Effect Of Intermediary Weak Layer On The Behaviour Of Piled Raft

V. Balakumar[1], Min Huang[2], Erwin Oh[3] and A. S. Balasubramaniam[4]
[1]*Simplex Infrastructures Limited, Chennai, Tamil Nadu, India.*
[2]*Arup Geotechnics, Australia.*
[3]*Griffith School of Engineering, Griffith University, Australia.*
[4]*Griffith School of Engineering, Griffith University, Australia.*
E-mail: vb_kumar2002@yahoo.com; m.huang@outlook.com; y.oh@griffith.edu.au; a.bala@griffith.edu.au

ABSTRACT: Piled raft foundations are being used now extensively to support structures on problematic soils successfully in the last two decades. Large numbers of milestone works have been done but all these works appear to have used only homogeneous layers of sand or over consolidated clay. Few works have covered the behaviour of the piled raft in compressible clay but perhaps not in an extensive manner. Naturally available deposits many times have compressible layer in between two relatively stronger layers. The present work studies the effect of such intermediary compressible layers on the performance of the piles within a piled raft. The study has been carried out using PLAXIS 3D and the paper presents the results of the study.
Keywords: PLAXIS 3D, compressible layer, pile group.

1. INTRODUCTION

The main requirement in the design of a foundation for any structure is that it has to satisfy the defined requirements of bearing capacity and the settlement both total and differential. Practically most of the international codes of practice quantitatively recommend the permissible settlement for all types of structures based on the performance requirement or what is known as serviceability requirements. The first option for the designers to satisfy the above requirements had always been raft; this option may satisfy the bearing capacity requirements in most of the cases but in the case of structures sensitive for settlement raft may not become an ideal solution. The option under such cases would be to go for deep piles which are designed assuming that the entire structural load will be taken by the piles and the presence of raft and its capability to transfer the load to the ground had been ignored. While such a design satisfies all the safety requirements, it may not satisfy the economic requirements. Further such a design contradicts the behaviour predicted when the raft is seated on competent ground (Balakumar and Anirudhan, 2010). It has been established that in the case of large pile groups with smaller dia piles with closer spacing covered by a raft which would be seated on a competent ground the percentage of the load shared by the raft would be of the order of 20% or even more (Mandolini et al.,2017 ; Balakumar and Anirudhan, 2010) . It is evident that ignoring the presence of the raft and its contribution in transferring the load to the competent ground cannot be justified from engineering principles. When the ground has adequate bearing capacity and settlement alone is a problem in providing a large group of piles, the number of piles is governed by the geometry of the foundation leading to an uneconomical design with a very high factor of safety not justifiable from an engineering point of view to reduce the settlement.

The concept of introducing deep foundation elements namely piles with the raft in a strategic manner as settlement reducers to reduce raft settlement was developed by Burland etal., (1977) and subsequently many researchers have studied the behaviour of this combined foundation system comprising of raft, piles and the soil namely the combined piled raft foundation system adopting various methods like analytical modelling (Cooke etal., 1981; Clancy and Randolph,1993; Poulos etal.,1997), small scale model studies (Kim etal.2002; Weisner and Brown,1978, Balakumar and Ilamparuthi,2004) and by monitoring the real-time piled raft supporting tall structures. The piled raft foundation system is an intelligent geotechnical concept which uses the deep foundation elements placed strategically to enhance the overall stiffness of the raft to carry a much higher load at any settlement level compared to the un-piled raft at the same settlement. In the recent past such a development has enabled the designers to shift their design approach from the bearing capacity basis to a settlement based design process. Such a change has resulted in using the piles in a strategic manner to produce an optimum foundation design satisfying both the safety and the serviceability requirements.

