EQUIVALENT PIER THEORY FOR PILED RAFT DESIGN

V.Balakumar
Senior consultant, Simplex Infrastructures Limited, Chennai, Tamil Nadu, India.
Min Huang
Geotechnical Engineer, Arup Geotechnics, Brisbane, Australia.
Erwin Oh
Senior Lecturer, GriffithUniversity Gold Coast Campus, Brisbane, Australia.
A.S.Balasubramaniam
Professor of Civil Engineering, GriffithUniversity, Brisbane, Australia.

ABSTRACT: The objective of generating an economical and safe foundation system reducing the settlement rather than eliminating has led to the change in the design philosophy recognising the fact that most structures can tolerate a certain amount of settlement The piled raft analyses and design is three dimensional interaction problems, wherein, the applied load is transferred by a complicated interaction process between the piles and the raft.. The necessity to have a relatively simple design procedure so that the preliminary design can give adequate but reasonably accurate data for the final analyses is explained. The paper presents such a simple design process in the form of equivalent pier approach by establishing its applicability by applying it to two cases.Also the study has brought out the effect of deep compressible deposit sandwiched between two dense layers.

RÉSUMÉ : L'objectif de créer un système de fondation économique et fiable, par la réduction des affaissements plutôt que de leuréradication, a entraînéun changement dans la philosophie de conception, admettant le fait que la plupart des structures sont capables de tolérer un certain nombre d'affaissements. Les analyses et la conception du radier sur pieux comportent des problèmes d'interaction tri dimensionnels, où la charge appliquée est transférée par un processus d'interaction complexe entre les pieux et le pilier. Il est expliqué la nécessité de disposer d'une procédure de conception relativement simple, de manière à ce que la conception préliminaire puisse apporter des données appropriées suffisamment précises pour les analyses finales. L'article présente un processus de conception aussi simple, sous forme d'approche de pilier équivalent, en prouvant sa faisabilité par son application dans deux cas. L'étude a également révélé les effets du dépôt fortement compressible coincé entre deux couches épaisses.

KEYWORDS: Piled raft, Pier, Peat.

1. INTRODUCTION.

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. Even though this approach produces a safe design, the economics of the design becomes questionable. The objective of generating an economical and safe foundation system reducing the settlement rather than eliminating, has led to the change in the design philosophy Keeping the above objective in mind researchers like Burland (1995) and subsequently Polous (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 large settlements. The piled raft analyses is a three dimensional interaction problems, wherein, the load transfer mechanism is a complicated interaction process by which the load is shared The interactive process between the Various procedures based on observational study (Katzenbach etal.,2000a) small scale model studies such as centrifuge models (Horikoshi 1995) 1g model studies (Balakumar,2008) and the resulting interactive process with the numerical modeling (Clancy 1993; Russo,1998;) supported by the development of new geotechnical computational facilities (Polous and Small 2007) has led to the the piled raft foundation system being extensively used to support tall and heavily loaded structures in a successful manner permitting larger settlements close to the permissible value (Polous,2008;., Yamashita et al .,2010).

2. DESIGN PROCESS

The satisfactory performances of piled raft largely depend upon the performance of the pile group of piled raft in providing the initial stiffness and then allow 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 analyses has to be done to finalize the computational details of the constituent elements. Primarily the number, length 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 efforts, not really warranted for the second stage of design, from the commercial design organisation 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.

3. SELECTION OF DESIGN PROCESS

Among the various methods studied, it was considered that the equivalent pier concept was found to be more suitable. The applicability of the equivalent pier theory to pled raft analyses has been established by Horikosh (1995) But the study was restricted only to a small pile group placed in the center of the raft , placed on a over consolidated clay layer. Although the study has produced very important and useful data, the applicability needs to be validated with other available results from a general soil profile. In this particular study the results of two such cases one from the observational study conducted on an instrumented piled raft supporting a 12 storeyed building and the other from the parametric study conducted independently are reanalyzed using equivalent pier concept.

