A Design Method For Piled Raft Foundations

Méthode de conception des fondations de type radier sur pieux

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ABSTRACT: The design of piled raft foundation involves two stages namely a preliminary stage and the final stage. The preliminary design stage involves the identification of the essential parameters namely the number of piles, their diameter and the length along with E_s value of the subsoil strata for an optimum design which can produce the required settlement reduction. The existing design methods, whose accuracy depends upon the accuracy of the evaluation of in-situ parameters like E_s although can produce satisfactory results, the computational efforts involved and the time does not justify the use of them for the preliminary analyses which will involve repetitions. This paper outlines a simple analytical procedure and the effectiveness of the pressuremeter tests in predicting the piled raft behaviour, so that the results can be used in the detailed design.

RÉSUMÉ : La conception des fondations de type radier sur pieux implique deux étapes, l'étape préliminaire et l'étape finale. L'étape préliminaire de conception implique la détermination de paramètres essentiels : nombre de pieux, leurs diamètres et leurs longueurs ainsi que la valeur de E_s de la couche de sol superficielle pour un design optimal qui pourra amener à la réduction requise du tassement. Les méthodes de conception existantes, dont la précision dépend de la précision sur la mesure des paramètres in situ conduisent à des résultats satisfaisants. Néanmoins les moyens numériques et le temps impliqués pour leurs réalisations ne sont pas justifiés pour l'analyse préliminaire qui nécessite des répétitions. Cet article synthétise une méthode analytique simple et efficace de tests de pression pour prédire le comportement des fondation de type radier sur pieux dont les résultats peuvent être utilisés pour des projet de conception.

KEYWORDS: piled raft, tri-linear pressuremeter.

1. INTRODUCTION.

The combined piled raft foundation system provides a skilful geotechnical concept wherein the applied load is transferred by means of a load sharing mechanism which is generated through a process of interaction between the pile soil and the raft. The piled raft foundation system differs from the traditionally designed pile supported raft in the fact that in the case of piled raft the presence of the raft and its contribution in sharing the load with the pile group is recognized. The piled raft foundation utilises the pile group for the control of settlement, with the piles providing most of the stiffness at the service loads while the raft elements provide the additional capacity at the ultimate load levels. The concept of piled raft system was born out of the fact that any structure has a certain magnitude of permissible settlement and the foundation system has to aim at reducing the settlement as close to the permissible value as possible rather than eliminating the settlement completely. In the last two decades researchers like Cooke (1986), Burland(1995), and Poulos(2001) have provided considerable insight into the behaviour of piled raft .

The development of sophisticated computational facilities and FEA codes like Defpig,Napra,and HyPr etc have enhanced the interaction process between the observational methods (Katzenbach etal., 2000 a; Balakumar and Ilamparuthy, 2007), small scale model studies (Horikoshi1995; Balakumar etal.,2005) and numerical and analytical simulations leading to the improvement of the design process. 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 may be used to refine the design in the future. (Poulos, 2008; Yamashita etal., 2010).

2. THE DESIGN PROCESS

In the design process of piled raft the initial stages of design involves the determination of the optimum number of piles, pile length and diameter required to be placed in a strategic manner to produce the required settlement reduction along with the load shared by the pile group. This process may require a large number of trials depending on the nature and requirement. Hence the analytical procedure has to be computationally simple so that the efforts and the time will be less. The existing methods although produce satisfactory results, involve more complicated computational efforts .Further in solving the complicated three dimensional problems such as piled raft, many simplified assumptions are to be made and the rigourousness of the method may have to be diluted to make the problem computationally viable. Therefore there is a need for a simple method that can solved by treating the problem as axisymmetric or plane strain problem in the case of preliminary design to establish parameters like pile length, numbers diameter and the layout to be used in the final design.

It is always recognized in geotechnical engineering that the most difficult part is the evaluation of the in-situ parameters particularly the elastic modulus. 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 pressuremeter 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 Roger Frank et al (1991) using pressuremeter tests. Therefore it was felt necessary to study whether such predictions can be used to evaluate the numerical details such as the number of piles, length, diameter, and layout required for the design of the piled raft.

3. SCOPE OF WORK

With the above in mind it was decided to study the various options available to idealise the piled raft model which would be amenable for a simple numerical procedure and will give the load settlement, settlement reduction and load sharing behaviour of the piled raft. Further in order to evaluate the elastic modulus and other parameters over the pile depth various in-situ test options were also studied. It was found that the equivalent pier approach would be the most suitable approach for modelling the piled raft. The paper presents the details of the study and the conclusions of the study.

