A Critical and Comparative Study on 2D and 3D Analyses of Raft and Piled Raft Foundations

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ABSTRACT: The piled raft foundation has gained a very high level of acceptance as a foundation system whenever settlement alone governs the design. In the design of piled raft many of the traditional methods could not be applied due to the complex nature of interactions involved. Hence there is a need to use detailed three dimensional finite element analyses for the final design. But in the initial stages of design a simpler but effective analytical process need to be used to save the computational efforts. Since the primary requirement in the piled raft design is the design of optimum pile group to achieve the desired settlement reduction, through number of trials, the applicability of simpler two dimensional analyses are examined to save the computational efforts during the initial trials. It was found that simple two dimensional analyses provide results of acceptable accuracy for the design office requirements.

KEYWORDS: Plane strain, Axisymmetric, ANSYS, PLAXIS.

1. INTRODUCTION

The exponential growth in the infrastructure development has forced the designers to accept any ground condition and have to face the challenge of designing a suitable foundation system which will satisfy the safety and economy irrespective of the ground conditions. In the design of foundation system for structures that cannot tolerate settlements, the aspect of balancing the performance and cost, had always been a challenge for the foundation designers. Due to the complexity involved in the soil structure interaction analyses, required for an optimum design, designers have so far been resorting to the traditionally designed pile foundations system permitting very small limiting settlements. Such a foundation system would satisfy the safety and the serviceability requirements effectively but may not satisfy the economic requirements both from cost and time point of view. In many cases raft was found to satisfy the bearing capacity requirements but the control of settlement would not possible. In these cases the presence of the raft and its capability to transfer the load to the soil was completely ignored and the piles were designed as though they would take the entire structural load. Keeping the above objective in mind researchers like Burland (1995) Burland et al., (1997), and subsequently Poulos (2001) had brought out the use of piles with the raft to reduce the settlement of the raft. This had led the advent of the combined piled raft foundation system, which provides a skilful geotechnical concept to design the foundation for structures which are sensitive to settlements.

The concept of piled raft foundation system recognizes the fact that any structure has a certain amount of permissible settlement and the economy of the foundation design depends upon reducing the settlement to the permissible level rather than eliminating it in total. In the combined piled raft system the addition of piles enhances the stiffness of the entire system in the initial stages, and at higher loads provides the additional capacity for the raft to take a higher load at any given settlement compared to the unpiled raft (plain raft).

Piled raft foundation system transfers the load by means of a complicated three dimensional interaction among the constituent elements namely the pile, raft, and the soil. Unlike the traditionally designed pile group wherein the interaction is only between piles and the soil, in the case of piled raft there are four interactions namely raft and the soil, pile and the soil, raft and the pile and pile to pile. Further in the case of piled raft the pile group alone is not intended to ensure the safety of the system but it is the combined system of raft, pile and the soil ensures the safety of the structure. Hence in designing the piled raft it is not the pile capacity alone to be considered but the combined capacity of the whole system has to be considered at any given settlement reduction. Therefore the analyses become complicated.

Studies on the behaviour of piled raft can be classified broadly under three heads namely small scale model tests with 1g model (Weisner and Brown,1978; Balakumar,(2008); Turik and Katzenbach(2003)); centrifuge models (Horikoshi,1995) and observational methods (Katzenbach etal.,(2006), Yamashita etal., (1994) Hooper (1974), Poulos(2008)). The recent developments in the computational facilities in the form of FEA supported by the softwares and hardwares have enhanced the interaction process among the various methods of studies. Consequent to this number of tall and heavily loaded structures have been supported on piled raft and the performance of some of these piled rafts have been monitored and the results are being used to refine the design in the future (Poulos, 2008; Yamashita et al, 2010).

2. OBJECTIVE AND METHODOLOGY

The main problem the designers were facing was that many of the traditional methods of analyses could not be applied since they require a high level of extrapolation and approximations which were beyond the comprehension of past experience. As Russo (1998) has pointed out, to move from the traditional capacity based design to settlement based design method, the analyses must be capable of taking into account properly the soil structure interaction within the foundation system. Finite element analyses are one method which is by far well developed and found to be more suitable to analyze the piled raft problem. However, it has been found that in order to reduce the computational efforts, under many circumstances the rigors of the method has to be diluted by some approximations and simplified assumptions. While a number of simplified methods have been developed to analyze the large pile groups, no such method appears to be available for the analyses of piled raft. The present work makes an effort to establish the applicability of simple two dimensional models for the preliminary analyses and design of piled raft.

Two 1g models of piled raft (circular and strip) whose load settlement response had been established (Balakumar, 2008) were subjected to axisymmetric analyses and plane strain to establish the accuracy of the analytical procedure. Typical problems, one hypothetical and the other from a monitored piled raft were also subjected to analyses with PLAXIS 2d and PLAXIS 3d based on plate on piles approach and equivalent pier method to establish that the type of softwares has no influence on the results.

3. DESIGN PROCESS

The design of piled raft has got three stages as pointed out by Poulos (2008) in many of his publications. They are: i) Preliminary, ii) Approximate iii) Detailed Analyses. Since there are three stages of design, it becomes necessary that appropriate analyses methods have to be adopted so that there will not be any unnecessary loss of computational time and efforts. Further for the detailed analyses the main requirement is the evaluation of in situ geotechnical parameters which will be the critical input data. In the geotechnical design the most difficult part is the evaluation of the in-situ parameters of the soil. This process can prove to be expensive but the accuracy of the output from the analyses largely depends upon the reliability and accuracy of the parameters and methods adopted for their evaluation. The first and the second stages of design and analyses must be such that with reasonably minimum computational efforts it must be able to establish a reasonable data and the limitations of the available parameters so that any additional requirements can be planned and obtained.

The satisfactory performance of piled raft largely depends upon the performance of the pile group of piled raft in providing the initial stiffness and then allows the raft to have a higher capacity by functioning as settlement reducer. Hence after ascertaining the feasibility of the piled raft to support the structure, a preliminary analysis has to be done to finalize the conceptual details of the constituent elements. Primarily the number, lengths of the piles, the load shared by the pile group are the essential parameters in addition to the properties of the supporting soil layers. In the case of the piled raft the pile group capacity and the overall capacity of the piled raft play an important role.

The second stage of analyses has to produce these data in a reliable manner such that when used in the final analyses, the analyses will produce a design which need not be subjected to any iteration process. This requirement makes the procedure to be more realistic and simple enough such that the computational efforts are minimum and economical. Even though the existing methods can provide a design approach, these involve a very detailed computational effort, not really warranted for the second stage of design, from the commercial design organization point of view. Therefore it is essential to have a relatively simple design procedure so that the second stage of work can give adequate but reasonably accurate data for the final analyses.

In the third stage once the parameters are finalized a detailed analyses need to be done to effectively establish the design forces and the economics by confirming the achievement of the settlement reduction required, and the load shared by the pile group at the required settlement reduction and other needed parameters needed for design is established. Also the ductile behaviour is also established by assessing the shaft friction distribution and ensures that the tip stresses are very small.

In most of the cases, such parameters are obtained either from laboratory tests or from standard correlations between tests like SPT and Es values, which can affect the accuracy of results. However over the past few years there is a considerable shift from the laboratory testing to in-situ testing and this has led to the use of the results from in situ tests such as CPT and pressure meter tests extensively to determine the stress strain characteristics and essential parameters like the in-situ elastic modulus of the soil over the length of the pile. A well tried procedure for predicting such parameters along with the shaft friction development has been published by Frank et al., (1991) using pressure meter tests.

However it appears that the phenomenon of the interaction between the constituent elements has not been studied in detail. The complex interaction can become favorable like increase in the group capacity or unfavorable like causing additional settlement. The study on the interaction behaviour gains importance, as in the case of piled raft the interaction takes place between the pile – raft –and the soil.

4. SELECTION OF SOFTWARES AND ANALYSES

The role of analyses in the design process becomes clear only when the design objectives are established. The facets of analyses such as identification of appropriate parameters and a clear understanding of empirical methods play a very important role. Since the piled raft analyses is a three dimensional problem any particular software must have provisions to represent the continuum in a realistic manner. This would mean that the software must have a good element library, an array of material models and provisions for mesh refinement. Hence the selection of software also plays a very important role. Further problems can arise if the elements representing the soil become too large and interface elements are not used. To avoid this, solid elements are used with or without interface elements and the properties are assigned to the soil with adequate care.

Considering the various uncertainties coupled with the difficulties involved, there is every possibility of designers getting confused to decide the methodology for the preliminary design and analyses. This appears to have resulted in the designers adopting empiricisms in the analyses. Therefore it is felt that there is a need for studying the extent to which simpler methods can be followed and when the detailed three dimensional analyses is necessary. In the present work three different cases are considered namely linear elastic analyses, axisymmetric and plane strain conditions in modelling and detailed three dimensional analyses are carefully discussed. The details of finite element analyses carried out are discussed in the various publications of the author (Balakumar, 2008; Balakumar and Ilamparuthy,2010). For this purpose the results of small scale 1g model tests on circular piled raft (Balakumar and Ilamparuthy, 2005); and rectangular piled raft Balakumar and Ilamparuthy, 2008) are studied with ANSYS. For getting the raft contact stress, pile head and tip stress along with shaft stress distribution 3-D nonlinear analyses has been performed on the circular piled raft. The results from the 1g tests on the rectangular piled raft are compared with the load settlement response from the plane strain analysis with ANSYS. In all these cases the loading was applied in the form of uniformly distributed pressure load as done in the case of model tests. The result obtained by monitoring the piled raft supporting a twelve storied building is validated with three dimensional analyses, by equivalent pier method. One grid was taken to be analyzed with plate on piles method using PLAXIS-2D and PLAXIS-3D.

