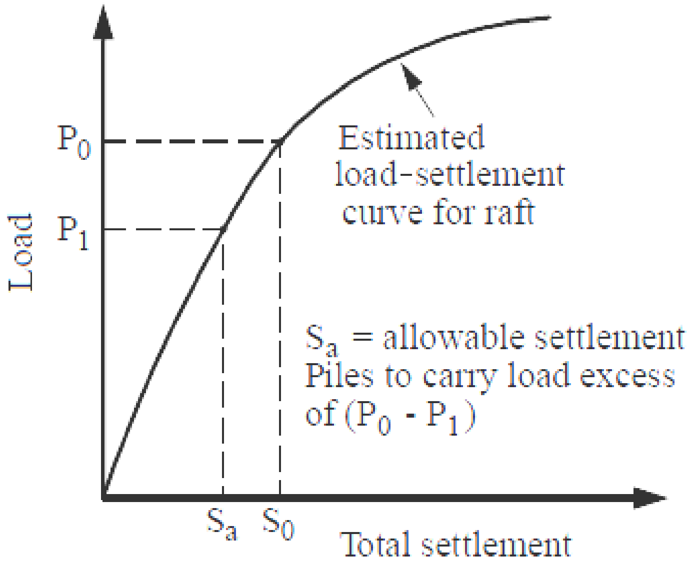

Fig. 4 Load-settlement curve for raft (Burland, 1995)

Another simplified method for analysis of piled-raft foundation that presented by Hamsley [14]. According to its stiffness, the raft distributes the total load transferred from structure (S_{tot}) as contact pressure below raft represented by R_{raft} , as well as load over each of the 'n' piles represented by $\Sigma R_{pile,i}$.
Therefore, the total resistance of the piled raft (R_{tot}) is given by:

$$R_{tot} = R_{raft} + \sum_{i=1}^{n} R_{pile,i} \geq S_{tot} \qquad (2)$$

In piled raft foundations, the contribution of the raft and piles is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system. Moreover, the interaction between the raft and the piles makes it possible to use the pile up to a load level which can be significantly higher than the permissible design value of a comparable single isolated pile. Thus, the behavior of a piled raft foundation can be characterized with an interaction coefficient β_{pr} defined as:

$$\beta_{pr} = \frac{\sum_{i=1}^{n} R_{pile,i}}{R_{tot}} \qquad (3)$$

Equation (3) describes the load shearing between the pile and the raft. A coefficient of β_{pr} = 0 represents the case of a shallow foundation, and a coefficient of β_{pr} = 1 represents the case of a fully piled foundation without contact pressure beneath the raft.

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The influence of the piles to diminish the settlements of raft depends on the piled raft interaction coefficient, which in turn depends on the subsoil surrounding and the geometric proportions of the piled raft. For the same subsoil conditions and the same area of the raft, the coefficient is a function of the number and length of the piles, as shown in Fig. 5.

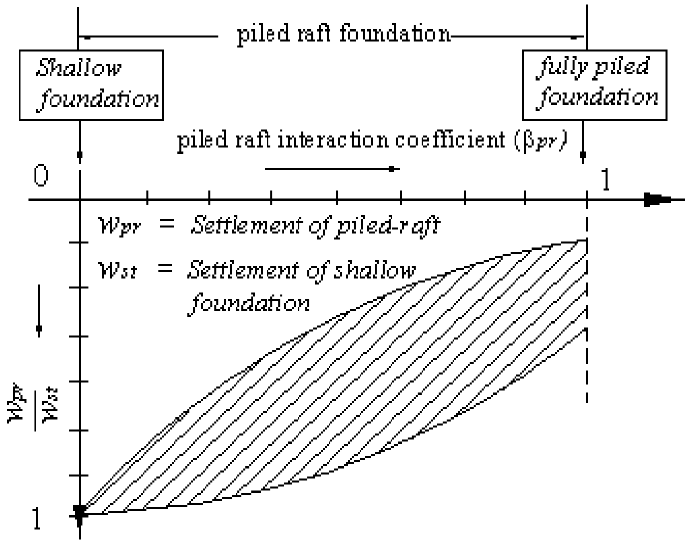

Fig. 5 Foundation settlement as a function of piled raft coefficient (Hemsley, 2000).