4. THE STUDY

In the design of piled raft the requirement is the settlement reduction and the data for the design is the load shared by the raft and the pile group. It is only from the group capacity required, the number of piles required, diameter and the length can be evaluated. In order to study the load settlement response, a series of 1g small scale model tests were carried out on circular and square shaped piled raft placed on sand bed. Poorly graded sand was rained in pre-calibrated manner so that the required densities could be achieved; the tests were carried out on unpiled raft, free standing pile group and piled raft. Extensive parametric studies were also carried out but the presentation is restricted to the load settlement and load sharing response typically for circular piled raft under medium dense bed condition. The studies showed that the performance of the piled raft was identical in all the other cases. Details of the models test set up and other details are presented elsewhere (Balakumar etal., 2005)

5. LOAD SETTLEMENT AND LOAD SHARING RESPONSE.

Figure 1 presents the load settlement response of circular piled raft with varying pile lengths and and figure presents the charecterised form of the load settlement response.It is clearly seen that at any given settlement the load taken by the piled raft is more than the unpiled raft for the corresponding settlement.It is seen that the load taken by the piled raft with pile length of 200mm is far higher than the other lengths namely 75mm,100mm and 120mm. The typical characterisation curve of the piled raft shown with various pile lengths are given in Figure 2 for a pile diameter of 10 mm, which shows that irrespective of the pile length, the behaviour has three phases. Although the settlement up to which the linear elastic stage (portion OA of the curve) remains same as 1mm, the load corresponding to this varies. As can be seen at higher length the linear behaviour extends nearly upto 30% of the load taken by the piled raft corresponding to settlement equal to 10% of the pile length. The second stage of the curve AB is the stage where the behaviour tends to become elasto- plastic, which extends up to a settlement level 9 mm for 200 mm long pile, 7.5 mm for 120 mm long pile and 4.5 mm for 75 mm long pile.

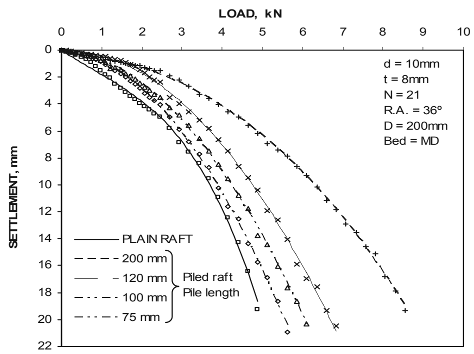

Figure 1. Load-Settlement Response of Circular Piled Raft with Various Pile Lengths

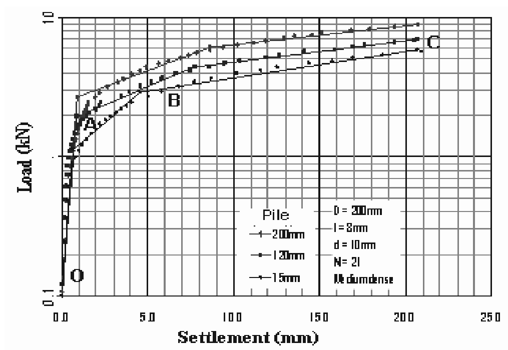

Figure 2. Characteristic Response of Piled Raft

To have better understanding on load sharing between the raft and pile group of piled raft, three dimensional nonlinear analysis was carried out using ANSYS code. Only quarter model of piled raft was analysed taking advantage of the symmetry (Figure 3).

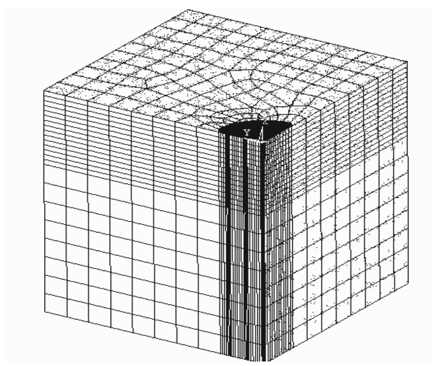

Figure 3. Finite Element Mesh of a Circular Piled

The bed density was kept as medium dense with φ = 37.5° and dry unit weight = 15.5 kN/m3. MISO material model was used for the soil. The continuum was modelled using solid 45 elements with three degrees of freedom at each node. In the analysis the bed dimensions were kept same as that of the model tested in the laboratory. The raft and piles were also modelled as solid 45 elements in order to maintain the elements compatibility. The load was applied as pressure in small increments till the load on the raft equal to the final test load. Figure 3 shows the quarter model including finite element meshing adopted in the analysis.