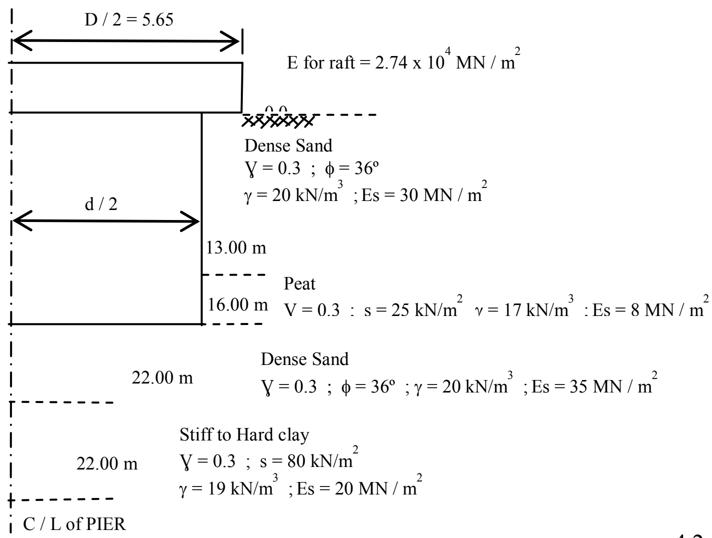

Figure 1 PIER & GEOTECHNICAL DATA (NUMERICAL STUDY)

In this particular case the ratio Le/L namely the ratio of the pier length to the pile works out to unity and hence the equivalent length of the pier is taken to be the same as that of the pile. Once the piles are replaced by a pier then the solution for the single pile can be applied to estimate the load settlement characteristics, and the load sharing response; the load shared by the pier becomes the load shared by the pile group. With this idealisation it is possible to run the analyses as an axisymmetric two dimensional problem.

4. VALIDATION

In order to establish the applicability of the equivalent pier theory two cases were considered for which published results are available. The models were selected, one from a parametric study carried out analytically and the other model was from an observational study carried out on the behaviour of piled raft supporting a 12 storied structure.

4.1VALIDATION BASED ON NUMERICAL STUDY

Extensive parametric studies have been carried out in Griffith university Gold Coast campus and the results had been published by Oh etal.,(2008).These studies had been based on the general soil profile compiled from the number of geotechnical investigation data collected. A 9 pile group (3x3) with 5d spacing has been considered The spacing of the piles considered is 5d (d – diameter of the pile). The d/t ratio is taken as unity and accordingly the raft thickness and the pile diameter have been taken as 800mm. The general soil profile comprises of 13m thick medium dense to dense sand layer, followed by 3m thick highly compressible organic layer termed as peat. This layer is followed by dense sand and hard clay. The Es values of various layers have been taken based on the N- values from the standard correlations. The equivalent pier modulus is taken from the expression,

$$E_{eq} = E_s + (E_p - E_s)A_t/A_g \qquad (1)$$

Where Eeq is the equivalent pier modulus, Es is the elastic modulus of the soil, Ep is the elastic modulus of the pile, At is total cross sectional area of the pile , and Ag is the plan area of the pile group. The pier considered along with the parameters is presented in Figure 1.