V. APPROXIMATE APPROACHES

A. Strip on Spring Approach

Strip-superposition method that describe by Brown and Wiesner [7], in which solutions for pile-strip footings are superimposed to obtain the settlement of the raft. This method does not require the use of computer but is limited to giving settlement only. Poulos [16] developed a method that has been implemented via a computer program GASP (Geotechnical Analysis of Strip with Piles). In this method a section of the raft is represented by a strip and the supporting piles by springs, which is illustrated in Fig. 6. Approximate allowance is made for all four components of interaction (raft-raft elements, pile-pile, influence of a raft element on a pile, influence of a pile on a raft element), and the effects of the parts of the raft outside the strip section being analyzed are taken into account by computing the free-field soil settlements due to this part these settlement are then incorporated into the analysis, and the strip section is analyzed to obtain the settlements and moments due to the applied loading on that strip section and the soil settlement due to the section outside the strip.

The settlement obtains from the analysis is reasonable in compared to other complete methods. However, it has some significant limitations, especially as it cannot consider torsional moments within the raft and also it may not give consistent settlements at a point if strip in two directions through that point are analyze.

Soil non-linearity can be taken into account in an approximate manner by limiting the pile load to not exceed the compressive and uplift capacities of the piles. In carrying out a non-linear analysis, it has been found desirable to only consider nonlinearity in longer direction and to consider the pile and raft behavior in the shorter direction to be linear. Such a procedure avoids unrealistic yielding of the soil beneath the strip and hence unrealistic settlement predictions.

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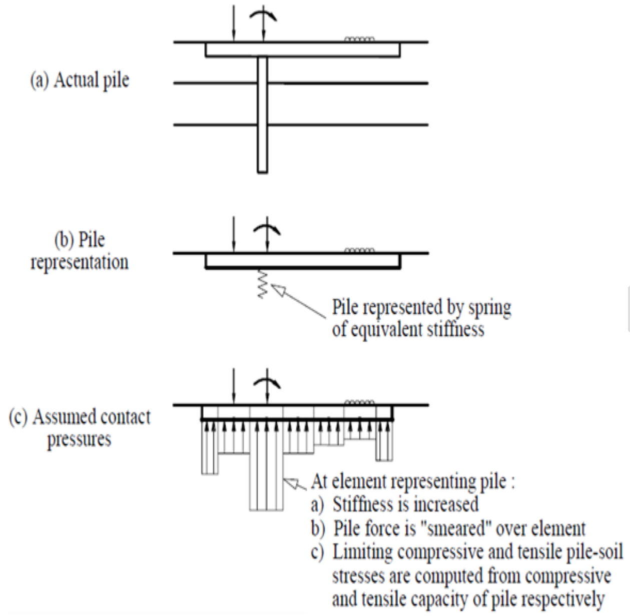

Fig. 6 Representation of piled strip problem via GASP analysis (Poulos, 1991).

B. Plate on Spring Approach

One approach that treated the raft as a thin plate, the piles as springs and the soil as an elastic continuum, was used by Hongladaromp et al. [26] in which the interaction effect between the piles were ignored. Poulos [17] presented a method of analysis of piled-raft foundations in which the raft is modeled as a thin plate and the piles as interacting springs of appropriate stiffness. The analysis is based on elastic theory, but allows for the important non-linear features of the system: the development of limiting pressures below the raft and of the ultimate load capacity of the piles. It allows consideration of the foundation response to applied loads and moments and also to free-field vertical soil movements. The analysis is implemented via the computer program GARP (Geotechnical Analysis of Raft with Piles) which employed a finite difference method for the raft with the consideration of various interactions via approximate elastic solution. Fig. 7 illustrates the basic problem considered, a rectangular raft with piles at various locations subjected to a combination of concentrated vertical loading, concentrated moment loading, uniformly distributed loading over discrete areas.

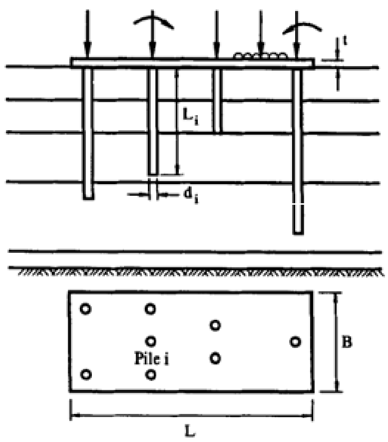

Fig. 7 Definition of piled raft problem (Poulos, 1998).

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Comparisons between other solutions and those obtained from GARP Poulos showed that the later can provide accurate solution for problems involving elastic soil and pile response. Comparisons with centrifuge test data confirm that the analysis provides a reliable indication of the effect of pile length, pile diameter and the number of piles. However, the consideration of the limited load capacity of piles is necessary to avoid under- predicting settlement and over-predicting the amount of load transfer to the piles.