6. LOAD-SETTLEMENT BEHAVIOUR

Figure 4 presents the load settlement curves of circular piled raft obtained from 1g model test and the numerical model. Figure 5 presents comparison of characteristic load-settlement response of circular piled raft between experiment and numerical analysis. The results obtained from the 1g model test and numerical model agree very closely, till the settlement level of 4 mm.

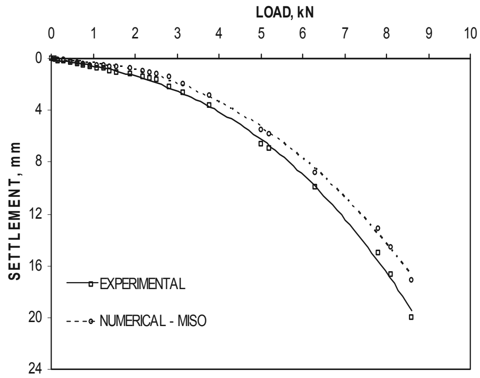

Figure 4. Comparison of Load-settlement

As the load increases, the difference in the settlement between the 1 g model and the numerical model results increased marginally. However the maximum variation in the load between the numerical model and the small scale model results was less than of 5%. This comparison indicates a close agreement between the numerical model and 1g model test. Similar observation is made in the analyses of piled raft in loose and dense sand. Thus the nonlinear analysis using MISO model idealization for the soil predicts the performance of piled raft reasonably well.

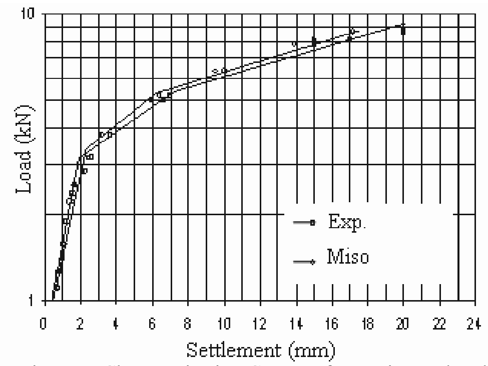

Figure 5. Characterisation Curves of Experimental and Numerical Analysis

Although it has been established that the characterised load settlement response predicted by analytical study and the 1g model tests have agreed very closely, the basic parameter namely the Es value of the soil was obtained from the direct shear tests and the standard correlations available from the literature The agreement in the results of 1g model and the numerical analyses can be attributed to the fact that the supporting medium was prepared under laboratory conditions. However in the case of field samples the accuracy of the parameters obtained largely depends upon the sampling efficiency and the care taken in the extrusion of the specimen and the preparation of test conditions. The probability of wide variation while correlating the field data with the laboratory test results cannot be ruled out. Therefore the evaluation of parameters from the in-situ tests gain considerable importance.A well tried procedure for predicting the shaft friction development has been published by Roger Frank et al., (1991) using pressuremeter is discussed below.

7. PREDICTION OF PILE BEHAVIOUR. PRESSSUREMETER AND ITS APPLICABILITY

The pressuremeter is an effective tool that has been extensively used to obtain the in-situ parameters and for the last three decades foundations have been designed based on the parameters obtained from the in-situ tests. The large volume of data collected over a period of time particularly the French Highway authorities has enhanced the confidence level of the designers in using them for the design of deep foundations. Frank etal., (1991) have studied the load settlement response of two piles forming a part of a bridge foundation. and had established that their behaviour can be predicted by conducting the pressuremeter test.Their prediction of pile behaviour is based on a tri-linear relationship for the skin friction mobilisation based on the pressuremeter tests The model they had used is given in Figure 6.

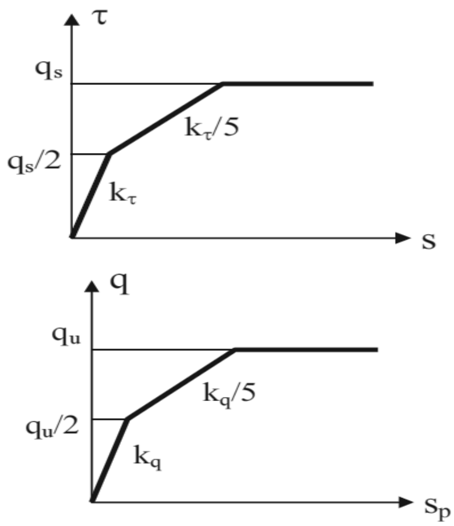

Figure 6. Tri-linear Model, Frank et al (1991)

The first segment has a constant slope .The slope of the second line as more flat and third segment represents the mobilisation of total skin friction. A typical tri-linear model of shaft friction mobilisation. The end of the second part is the limiting value of the friction .The evaluation of the friction is done in their case based on LCPC-SETRA (1985) RULES. The slopes of the lines depend upon the pressuremeter modulus and radius of the pile. The prediction experimental load distribution given by them has a similar trend as predicted by the numerical analyses of the 1g model tests.