To revalidate the analyses a hypothetical problem of piled raft resting on a generalized soil profile obtained from various reports of investigations done in GoldCoast, Australia has been analyzed with PLAXIS 2D and PLAXIS 3D and are compared. The details of the material model and the procedures are explained in detail by the second author (Min Huang, 2006). The results are discussed to arrive at a conclusion of when simpler methods can be used and when three dimensional methods become essential. The essential requirements in all these things are the study of the mechanisms of failure. In this present case this has been based on the 1g model tests on piled raft.

5. PILED RAFT-MECHANISM OF FAILURE

Before reviewing the merits and demerits of the different types of analytical procedures the behaviour of piled raft at various settlement levels need to be discussed. The behaviour is explained in the following parts based on the results of 1g model tests conducted by the first author (Balakumar 2008). As pointed by Murray and Geddes (1989) although the results of 1g tests do not provide a direct comparison with full scale behaviour, they can be of value in providing an understanding of the behaviour patterns and can be a guide to full scale performance particularly when examined in conjunction with the developed theoretical solutions

Figure 1 (Balakumar etal., 2005) presents a comparison between the load settlement response of free standing pile group (wherein the raft is not in contact with the bed) and the pile group of piled raft. In the case of free standing pile group, it is seen that once the friction is overcome the pile group settles instantaneously where as in the case of pile group of piled raft even after the friction is overcome the pile group continues to take further load;. The settlement level at which the friction is overcome is termed as critical settlement and this magnitude is far higher than that of free standing pile group. It can also be seen that at any particular settlement level the load taken by the pile group of piled raft is higher than the free standing pile group The enhanced carrying capacity of the pile group of piled raft is mainly due to the enhanced confining pressure caused by the raft transferring the stress due to the applied load on the soil surrounding the piles.

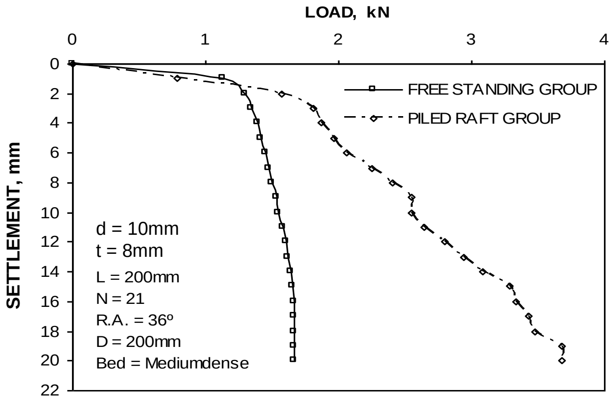
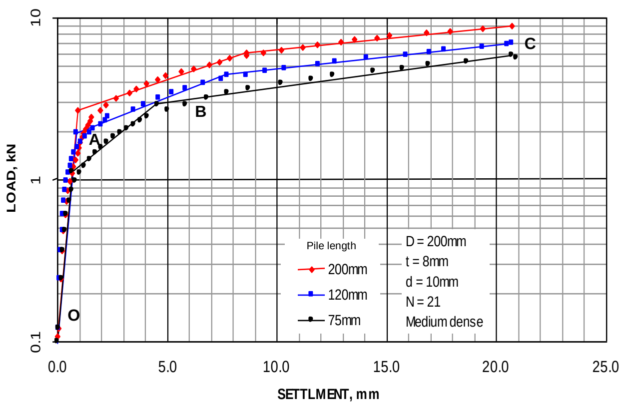


Figure 1 Comparison of load-settlement response of free standing pile group and pile group of piled raft

Figure 2 presents the characterised load settlement response and Figure 3 is a plot between the load sharing ratio α_{pr} which is the load carried by the pile group to the total load carried by the piled raft at any particular settlement level and settlement of the piled raft which is the load sharing response of the piled raft. From the Figure 2 it can be seen that the load settlement response of piled raft has three phases. Phase OA exhibits a very high stiffness indicating that the pile group mobilizes the entire friction and the major part of the applied load is taken by the pile group. In the Figure 3 till a settlement level of 1.5 mm to 2mm the load sharing ratio is very high confirming this. The phase AB is the elasto plastic response where in the loss of stiffness is gradual and the load sharing ratio drops down till a settlement reaches 5mm to 6mm; the phase BC shows a plastic response wherein even for a small increase the loss of stiffness is very rapid although the behaviour exhibited is elastic work hardening.

Figure 2 Characteristic response of piled raft for various pile lengths



Correspondingly as seen in Figure 3 the load sharing ratio remains constant with the increase in the settlement indicating that the pile group at this stage becomes a non load bearing member but functions as settlement reducer for the raft. The behaviour was found identical irrespective of the shape of the raft and the physical features of the piles.

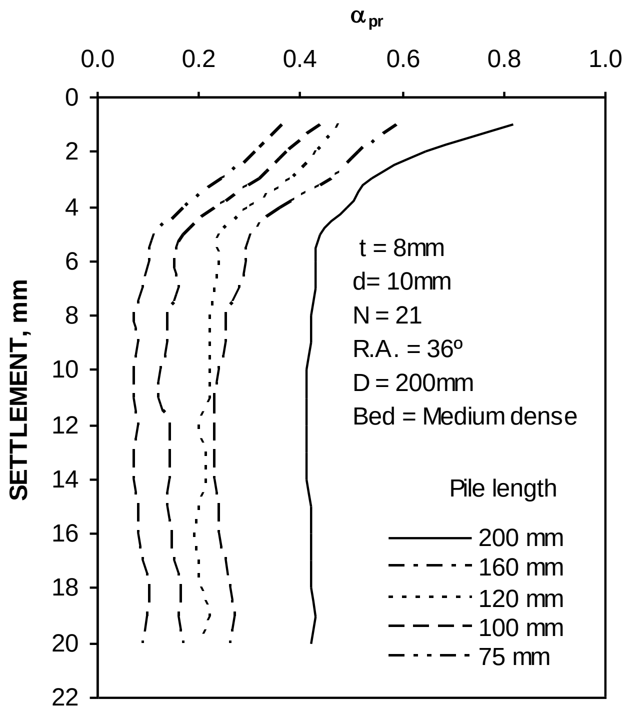


Figure 3 Settlement v/s LS ratio α_{PR} for 10mm dia pile

The ratio α_{pr} is defined as the ratio between the amount of load (shaft resistance + base resistance of all piles) shared by the piles at a given settlement of piled raft (Q_p) to the total load on the piled raft causing same settlement (Q_{pr}).(Balakumar,2008)

$$\alpha_{pr} = Q_p / Q_{pr} \tag{1}$$

where $Q_p = Q_{pr} - Q_r$ and Q_r = load shared by the raft at the same settlement.

Therefore the mechanism of the piled raft behavior has three phases and it is the second phase, namely the elasto plastic stage is very critical for the design and perhaps we can say that this is the limiting level of piled raft for serviceability requirement. Based on the above Balakumar et al., (2013) had presented a quantitative assessment of interaction and it was found that the interaction factor was found to be around 0.6 to 0.8 which is the maximum. Balakumar et al., (2015) had presented that the limiting capacity shall be restricted to the end of elasto plastic stage when the settlement level reaches around 5% of the pile length.

6. NUMERICAL ANALYSES

6.1 Linear Analyses

The linear analysis has been carried out in the case of circular piled raft to serve as a preliminary study and also to check and compare the settlement level up to which the results of 1g model studies and the numerical analysis agree with each other. The three dimensional linear analysis using ANSYS software was carried out on the circular piled raft with 21 piles in radial grid. Half model was used as given in Figure 4.

Table 1 and Table 2 present the basic data of the circular piled raft and the bed materials characteristics.

Table 1 Properties of circular piled raft

Raft		Pile			E_r N/mm^2	μ_r
Dia, mm	Thickness, mm	Dia, mm	Length, mm	Area ratio		
200	8	10	160	5.2%	3000	0.30

Table 2 Properties of bed material

Material	γ' kN/m^3	ϕ	E_s N/mm^2	μ_s	State of compaction
Poorly graded sand	15.5	37.5^0	35	0.30	Medium dense

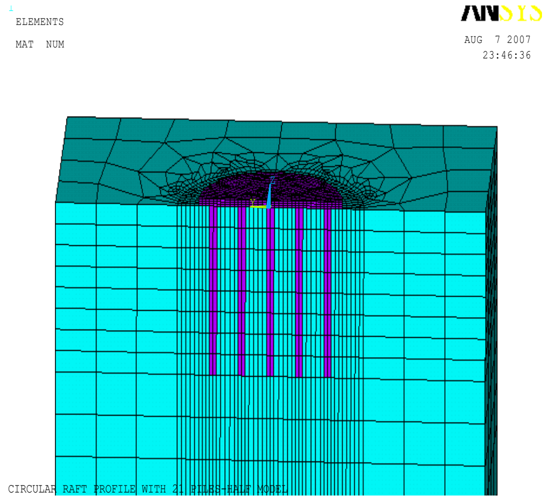


Figure 4 Finite element mesh for piled raft (linear analysis)

The ANSYS material table contains more than 40 material models. Out of these, the linear elastic and the multi-linear isotropic hardening material (MISO) model are used to simulate the linear elastic and the nonlinear behaviour of the soil respectively. The soil medium below the raft was modeled using an eight-node brick element (SOLID 45) having three degrees of freedom of translations in the respective co-ordinate directions at each node.