Russo [18] employed a similar method where the piles and soil were modeled by linear or non-linear interacting springs. The soil displacements were calculated using Boussinesq's solution thus yielding a closed form solution. The non-linear behavior of the piles was modeled by the assumption of a hyperbolic load-settlement curve for a single pile. The method has the limitation of only allowing for pure vertical interaction between the raft, piles and soil.

Kitiyodom and Matsumoto [19] presented a similar approach to Hain and Lee [27], but the piles were modeled by elastic beams and the interactions between structural members were approximated by Mindlin's solutions. The foundations can be subjected to both axial and lateral loads and embedded in non-homogeneous soil. This approach incorporated both the vertical and lateral resistance of the piles.

In most of the analysis of piled rafts, the raft is being treated as thin plate. It should be the interest to see the effect using raft as thick plate. Poulos [15] has examined the effect by taking raft thickness of 0.5m. He found no significant difference in the computed deflections for the raft, for both a stiff raft and a flexible raft.

VI. MORE RIGOROUS APPROACHES

A. Hybrid Approach

Clancy and Randolph [20] employed a hybrid method which combined finite elements and analytical solutions. The raft was modeled by two-dimensional thin plate-bending finite elements, piles were modeled by one-dimensional rod finite elements and the soil response was calculated by using an analytical solution. The pile was attached to a raft element at a common node, such that the vertical freedoms are common at the connected nodes. Interaction effects between all pairs of nodes are calculated using the elastic solution of Mindlin (1936) in a point-to-point fashion. The major features of this hybrid finite element-elastic continuum-load transfer approach are presented in Fig. 8.

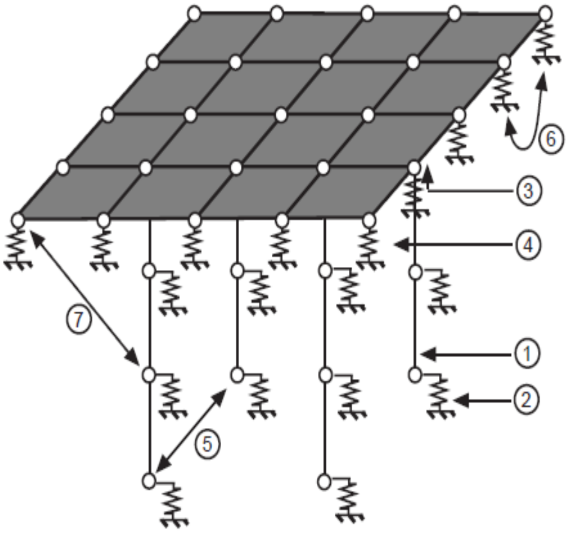

Fig. 8 Numerical representation of piled raft foundation (Clancy et al., 1993). (1) one-dimensional pile element; (2) lumped soil response at each pile-node-load transfer spring; (3) two-dimensional plate-bending finite element raft mesh; (4) ground resistance at each raft node represented by an equivalent spring; (5) pile-soil-pile interaction effects calculated between pairs of nodes-Mindlin's equation; (6) raft-soil-raft interaction; (7) pile-soil-pile interaction.

The hybrid method provides a relatively rigorous and considerably more efficient method of analysis for pile rafts. Fewer equations need to be solved than for the finite element method and the time-consuming numerical integrations of

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International Journal of Innovative Research in Science, Engineering and Technology

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boundary element method are not necessary. The hybrid method allows for variable geometry, pile stiffness, soil stiffness and raft stiffness. Although only vertical applied loading and linear elastic soil conditions are considered here, it is relatively straightforward to allow for non-linear response at the pile-soil interface, or to extend the analysis to include horizontal or inclined loading. However, the method is limited to homogeneous soil.

B. Mixed Technique Approach

A mixed technique based on finite element method and boundary element method was developed by Franke et al. [23] to model the three-dimensional nature of a piled raft. Plate-bending finite elements were used to model the stiffness of the raft, whereas the piles and soil were modeled by non-linear elastic springs and were attached to each node of the finite element mesh of the raft. Boundary elements at the raft-soil and pile-soil interfaces were used to model the contact pressure between the raft and soil and between the piles and soil respectively. The non-linear pile response was described by (i) a hyperbolic shear stress-shear strain relationship for the soil adjacent to the pile raft; (ii) a boundary element solution to obtain the skin friction distribution; (iii) a hyperbolic load-deformation relationship for the soil near the pile base. In the analysis, the effects of construction sequence and pile installation on the non-linear pile response were also taken into account.