8. APPLICABILITY TO PILED RAFT DESIGN

Figure 7 and Figure 8 present the shaft stress distribution over the length of the pile by pressuremeter test results and from the numerical analyses of the 1g model tests. it is seen that the trend of the shaft stress distribution obtained from both the cases agree closely,indicating that the tri-linear model assumed in the analyses of the pressuremeter results and the actual behaviour of piled raft obtained from the 1g model are identical.

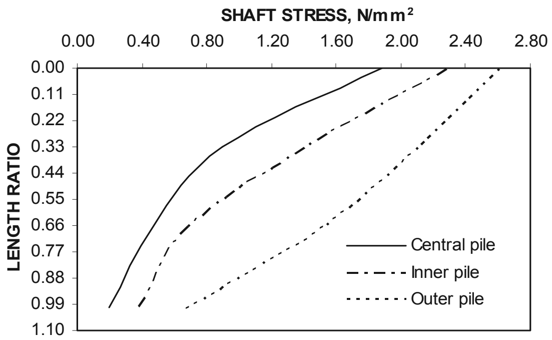

Figure 7. Variation of stress along the shaft of typical piles along the centre line of raft for 8.10kN

This establishes the fact that if the pile group of piled raft can be idealised as a single large pier,then the procedure adopted by Frank et al(1991) can be used to predict the behaviour of pile group of piled raft foundations. Poulos (2001) has shown that while studying the settlement behaviour of the pile group, that if the pile group with the soil prism can be considered as a single pier, then the procedure applied for a single pile behaviour can be used for the prediction of the load settlement response of the equivalent pier numerically using axisymmetric analyses.The equivalent pier modulus E_{eq} is given by the expression

$$EEQ = E_S + (E_P - E_S)\, A_T/A_G \quad (1)$$

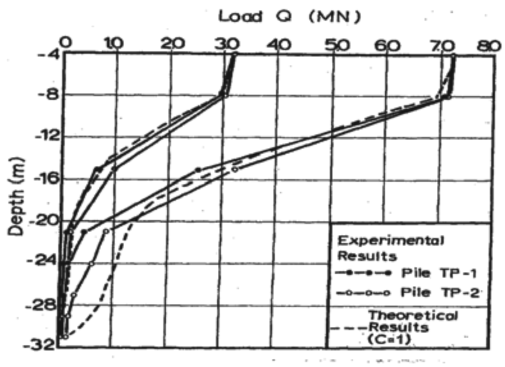

Figure 8. Comparison of Theoretical and Experimental Load Distributions for Test Piles (Roger Frank et al.,))1991)

The value of the Es can be the pressuremeter modulu,E_p is the pile material modulus, A_t is the total cross sectional area of the piles and A_g is the gross plan area of the group. The equivalent pier has the same plan area of the pile group and the length of the pile can be taken as the length of the pier.The load settlement response predicted by the pressuremeter with the shaft friction mobilisation can be compared with the equivalent pier analyses to validate the in-situ E_s value over the length of the pile (pile group) and the shaft friction over the length of the pile group. This will also establish the shaft stress distribution at any given settlement level and the in-situ E_s value which can be used in the detailed analyses.

9. CONCLUSIONS

The design economy in the piled raft design depends upon the optimum design of the pile group of piled raft. Therefore before the final design number of trials has to be made and also the evaluation of in situ parameters has a considerable influence. Keeping the above in mind the study carried out has shown that the tri-linear relationship for the shaft friction mobilisation adopted by Frank etal.,(1991)to study the performance of two single piles was in agreement with the trend of the characterised load settlement response of the piled raft. Also the trend of shaft friction mobilisation over the length of the pile agreed with the prediction made from the pressuremeter test results in the case of single pile. Based on the above it is concluded that the equivalent pier theory can be used in combination with the pressuremeter test results to predict the load settlement and load sharing behaviour of the piled raft adopting parameters determined from in-situ tests which are more reliable.

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