Figure 5 presents the comparison of the load settlement response of the piled raft obtained from the 1g model test and the linear analyses. A study of the curves indicates a very close agreement upto a settlement of 1.5 to 2.0mm at which the full friction was mobilised. This settlement value can be called as critical settlement. As the load increases the linear analyses exhibited a very high stiffness indicating that the load sharing behaviour is independent of the stress level. But the 1g model test showed non linear behaviour beyond the critical settlement and hence the linear analyses is not applicable to capture the load settlement response of piled raft over the entire load range as the response changes to elasto plastic and plastic behaviour. However the linear analyses can be considered for use when the loading is small namely within the elastic limits for obtaining the settlement.

6.2 2-D Axisymmetric Analyses

The axisymmetric analyses is carried out using the same circular piled raft model used for the 1g test with the intention of establishing the adequacy of the method in predicting the load settlement response and the settlement reduction possible for the given pile layout. The same model is used for the 3D analyses subsequently.

The axisymmetric analyses retains the essential features of the three dimensional analyses. Hooper (1978) in his study on the behaviour of the Cavalry Barracks building had used the axisymmetric analyses to study the settlement response of the piled.

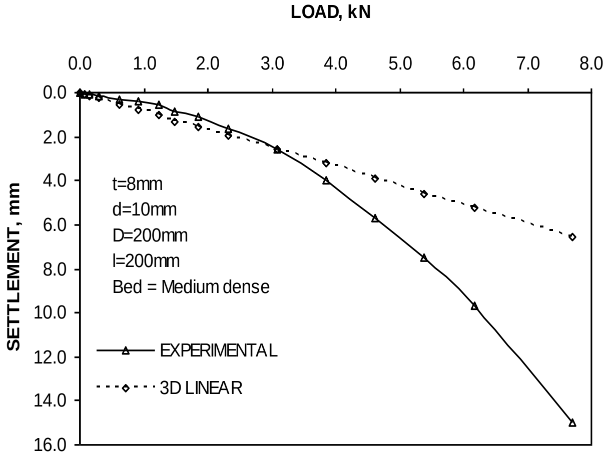


Figure 5 Comparison of load – settlement response between ANSYS (linear) and model test results for circular piled raft

raft supporting the above structure. In the analyses the pile cap was assumed to be flexible. The procedure simulates each concentric row of piles by a continuous annulus with an overall stiffness equal to the sum of the stiffness of each individual pile. The modulus of elasticity of each annulus was taken as an equivalent modulus .The problem is a large deformation problem. The equivalent modulus was worked out as outlined by Desai (1974) for the plane strain wall and subsequently used by Prakoso and Kulhawy (2001) for piled raft analyses using plane strain model. No slip between the raft and the pile is implicit in the finite element formulation of the problem. In this case the problem is much simpler satisfying the requirement of the normal stress at the interface of soil-raft along which the common nodes joining with dissimilar properties.

Here each row of piles in the plane is converted into a plane strain pile wall of an equivalent pile Young's modulus as indicated in the equation below

$$E_{eq} = \frac{n_{p-row} A_p E_p}{L_r B} \tag{2}$$

where, np-row : number of piles in a row
A_p : area of pile crosses section
E_p : pile Young's modulus
L_r : raft length in plane
B : pile diameter.

Figure 6 presents the model. The soil was idealized by MISO model. The features of the model were maintained as the same as that used in the earlier analysis. The analysis was carried out with the pressure load applied in steps of small increment. This case also the agreement between the two was very close till the critical settlement level of around 2.0mm

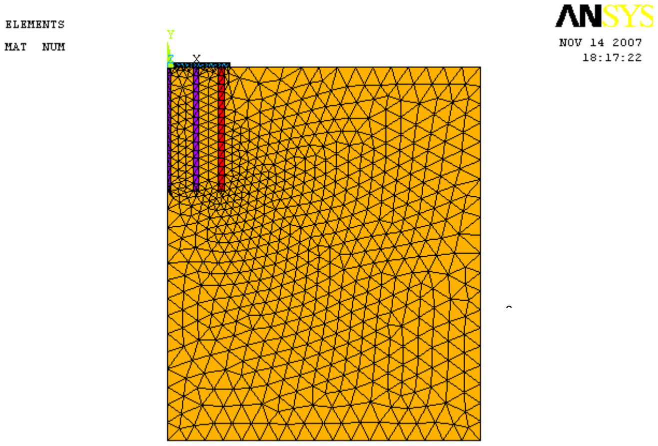


Figure 6 Axisymmetric model and mesh used in ANSYS analysis

Figure 7 presents the comparison of the load settlement response obtained from the 1g model test and the axisymmetric analyses. As the load increases the model was predicting a higher stiffness and at the maximum load the variation was of the order of 10%. Figure 7 represents the characteristic load settlement response obtained from the 1g model tests and the axisymmetric analyses. The very close agreement upto the elasto plastic region clearly indicates that the axisymmetric analyses can be used for circular piled raft. The stiffer behaviour in the analyses can be attributed to the idealization of the pile group as a pile wall comprising of two dissimilar materials. Russo and Viggiani (2001) has explained that the accuracy of available computer software is probably no better than +/_ 20% but in this case it is only 10%., although the medium is homogeneous poorly graded sand. Katzenbach (2005) had also observed that the implementation of linear and non-linear soil modulus depends upon cases under study as the results can vary to an extent of 20% to 30%. It is to be noted the change in the slope of the load settlement curve indicates the change in the load haring process between the pile and the raft. This was not exhibited in the linear analyses. In the case of axisymmetric model higher stiffness is mainly due to the computation of equivalent modulus which comprises of mainly the soil prism which has not been properly accounted for.

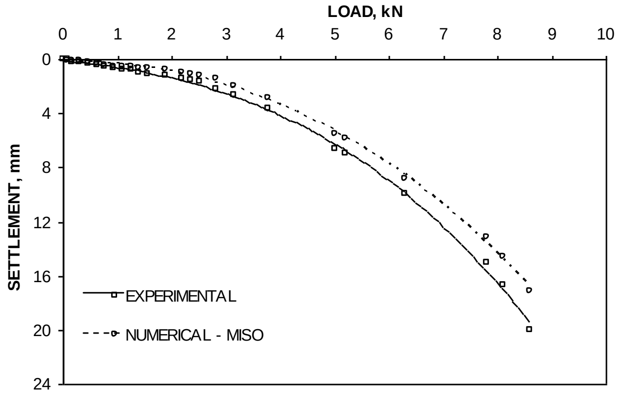


Figure 7 Comparison of load-settlement behaviour between numerical and 1g model test data
(D=200mm, t=8mm, d=10mm and l=100mm)

However the study truly represents the non-linear behaviour and is capable of identifying the change in the load sharing behaviour of the pile group. Hence this procedure is adequate for predicting the behaviour of circular piled raft or a piled raft with radial pile layout or in a circular pile layout with square grid pattern. But the limitation in this case is that the load sharing behaviour or the ratio cannot be estimated as the contribution of the soil prism in the annulus cannot be separated.

6.3 Plane Strain Analyses

The piled rafts supporting a rectangular storage structure have mostly piles placed in rows and columns with the raft covering them as common cap. Under favorable circumstances this can be designed as piled raft. A simpler procedure for analyses can be a plane strain analyses. To establish the nature of such behaviour a 1g model test was carried out on a rectangular piled raft (Balakumar and Ilamparuthy, 2010). The bed material used is the same as in the previous tests namely medium dense poorly graded Palar sand. The model had two rows of piles at 4d spacing (where d is the diameter of the pile). The plane 42 elements were used and the problem was defined as plane strain. The value of E_S and the bed density were retained as same in all the studies. The equivalent modulus for the plane strain pile soil was computed using the same expression as done by Prakoso and Kulhawy (2001).The details of piled raft and bed material is presented in Table 3.

Table 3 Details of piled raft and bed material

Raft		piles			Sand bed		
Size B×L	Thickness mm	N	Length mm	Area ratio %	Bed density kN/m^3	E_s KN/m^2	ν_s
70×200	8	14	75	7.85	15.5	35	0.30

Figure 8(a) provides the model. The settlement contour, Figure 8(b) indicates a maximum settlement of 12.5 mm and 11.4mm at its center and the edges respectively. At pile locations the settlement obtained were 11.4mm and 11.3mm and the pile tip settlement was found to be 8.4mm.