A coupled boundary element and finite element formulation has been describe by Mendonca and de Paiva [28]. In this approach the bending plate is assumed to have linear elastic properties and is modeled by Finite Element Method (FEM) while the soil is considered as an elastic half-space in the Boundary Element Method (BEM). The pile is represented by a single element and the shear force along the shaft is interpolated by a quadratic function. The plate-soil interface is divided into triangular boundary element (soil) and finite elements (plate) and the subgrade reaction is linearly interpolated across each element. The subgrade reactions are eliminated from the FEM and BEM algebraic systems of equations, resulting in the governing system of equation for plate-pile-soil interaction problem. The system of equations from the BEM (soil and pile) and FEM (bending plate) are coupled through matrix operations. The analysis dealt with a raft subjected to vertical load only.

C. Software Based Analysis

Reul and Randolph [21, 29] presented a three-dimensional elasto-plastic finite element method for the analyses of piled-raft foundations. The analysis was implemented by finite-element based software code ABAQUS. The structural model based on the finite element method for this analysis has presented in the Fig. 9.

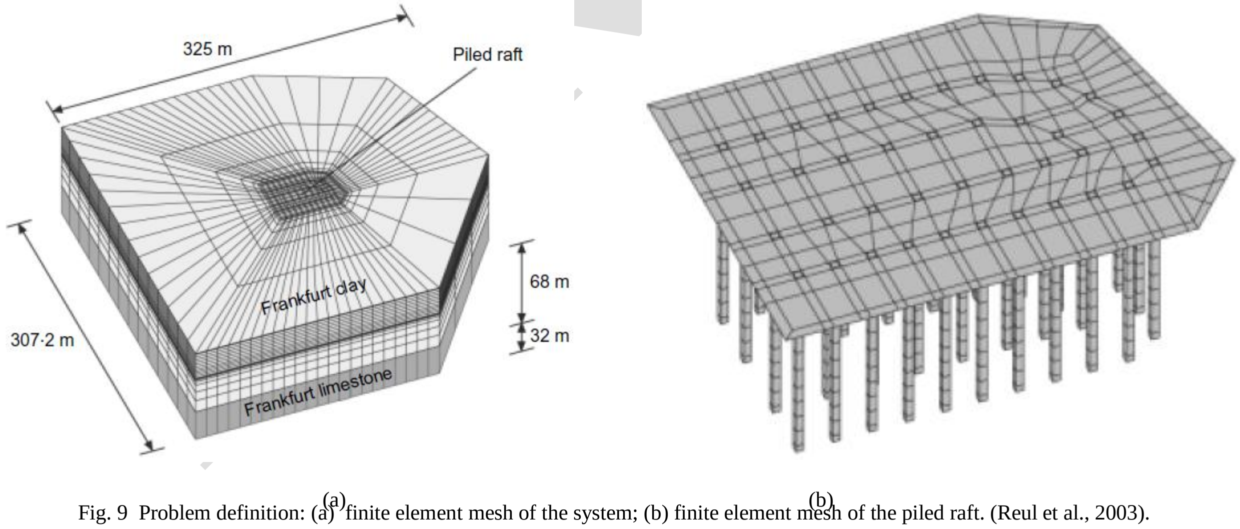

Fig. 9 Problem definition: (a) finite element mesh of the system; (b) finite element mesh of the piled raft. (Reul et al., 2003).

The soil and the foundation are modeled with finite elements, which allow the most rigorous treatment of the soil-structure interaction. The soil and the piles are represented by first order solid brick elements and wedge element respectively. For the modeling of the raft, first order shell element of square and triangular shape with reduced integration has been used. Only the soil below the foundation level is modeled with finite element. The soil above the

DOI: 10.15680/IJIRSET.2014.0310037

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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foundation level is considered through its weight. The circular piles have been replaced by square piles with the same shaft circumference. Soil is simplified to a one-phase medium instead of multiphase by considering drained shear parameters. The soil is modeled by a cap model to simulate the non-linear behavior. The cap model consists of three yield surface segments: the pressure-dependent, perfectly plastic shear failure surface; the compression cap yield surface and the transition yield surface, whereas changes of stress on the yield surfaces cause plastic deformation. The shear failure surface is perfectly plastic, whereas volumetric plastic strains cause hardening or softening of the cap. Plastic flow is defined by the non-associated flow potential of the shear surface and the associated flow potential of the cap. The cap model with yield surfaces in principal stress space and p-t plane is shown in Fig. 10.