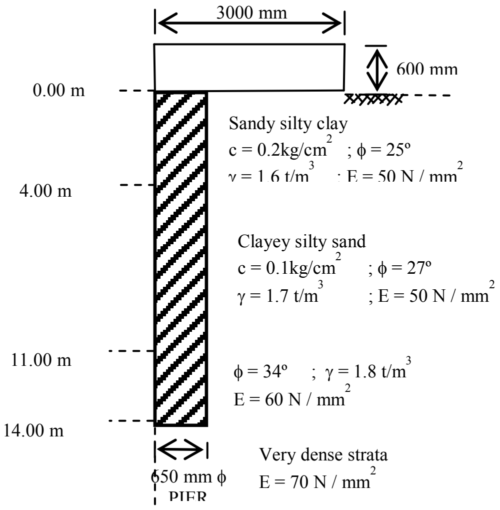

Figure 2 OBSERVATIONAL STUDY

4.2 THE OBSERVATIONAL STUDY

As a part of an extensive research programme, a 12 storeyed commercial cum residential apartment was designed and supported on piled raft (Balakumar and Ilamparuthy) was instrumented and monitored .The piled raft system comprised of 93piles of 600mm diameter and 14M deep from the bottom of the raft. The raft thickness was 600mm so that the d/t ratio was maintained as unity. The layout of piles and other pertinent data are given in earlier publications .A two pile groups with a tributary raft diameter of 6m was converted into an equivalent pier and was loaded in small increments till the settlement reached 100mm. The pier was resting in a medium dense to dense sand. The details of the pier,and the geotechnical parameters together are presented in Figure 2.The analyses in both the cases were carried out with Plaxis 2D the model and the mesh are given Figure 3.

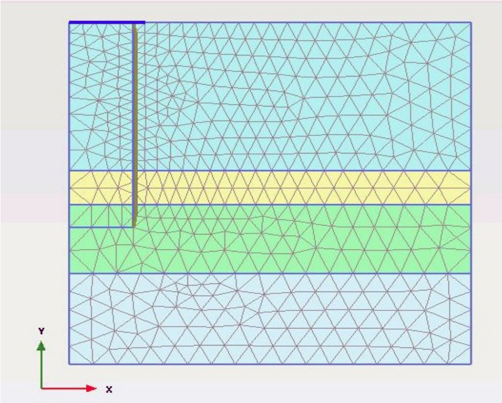

Figure 3. TYPICAL MESH PLAXIS 2D

5. RESULTS, ANALYSES, AND DISCUSSION.

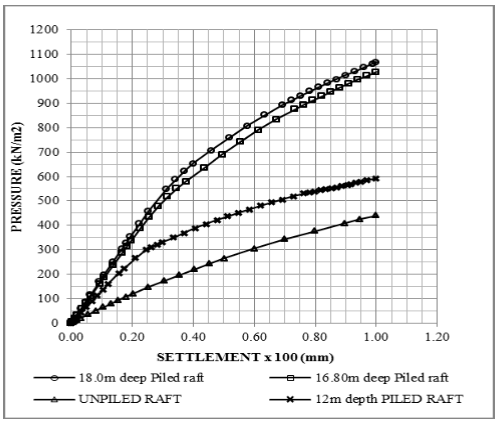

Figure 4 LOAD SETTLEMENT RESPONSE

The results obtained from the model 1 are plotted in the form of load settlement response curves and presented in Figure 4. The load settlement response of 12m pier is presented separately in figure 5.

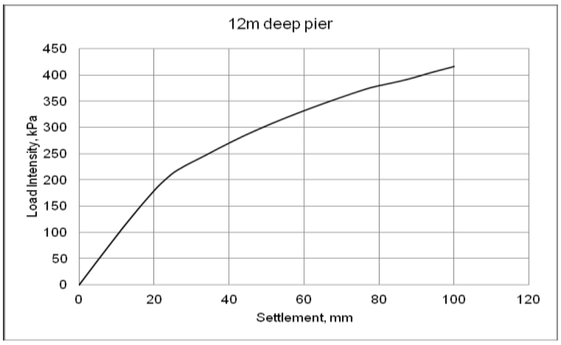

Figure 5. LOAD SETTLEMENT RESPONSE 12m PIER

For the pier lengths of 12m, 16.8m, and 18mm. At any stage of settlement, it was found that the load taken by the piled raft was far higher than the load taken by the unpiled raft for the corresponding settlement. The results are studied independently for the three cases analysed, and then they are compared. From the load settlement response of the unpiled raft and the piled raft, the load shared by the pier (pile group) is computed at different settlement levels namely 12mm, 25mm, 50mm, 80mm and 100mm and has been presented in Table 1.