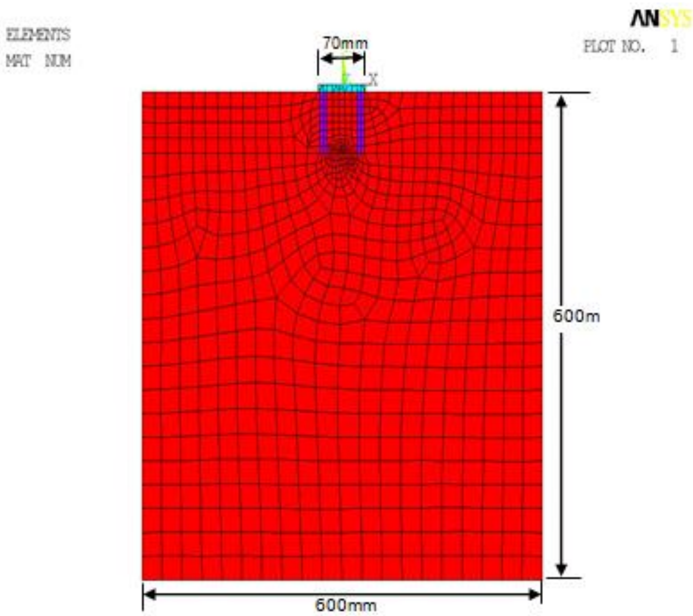


Figure 8(a) Rectangular piled raft model with finite element mesh used in plane strain analysis of ANSYS

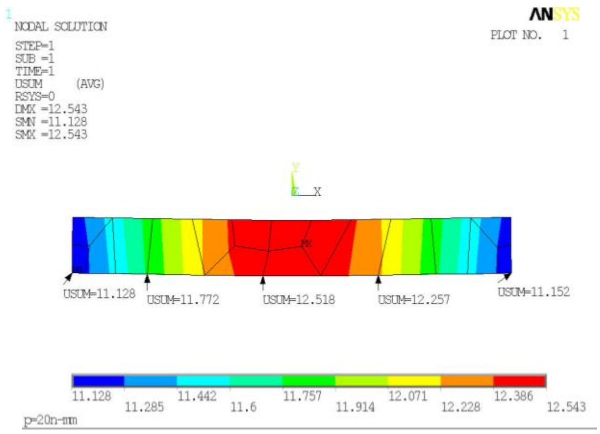


Figure 8(b) Settlement of piled raft at the load of 1.55 kN

Figure 9 presents the comparison of the load settlement response obtained from the 1g model tests and the numerical analyses. The plane strain model has predicted a stiffer behaviour and the variation increases as the load level increases. It is seen clearly that the two dimensional plane strain and axisymmetric models predict identical response of higher stiffness mainly due to the idealization of the equivalent modulus. Consequent to this the load shared by the pile group based on the plane strain analyses is expected to be higher because of the influence of the soil prism.

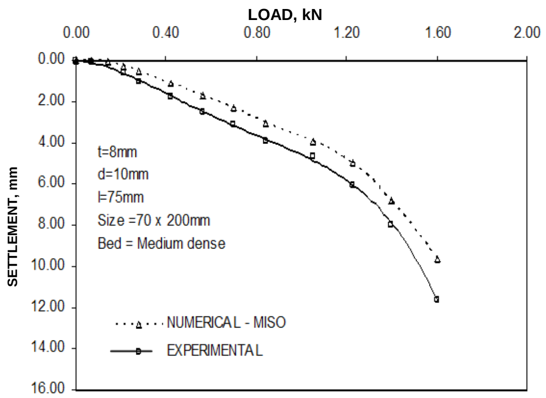


Figure 9 Comparison of load-settlement response between ANSYS and test data for rectangular piled raft

6.4 Non Linear 3D Analyses of 1g Model Tested

From the previous study it is seen that the axisymmetric model and the plane strain model which could bring out the load settlement response but because of the stiffer behaviour they exhibited, the load sharing ratio and the pile shaft stress distribution can be on the higher side and may not be realistic. Hence it was decided to conduct a three dimensional non linear analysis.

For the three dimensional analyses the bed density was retained as medium dense as in the two previous cases with the phi value as 37.5 and the unit weight was taken as 15.5 kN/m^3. The bed material was represented by MISO model. Solid 45 elements with three degrees of freedom at each node were taken to represent the bed material.

The soil was idealized as an isotropic homogenous half-space. The nonlinear behaviour of the soil is modeled using the multi-linear isotropic hardening (MISO) material model of ANSYS. This model incorporates the Von-Mises yield criterion with associated flow rule and isotropic work hardening.

To provide the required parameters as the input for the MISO model triaxial tests were conducted on dry Palar river sand used in the experiments. The test was conducted at an average unit weight of 15.5kN/m^3 (15.5 + 0.1kN/m^3) under different confining pressures. A value of 0.35 was used in computation for Poisson's ratio.

In selecting the elements for the various structural components of piled raft, certain important aspects as given in the manual were considered. When elements having different degrees of freedom are selected, there will be inconsistency at the interface. When elements are not consistent to each other, at the interface, the analyses may not transfer appropriate forces or moments among the different connecting nodes of the various elements at the interface. To ensure compatibility between the elements used for modelling different structural elements, they must have the same degrees of freedom. The DOFs must overlay each other and must be continuous across the element boundaries at the interface. For example if a solid 45 element is joined either to shell 63 or beam 4 element, the nodal forces corresponding to displacement DOFS will be transmitted to the solid element. But the nodal moments corresponding to the rotational DOFS of the shell element will not be transmitted to solid 45. Although these conditions may not invalidate the analysis, it is appropriate to select compatible elements for various components of structure. Solid 45 elements were used to model raft, pile and soil continuum.

In the analysis the bed dimensions were kept same as that of the lab model tested in the laboratory. The raft and pile were modelled as solid 45 elements in order to maintain the element compatibility. Reasonable mesh refinement was done with an achieved aspect ratio of 5. Required checks were made for element continuity and continuity at nodes. The material property was fed in the form of stress-strain data. The mandatory check for proper meshing at various levels, element continuities etc. were made and then the solution command was activated to solve the model after applying the load. The load was applied as pressure in small increments till the load on the raft equal to the final test load. Figure 10 shows the quarter model including finite element meshing adopted in the analysis. At the maximum load of 8.1 kN the settlement was found to be 17.7mm.

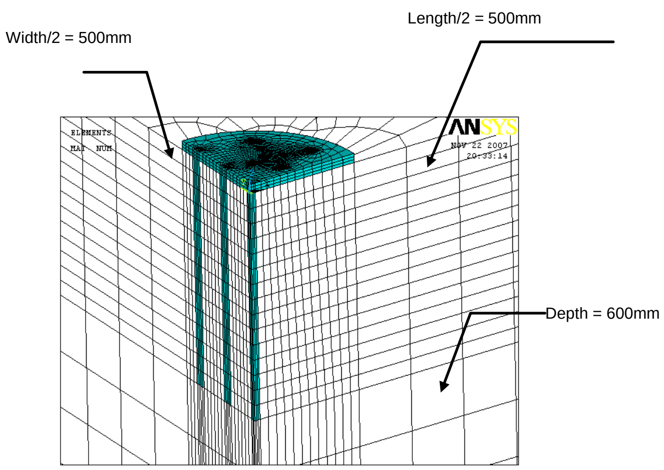


Figure 10 Finite element mesh of a circular piled raft (Quarter model) used in ANSYS analysis

Figure 11 presents the settlement contour. From the contour the piles had settled uniformly and the settlement was 15mm.The settlement of the soil below the raft decreased with the depth and the influence was up to a depth of 2.5 times the raft size.

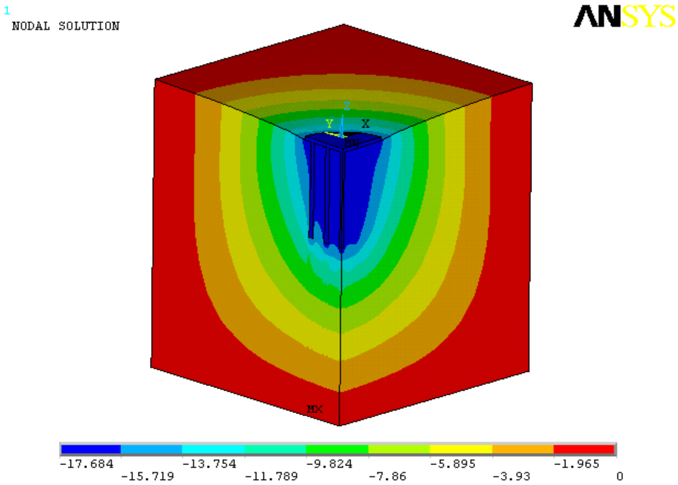


Figure 11 Settlement contour for a circular piled Raft for the load of 8.1 kN

Figure 12 presents the comparison of the load settlement response obtained from the 1g model tests and the non-linear 3D analyses. It can be seen that the agreement is far better when compared with the axisymmetric analyses. The variation at the higher loading was found to be of the order of 5% only. The comparison of the characterised response given in Figure 13 confirms that the three dimensional analyses presents closer response to the actual behaviour obtained from the 1g tests. Therefore the results can be used to predict the raft stress and the pile shaft stress distribution.

Figure 14 presents the raft stress distribution under a loading corresponding to 2mm settlement and 17.7mm settlement at the maximum load. It can be seen that in both the cases the stress distribution is uniform; at 2mm settlement the contact stress was found to vary from 0.02N/mm^2 to 0.4 N/mm^{2}.. From this it can be computed that the load shared by the raft was of the order of 35% of the applied load at the final settlement level the raft stress varied from 0.162 N/mm^2 to 0.169 N/mm^2.The load shared by the raft at this level was found to be 64% of the final load.

Figure 15 and Figure 16 represents the pile head stress and the tip stress at the maximum. It can be seen that the pile head stress increases with the load. The tip stress is very small and the increase in the tip stress is not in proportion with the load applied. The ratio of the head stress to the tip stress is of the order of 11%, 9% to 10% and 17% to 19% in the central, the inner ring and the outer ring of piles respectively.