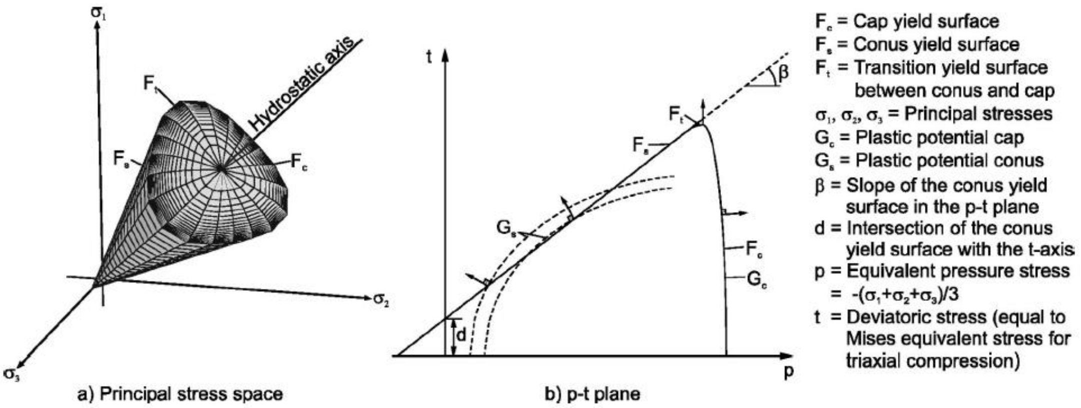

Fig. 10: Cap model: Yield surfaces in principal stress space and p-t plane (Reul et al., 2004).

The interface between the raft and the soil and between the pile and the soil were modeled by thin solid continuum elements and were assumed to be perfectly rough.

Maharaja and Gandhi [22] presented the results of three-dimensional non-linear finite element analysis of raft and piled raft foundations that have been loaded until failure. This method combined an incremental iterative procedure with a Newton-Raphson method to solve the non-linear equations involved in a plasticity analysis. The raft, pile and soil are discretized into eight noded brick elements, which have shown in Fig. 11. In this study the raft and piles are assumed to be linearly elastic and the non-linear behavior of the soil was modeled by the Drucker-Prager yield criterion.

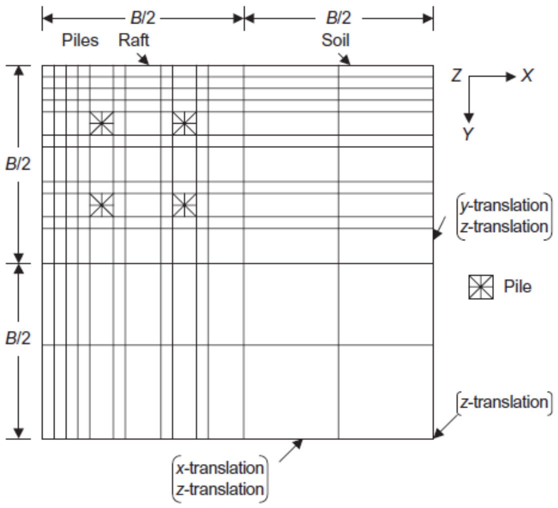

Fig. 11 Finite element discretisation for piled raft foundation (Maharaj and Gandhi, 2004).

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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VII. SOME INNOVATIVE APPROACHES

In soft clay a new type of foundation can be applied successfully where a granular cushion below the raft and short piles made of stone arranged around the long piles of the piled raft system (Liang et al., [2]).

The stone columns are applied to improve the bearing capacity of shallow natural subsoil (Madhav et al. [30]) and the granular cushion plays an important role in mobilizing the bearing capacity of subsoil and modifying the load transfer mechanism of piles. The pressure diffused by the granular layer on pile head mobilizes the negative skin friction on the upper part of the pile shaft (Fioravante and Giretti [31]).

VIII. CONCLUSION

Some of the available methods for analysis of piled raft behavior presented by different researcher are reviewed. All involved number of simplifications in relation to modeling of the soil profile and the loading conditions. The simple methods can be implemented with minimal computer requirements with some limitations. Three-dimensional analysis using numerical method based software like ANSYS; ABAQUA etc. can give more realistic solution. Analysis of foundations embedded in non-homogeneous soil can be done by using finite element based commercial software package. However, solutions those were given by Poulos (2001), Randolph (1994) are mostly used in the design analysis of piled raft foundations.

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