Table 1 Load Sharing Ratio At Various Settlement Levels

Pier length	Settlement				
	12m m	20mm	50mm	80m m	100mm
12.0m	0.54	0.53	0.37	0.30	0.25
16.8m	0.64	0.65	0.60	0.58	0.56
18.0m	0.61	0.56	0.64	0.59	0.59

In the case of load settlement response of all the three cases, in the initial stages upto a settlement level of 25mm,the piled raft exhibits a higher stiffness, with the very small rate of change in the stiffness. As seen from the table 1, the loads shared by the pier in the initial stages are higher and then gradually reduces with settlement. This indicates that the major part of the applied load is taken by the pile group or the pier. Beyond this level the rate of fall in the stiffness increases rapidly indicating that the full friction has been mobilised and the raft starts taking a higher load. This stage exists upto a settlement level of 75mm.Beyond this level the rate of fall of stiffness further increases rapidly even for a small increment in the load. In the case of piled raft with 16.8m deep pier the load corresponding to 25mm settlement is higher than the previous case by 100% indicating that the pier mobilises a higher friction in the linear elastic stage. At 75mm settlement level the increase in the load taken by the 16.8 m deep pier is higher by 60%, indicating that the load shared by the pier reduces gradually. and in the case of 18m deep pier this increase is only 15% when compared to 16.8m deep pier.

6. EFFECT OF PEAT LAYER

The study of the Table 1 and the Figure 6 which presents the shaft stress distribution with the depth indicates that the load sharing ratio and the shaft stress indicate an increase and then a fall. The shaft stress increase commences at a level of 13m and extends upto 16m level; and then it reduces. In the case of load sharing ratio the increase takes place at a settlement level of 20mm in the case of 16.8m deep pier and 50mm level in the case of 18m deep pier. This trend is absent in the case of 12 m deep pier which is above the peat layer.

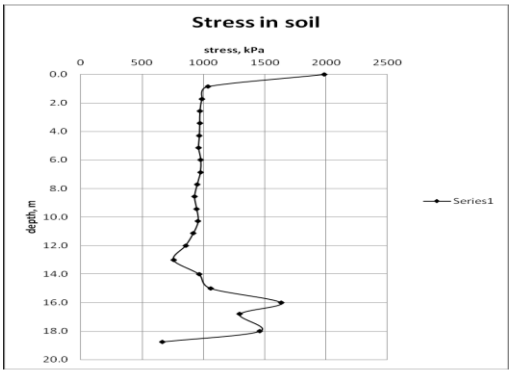

Figure 6 SHAFT STRESS MOBILISATION (18m DEEP PILE)

The most probable reason for this behavior is that at a higher load the peat layer generates a negative skin friction causing a higher load on the pile group. This results in the sudden increase in the shaft stress and the load sharing ratio value. Figure 6 presents the mobilisation of shaft friction with depth. It is seen that the shaft friction increases and then falls down rapidly with depth confirming the ductile behaviour in the sense that major part of the load is transferred by friction.

7. HYPERBOLIC BEHAVIOUR

The curve relating to the 12m deep pier exhibits in a distinct manner a three phase behaviour; namely OA, which is a linear elastic stage AB a visco- plastic stage and BC the plastic stage. In the other two cases the third stage is has not reached mainly because the piled was still capable of taking higher load.Typically the piled raft with 12 m pier depth had exhibited a hyperbolic behaviour and it has been loaded close to failure has exhibited a hyperbolic behaviour. It has been established that the hyperbolic behaviour can be expressed in terms of Chin-Kondtner type functions, when the inverse of the stiffness is plotted against settlement, a linear plot can be obtained. In that case the inverse of the slope gives the asymptotic ultimate capacity of the pier. Accordingly as atypical case the load settlement response of the piled raft with 12m pier was plotted as Chin's graph. Figure 7

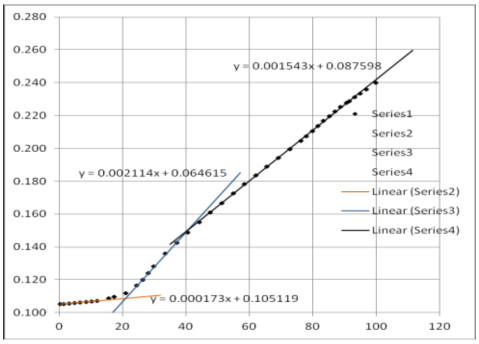

Figure 7 Chin's graph (12m pier)

The asymptotic ultimate capacity was found to be of the order of 750kN, indicating that the asymptotic ultimate capacity is three times the capacity at the elastic limit and 1.5 times the load corresponding to the elasto plastic stage. This would mean that the capacity has to be limited to the load corresponding to the elasto plastic stage. Therefore the limiting capacity of the piled raft can be the capacity at a settlement level of 10% of the pile diameter when the pile can be seated in the non-compressible layer and when the pile has to pass through a compressible layer, and then the negative friction has to be accounted for.