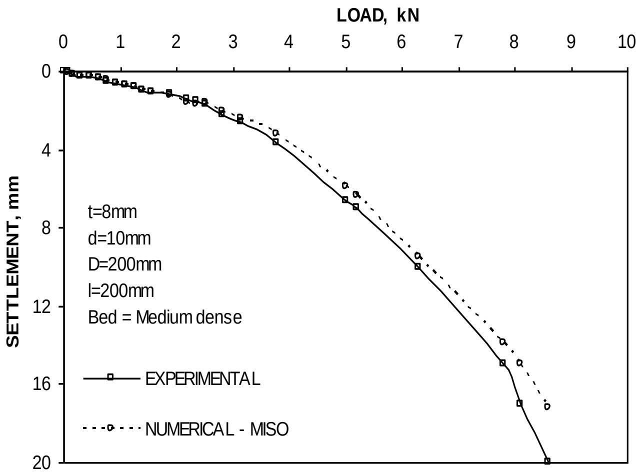


Figure 12 Comparison of load-settlement behaviour between ANSYS and model test data (Circular Raft)

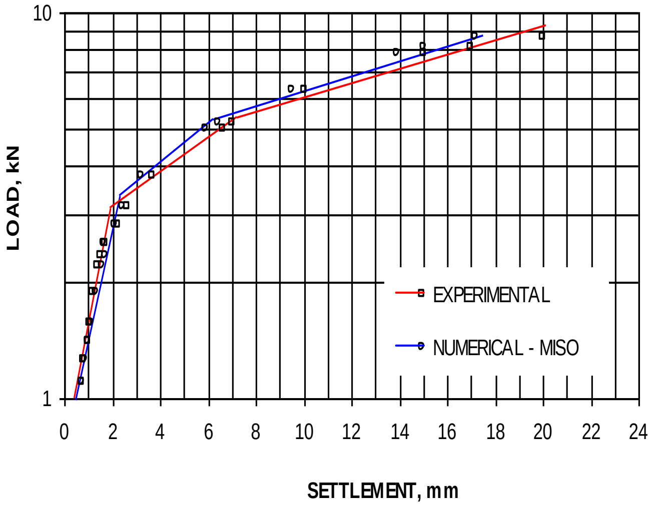


Figure 13 Characterization curves for experimental and numerical 3D Circular

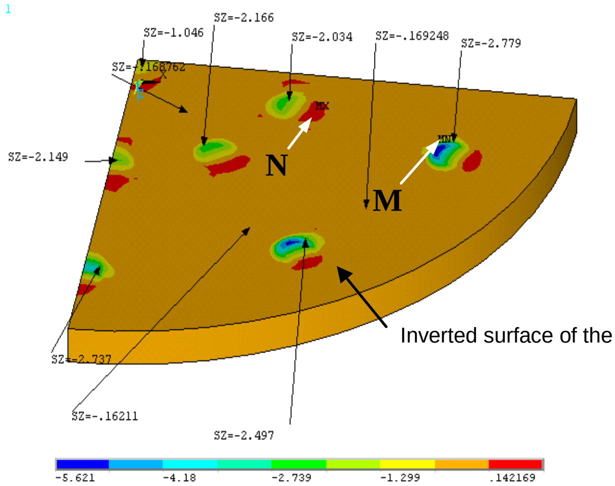


Figure 14 Vertical stress at typical locations of the raft for the load of 8.10 kN (settlement = 17.80mm)

Figure 17(a) indicates the shaft stress distribution and the variation in the shaft stress distribution also follows a similar trend. It is seen that the shaft stress reduces to a negligible value beyond a length of 0.8L which can be termed as critical length as predicted by Vesic (1969). A similar trend was seen in the case of square raft also as in Figure 17(b), establishing the ductile nature of the pile group.

It can be concluded that while the axisymmetric analyses and plane strain model could predict the load settlement response the load sharing response could not predict a reliable manner due to the stiffer load settlement response. On the other hand the three dimensional analyses could bring out not only the load settlement behaviour in a realistic manner but also the load sharing behaviour and the individual pile stress establishing the ductile behaviour of the pile group. Hence it can be concluded that the initial analyses for the preliminary designs for establishing the pile layout, length and the diameter needed to obtain the settlement reduction achievable and once this is done the layout and data can be used for the detailed analyses.

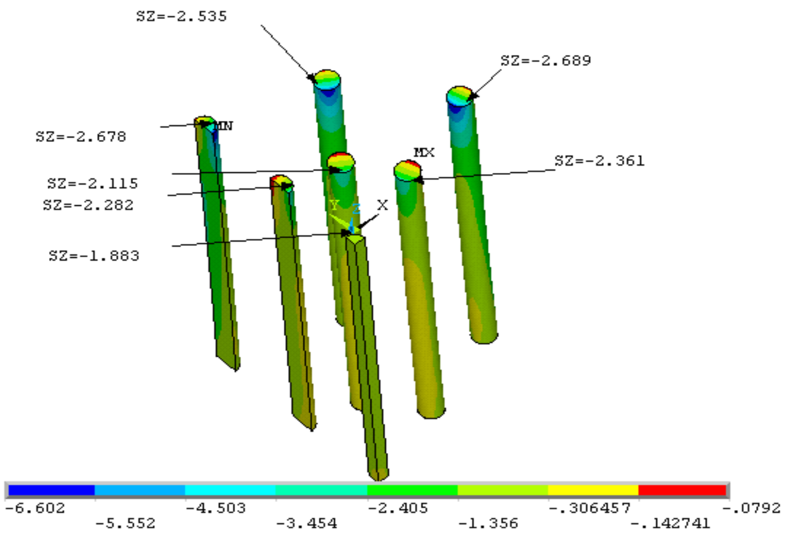


Figure 15 Pile Head stress for the load of 8.1 kN
(settlement =17.8mm)

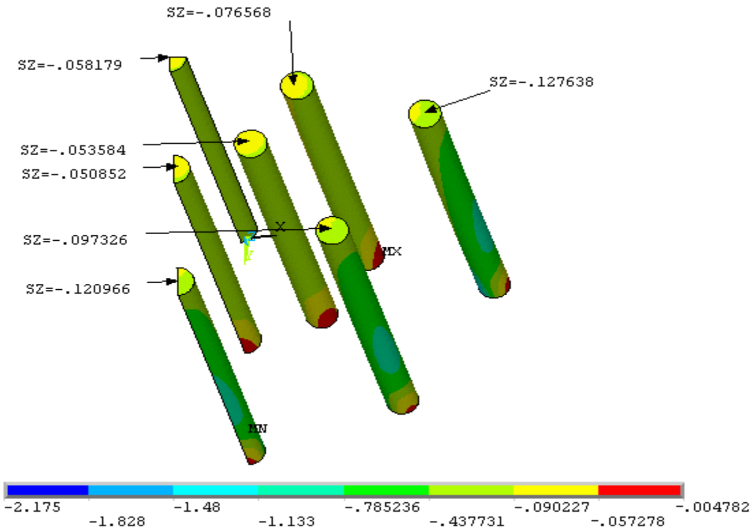


Figure 16 Stresses in pile tips for the load of 2.1 kN
(Settlement =1.8mm)

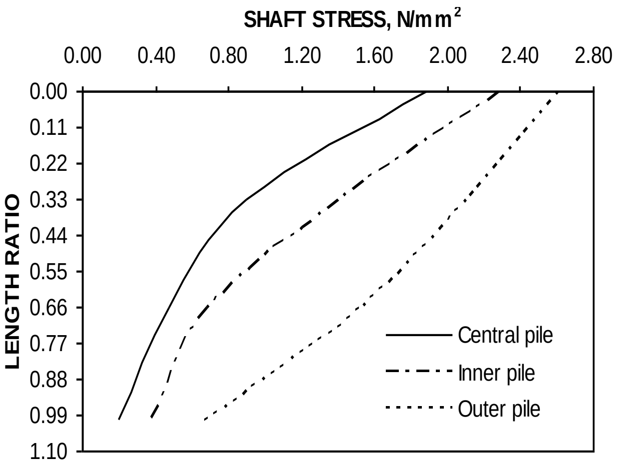


Figure 17(a) Variation of stress along the shaft of typical piles along the center line of raft for 8.10kN

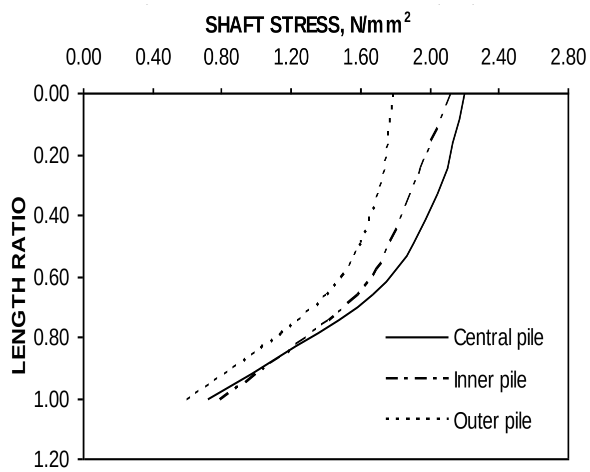


Figure 17(b) Variation of stress over the length of pile of square piled raft for the load of 8.7kN (No. of piles 25 at 4d spacing)

6.5 OBSERVATIONAL STUDY

Having established through the small scale model studies the applicability of simpler procedure and the load transfer mechanism and the tendency of the piled raft losing its stiffness rapidly, it becomes necessary to validate the above conclusions through an observational study. To achieve this, published results (Balakumar and Ilamparuthy, 2007) of an observational study conducted by monitoring the piled raft supporting a basement plus twelve storied structure namely Palace Regency are used.

The structure under study is has a plan measurement of 32mx 25m with the height being 36m.The frame was analysed with STAAD-PRO and the support reactions were taken to design the piled raft foundation system. The pile layout with the settlement markers are presented in Annex A. The piles are 14 m deep from the raft bottom and were resting on medium dense to dense sand with the N value of the order of 45. In all 93 piles of 600mm diameter were provided with a 600mm thick raft. The maximum coloumn load was 2700kN and the minimum value was 1100kN. The coloumn loads were applied as point loads in the coloumn locations. The C.G of the pile group and point of application of the coloumn were coinciding. The piled raft was monitored for a period of 790 days including the post construction period. The maximum settlement was 14mm.The loading was within the elastic limits and hence the linear analyses were fully justified. The analyses were done with ANSYS. The analysis shown in the present work are restricted to elastic condition for the following reasons:

(i) From practical point of view, elastic analysis is simple and most convenient for the piled raft system which involves complex interaction between the raft, pile and soil, in addition to the three dimensional nature of foundation.

(ii) The strain level around piled foundations is small, particularly under working loads. Thus majority of piled raft foundations can be delt with using elastic approaches with moduli chosen with due consideration of small strain condition.

(iii) Elastic methods (Poulos and Davis, 1980) contributed significantly to me practical analysis of different foundations. Further most of the references available on the behaviour of piled are based on elastic approaches. The interface characteristics between the raft and soil have been represented by the element Targe 170 and Conta 174.

In the analysis perfect contact between the raft and soil is ensured through default option available in the program. Half model has been taken to reduce the computing time. In order to generate the mesh, map meshing technique has been adopted. Reul and Randolph (2002) have studied the effect of mesh refinement on the quality and accuracy of the results and have proved that mesh refinement beyond a certain extent does not enhance the quality of the results. However in our analysis the maximum aspect ratio adopted were 5. The column forces (axial, lateral and moment) computed from the three dimensional frame analysis in the form of support reactions were applied at the respective column locations.

Figure 18 presents the model with meshing. The coloumn loads were applied in the respective column locations. The interface characteristics between the raft and the soil were represented by Tange170 and conta 174.In the analyses perfect contact between the raft and the soil was ensured through the default option available in the software.

Figure 19 presents a comparison of the observed settlements and computed settlements. .It is seen that that settlement profile matches very closely with observed settlement profile.. More details of this work is presented in another publication (Balakumar and Ilamparuthy, 2007). Figure 20 presents the raft stress distribution It is seen that the stress close to the pile locations are more intense than the stress between the pile groups. Figure 21 presents the head stress and tip stress values and it was found that the raft was sharing nearly 40% of the load

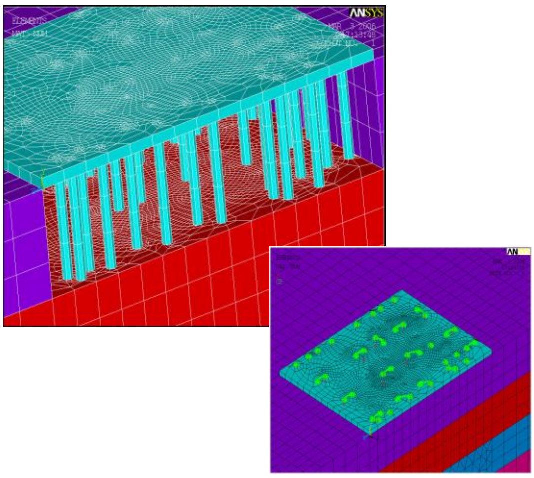


Figure 18 Finite Element Simulation and Meshing of Piled Raft

6.6 Plate on Piles Approach

The row of piles on grid G was analyzed using plate on piles approach which is also considered as an approximate analysis with PLAXIS 3D. The model and the settlement contour is presented in Figure 22 and Figure 23. The coloumn loads acting on the columns in the grid was applied as point load at the respective locations. The final settlement obtained was 16.3mm, as against 14mm observed and the agreement between the two is within the acceptable limits. The pile shaft stress distribution obtained from the plate on piles approach is presented in Figure 24. It is seen that the trend of the shaft stress variation with depth exhibits the same trend as the shaft stress distribution obtained from the 1g model tests presented in the Figure 17(a).

The head stress to tip stress distribution from the analyses of the real time piled raft varied from 20% to 40% depending on the pile location. From the shaft stress distribution obtained from the plate on piles approach the ratio of the head stress to tip stress was found to be 40% to 50%. It indicates that the analysis has shown a stiffer response as in the case of plane strain and axisymmetric idealization. But in the three dimensional analyses with ANSYS the load shared by the raft was shown as 35 to 40% and the pile group was found to take 60% to 65% justifying the stiff response shown by the plate on piles idealization.

A hypothetical model comprising of 16 piles as shown in Figure 25 of 700mm dia with the raft thickness of 800mm was analyzed and parametric study was conducted by Min Huang (2006). The PLAXIS 2D model and the shaft stress obtained from the study are shown in Figure 25 and 26. It is seen that the trend of the shaft stress distribution is identical to the distribution obtained from the 1G model tests establishing that the Plate on piles approach is as good as a detailed analyses to freeze the design data.