8. OBSERVATIONAL STUDY MODEL

Figure 8 presents the load settlement response of the pier representing the pile group and the raft which forms a part of the piled raft supporting the structure. Here it is seen that the elastic stage is seen upto a load level of 200kN per sq.m.

Figure 8 LOAD SETTLEMENT RESPONSE PIER

However in the analyses the pressure was applied continuously whereas during construction the load was applied in gradual manner over a period of time.

However the settlement shown by the equivalent pier analyses is 12 mm as against the observed value of 14mm reported in the referred publication, The load sharing behaviour and the shaft stress mobilisation exhibited a similar trend as in the case of earlier model and as observed in the observational study. In this case the load level was found to be well with in the elastic limits. The settlement observed from the observational study was 14mm and from the pier analyses the settlement obtained was 12mm indicating a very close agreement indicating that the equivalent pier concept can fill the need of a simple design procedure.

9. CONCLUSION

The extensive study carried out on the two independent cases adopting the equivalent pier theory has established that the equivalent pier theory, although involves numerical approximation, the performance of the piled raft in both the cases predicted by equivalent pier theory is in conformity with the earliar works by Oh etal.,(2008) and Balakumar (2008)The study has further pointed out that in the case of piled rafts with the pile group passing through seams of compressible layer the behaviour is affected by the mobilisation of negative skin friction and the equivalent pier concept is able to predict this effectively.The compressible layer generates negative skin friction and increases the load on the pile as shown by the increase in the load sharing ratio and then allows the pile group behaviour to be ductile. In short the equivalent pier theory is an ideal theory for the piled raft analyses.

10. REFERENCES

Clancy P. (1993), Numerical Analysis of Piled Raft Foundations, University of Western Australia, PhD Thesis.

'Katzenbach R., Arslan V. and Moorman ch (2000a), 'Numerical Stimulations of Combined Piled Raft Foundations for the New High Rise Building, Max in Frankfurt am main', Proc. 2nd Int. Conf. on Soil Structure Interaction in Urban Civil Engineering.

. Poulos H.G. (2001), 'Piled Raft Foundation: Design and Application', Geotechnique, Vol. 51, No. 2, pp 111-113

Horikoshi K. (1995), 'Optimum Design of Piled Raft Foundations', Dissertation submitted for the degree of Doctor of Philosophy, University of Western Australia.

E.Y.N OH, M. Huang, C. Surarak, R.Adamec and A.S.Balasubramaniam (2008), 'Finite Element Modeling for Piled Raft Foundation in Sand', Eleventh East Asia – Pacific Conference on Structural Engineering & Construction (EASEC – 11).

Polous H.G. (2008), "The Piled Raft Foundation for the Burj Dubai – Design & Performance". IGS – Ferroco Terzaghi, Oration – 2008.

Balakumar.V (2008), "Experimental Studies of Model Piled Raft on Sand and Field Study of Prototype Behavior". PhD. Thesis, Anna University, Chennai.

Burland J.B. (1995), 'Piles as Settlement Reducer' 18th Italian Congress on Soil Mech., Pavia.

Russo G. (1998), 'Numerical Analyses of Piled Rafts', Intl. Jnl. Num. and Anl. Methods in Geomech, Vol. 22, pp. 477-493.

Small J and Poulos, H.G. (2007) "A Method of Analysis of Piled Raft", 10th Australia Newzeland Conference on Geo Mechanics, PP. 555.

Yamashita.K , Hamada.J, Yamada.T. (2010), Field Measurements On Piled Rafts with Grid-Form Deep Mixing Walls on Soft Ground, Geaotechnical Engineering-SEAGS Vol.42 No 2 June 2011