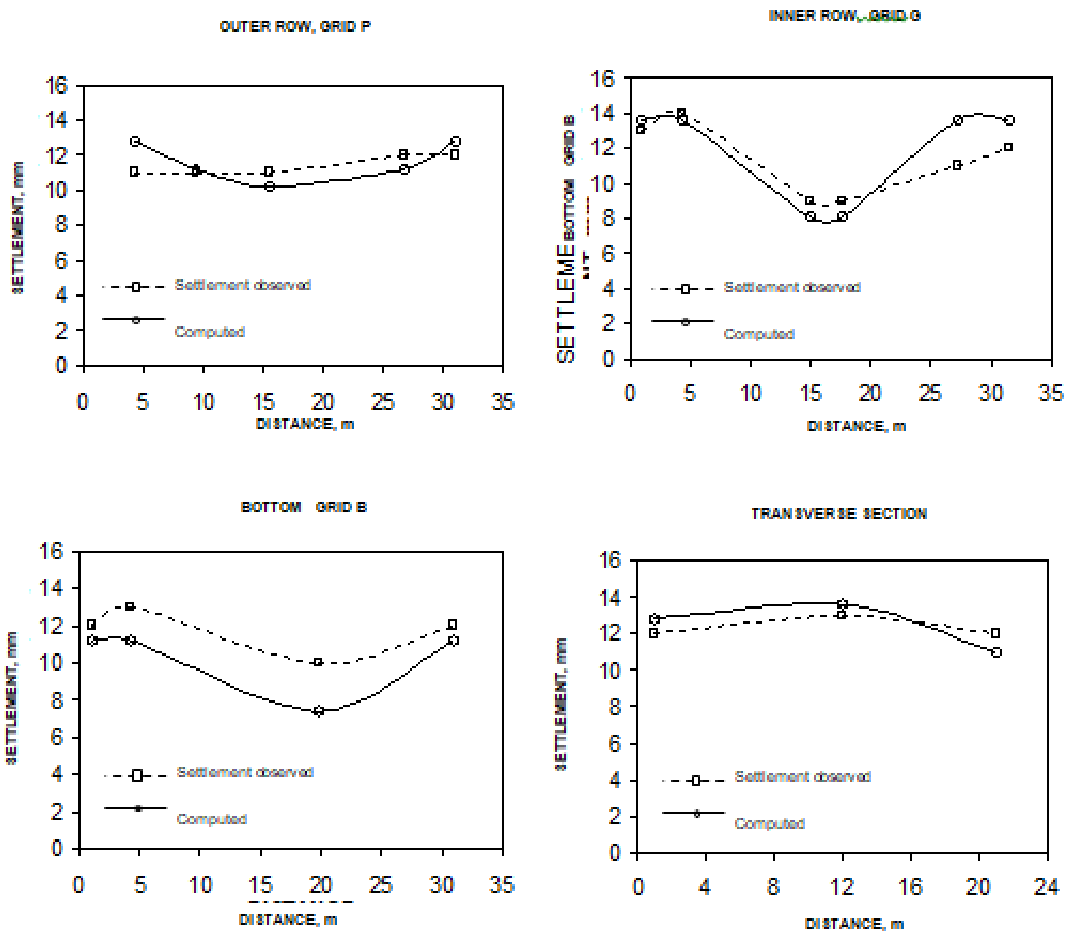


Figure 19 Observed Settlement Vs Computed
Value at Various Section

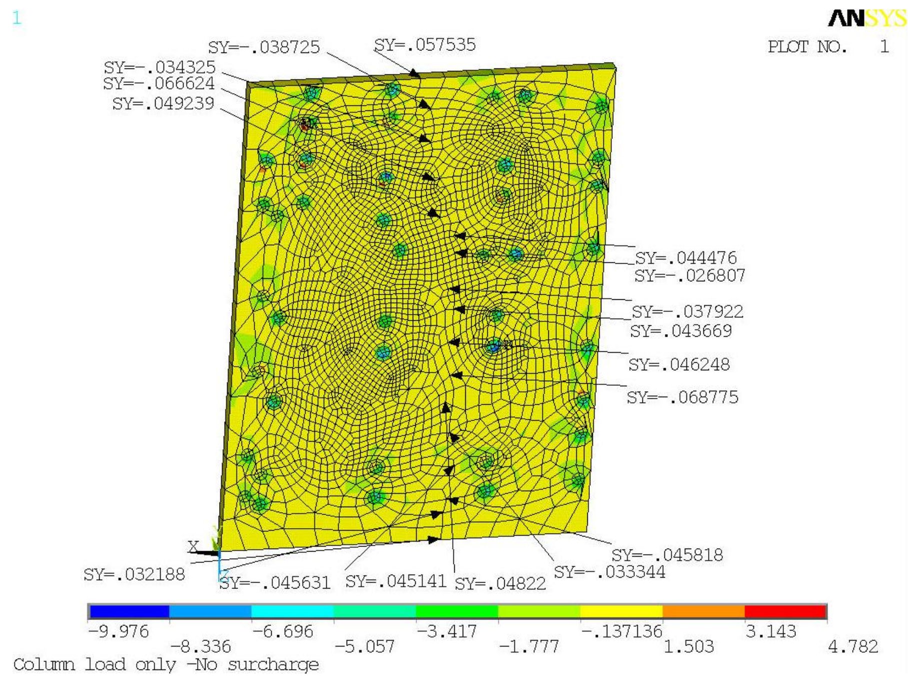


Figure 20 Raft contact stress along grid G

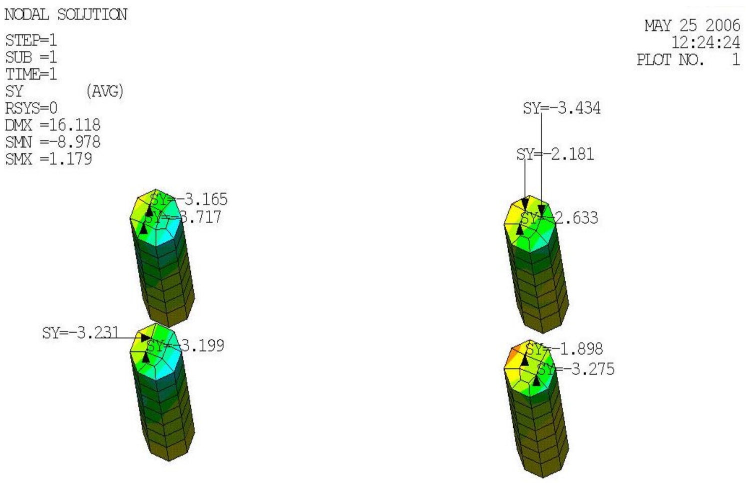


Figure 21 Typical head stress values

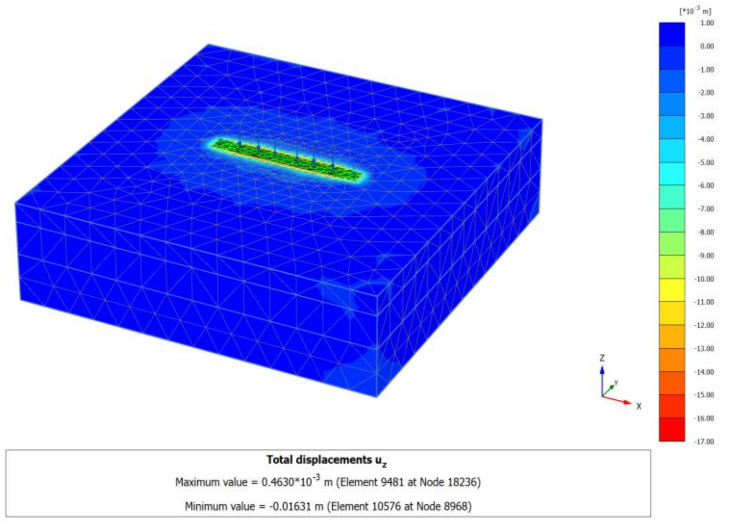


Figure 22 PLAXIS 3D Model

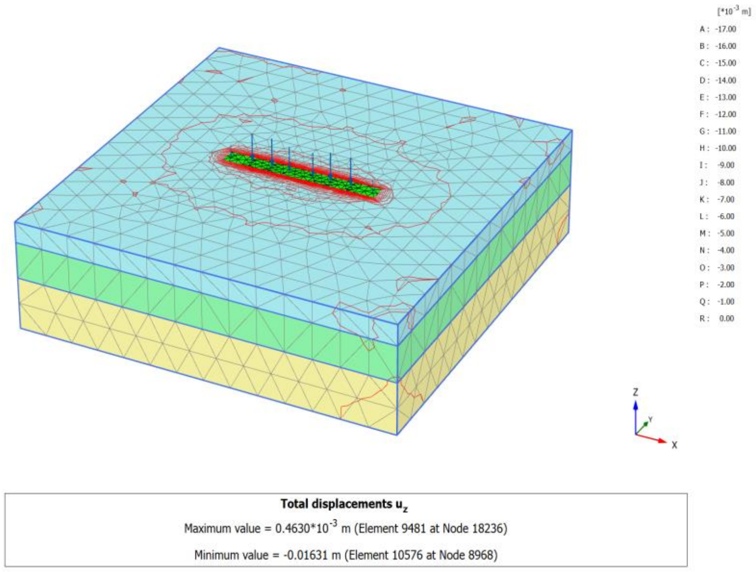


Figure 23 Settlement Contour

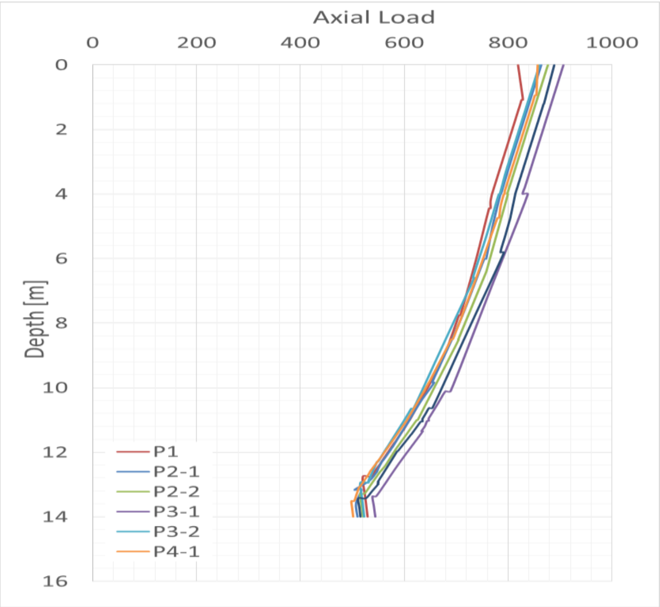


Figure 24 Pile Shaft Stress Distribution

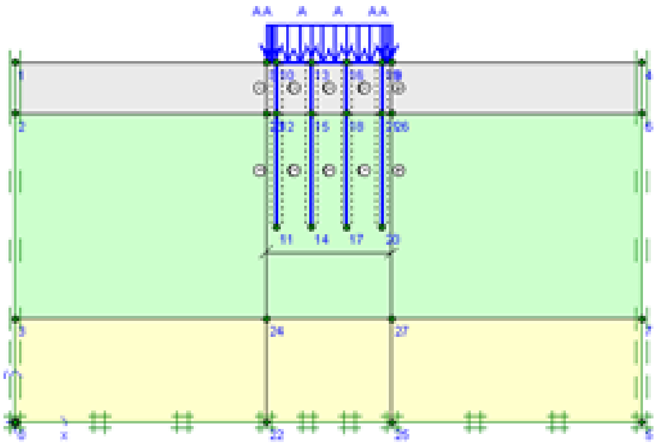


Figure 25 PLAXIS model for Pier

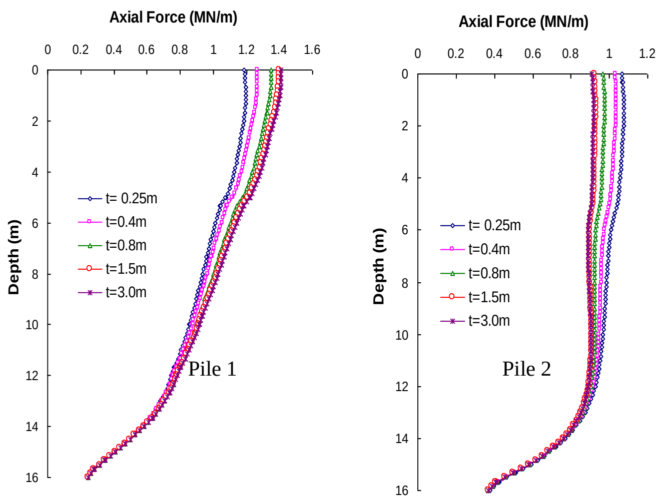


Figure 26 Effect of Raft Thickness on Pile Axial Force

7. CONCEPT OF EQUIVALENT PIER

The concept of equivalent pier was proposed by Poulos (1973) for evaluating the pile group settlement. The advantage of applying this concept to Piled raft is that the analyses can be done adopting two dimensional axisymmetric idealization to evaluate the settlement of the pile draft.

In order to establish the applicability of equivalent pier approach the pile group under the maximum loaded coloumn in the grid G13 along with its tributary area of the raft (6m dia) was modeled using PLAXIS 2D (Balakumar etal., 2013). The pier and the soil data are presented with the model in Figure 27 (a) and (b). The settlement at the maximum load was 12mm against 14mm showing a fair agreement between the observed and predicted value.

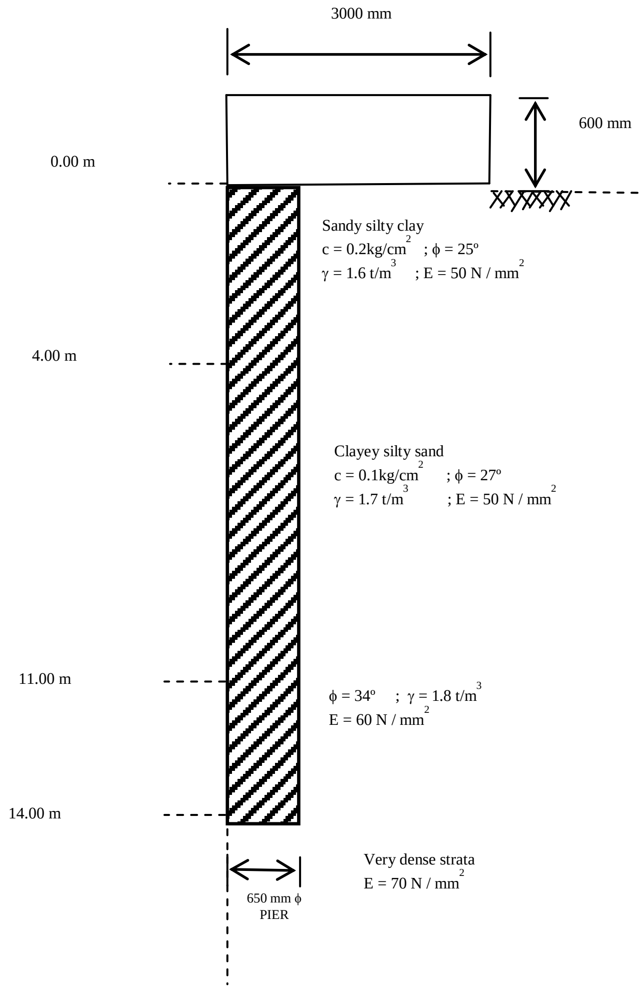


Figure 27(a) Observational study G 13 Pile group model

The second model shown in Figure 28 was a hypothetical model studied by Min Huang (2006) which has 16 piles and a parametric study was conducted by varying the pier length. Figure 29 indicates pier model and Figure 30 presents the shaft stress distribution obtained from the analyses The shaft stress distribution shows an increase in the stress from 12m level onwards upto 16m. It was seen that the layer between 13m to 16 m is a compressible peat layer. Probably it has caused an increase in the load due to the negative friction mobilized. Thus a simple axisymmetric analysis could bring out adequate details required for the detailed design.

For comparison the shaft stress distribution obtained by Min Huang (2006) is also presented for comparison, along with the model. The entire analyses was done with PLAXIS 2D. Both these curves are compared with the shaft stress distribution obtained from the model studies presented in Figure 28.

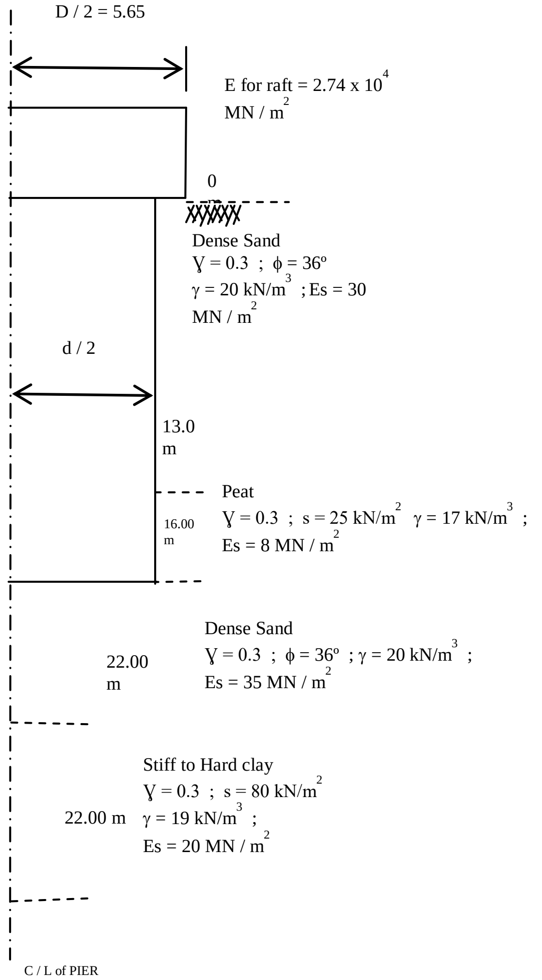


Figure 27(b) Pier & Geotechnical Data Hypothetical Problem

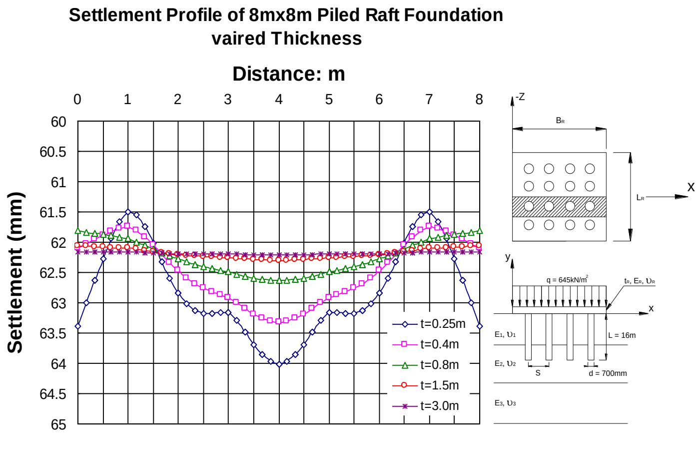


Figure 28 Diagrammatic view of boundary condition using for modeling

It is seen that the trend is identical irrespective of the software used and bed material and the pile group configuration. The ratio between the head stress and the tip stress was obtained from the various methods falls within a close spectrum.

8. DISCUSSION

From the above extensive study it is seen that the type of software appears to have no influence on the results 0btained from the analytical study. However the two dimensional analyses based on axisymmetric idealization and plane strain model predict a relatively higher stiffness compared to what the 1g model tests had shown. This is perhaps due the fact that equivalent modulus did not take the properties of the soil prism Because of this stress distribution on the pile may not be realistic. However the settlement for the given configuration of the pile group could be predicted within an acceptable le level of accuracy. The plate on pile approach with PLAXIS could predict not only the settlement but also the shaft stress distribution on the pile and raft contact pressure for the initial requirement. With all the details and parameters validated the detailed three dimensional analyses can be taken up for the final design. As a matter of comparison the shaft stress distribution obtained from the 1g model tests on a circular piled raft ,square piled raft of identical pile raft area ratio (the ratio of sum of the areas of piles provided to the area of the raft), the shaft stress distribution from the plate on piles theory and the hypothetical model presented present in the previous sections are all identical. Further the ratio of pile head stress to tip stress obtained from the analyses using ANSYS and the plate on piles idealization analyzed using PLAXIS are in a reasonable level of agreement indicating that depending on the data required two dimensional analyses or a simple concept like plate on piles or equivalent pier theory can be adopted before embarking on detailed three dimensional analyses.

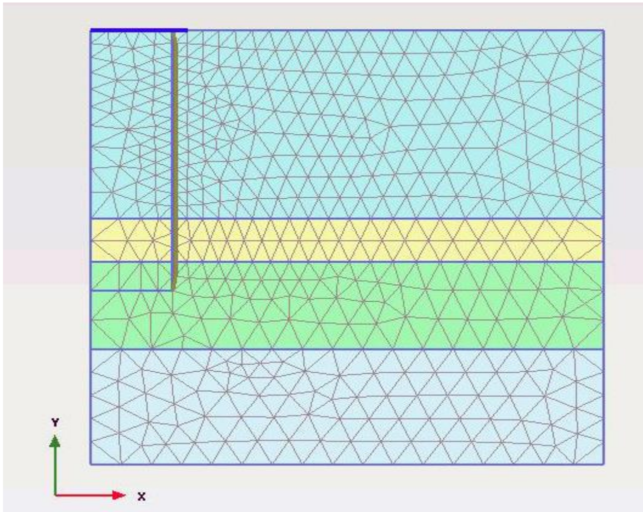


Figure 29 Typical Mesh PLAXIS 2D

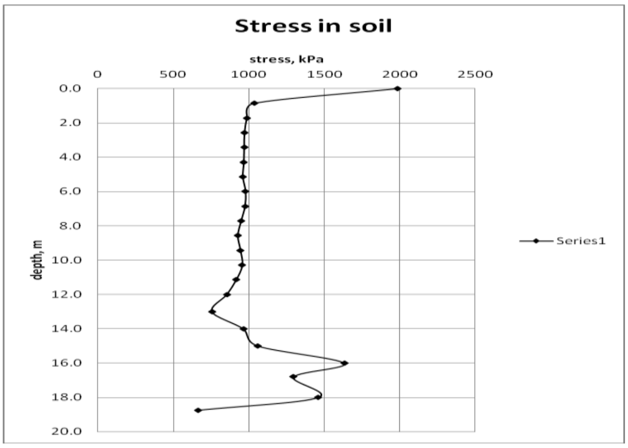


Figure 30 Shaft Stress Mobilisation (18m Deep Pile)

9. CONCLUSION

The present study has established the load transfer and failure mechanism of the piled raft through 1g model tests. The available results of three typical cases of piled raft namely a small scale 1g model, a real time piled raft supporting a basement plus twelve storied structure and a hypothetical piled raft resting on a generalized soil profile obtained from Gold Coast area were all studied with two different software namely ANSYS and PLAXIS both of them being finite element based and the results were compared. It is observed that:

The axisymmetric and plane strain model is found to be very convenient to study the load settlement response of the piled raft under consideration. Both the models are user friendly and number of repetitions can be made to finalize the parameters numerations requirements.

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Annex – A