2. NEED FOR THE STUDY

The awareness of settlement based design has increased among the designers particularly after the vast improvement that has taken place in the field of computational tools like FEA and the associated software. The present day designers have started accepting the fact that settlement based design can lead to considerable economy without sacrificing the safety and serviceability of the structure. Addition of piles below the raft and connected to it has proved itself to be a successful and a viable solution in bringing down the settlement level very close to the permissible settlement value. In addition the system has a higher bearing capacity that the unpiled raft at any given settlement level. Further considerable economy has also been achieved compared to the traditional fully piled system. The combined foundation system addressed as piled raft has been successfully used in supporting a number of tall and super tall structures in the last two decades.

However the combined piled raft foundation system has been viewed with suspicion mainly because of the following reasons:

1. The main problem the designers were facing was that many traditional methods of analyses could not be applied since they require a high level of extrapolation and approximation which were far beyond the comprehension of past experience.
2. The behaviour of piled raft had been studied by most of the researchers adopting homogeneous over-consolidated clay or loose to medium dense sand. In practice such a homogeneous profile does not exist
3. It is strongly believed that presence of compressible strata at near raft base (need not be below the raft) is not a favourable condition for piled raft.

The combined piled raft foundation system is a three dimensional interaction problem. Such a problem requires a detailed three dimensional analyses. As Russo has pointed out, to move from the traditional capacity based design to settlement based design the method of analyses must be capable of taking into account properly the soil structure interaction with in the foundation systems that is needed. Further the accuracy of analyses depends upon the accuracy with which the in-situ geotechnical parameters are evaluated and the skill in the use of software.

A complex problem like a piled raft can become further complicated due to the presence of a clay layer at an intermediary level. The complexity of interaction among the various constituent elements has made it necessary to adopt a detailed three dimensional analysis. But the presence of intermediary compressible deposits can influence the pile soil pile interaction process which will influence the load sharing behaviour of the pile group. The influence of the intermediary compressible layer can also depend upon its location below the raft The additional complexity generated by the presence of a clay layer at lower levels is the reason for the present study.

3. PREVIOUS WORKS

Based on all the milestone data number of structures have been successfully supported on piled raft and also have been monitored. In most of the cases the strata has been considered as over consolidated clay or medium dense sand. The study on the behaviour of piled raft on layered soil appears to be very limited (Chow and Small,2008 ; Yamashita etal., 2010) had used the piled raft with ground improvement and also supporting of tall structures supported on soft ground etc has been discussed and published results are available. However in reality there are number of instances wherein piles may have to pass through intermediary compressible layers as seen in the case of many sites in Brisbane Gold Coast areas (Oh etal, 2008; Moyes etal.,2006, Min.J.Huang 2006). In such cases many structures have been supported on a piled raft but appears not to have been monitored Therefore It is felt that a more detailed study needs to be done on the effect of such an intermediary compressible layer sandwiched between denser layers, on the behaviour of piled raft. A detailed study was planned and is being carried out by the above research group of Griffith University adopting analytical modelling and this paper presents the results of part of the study. Further studies are going on.

4. METHOD OF ANALYSIS

Complex three dimensional problems like a piled raft cannot be analysed by common traditional methods mainly because they require a very high level of extrapolation and approximation which are far beyond the comprehension of past experience The analysis of the interaction among the constituent elements becomes favorable in the case of sand and medium stiff to stiff clay.But the presence of soft clay like peat can take away this advantage. The role of analyses in the design process becomes clear only when the design objectives are clearly established. The facets of analyses such as identification of appropriate parameters and a clear understanding of empirical methods play a very important role. The essentials of analyses have to take into account the soil - structure interaction within the foundation. Keeping the above in mind, for the present study, analytical method the finite element method and the software PLAXIS 3D have been used in the rigorous analysis.

4.1 Basis of Model Definition

The selection of model was done based on the problem requirement. Since the present study attempts to find the behaviour of the piled raft with an added complexity, the model has to be computationally simple and at the same time must be able to produce the desired results with minimum computational time .Hence a simple square model has been assumed for the study. The model is briefly discussed in section 4.3

4.2 Geotechnical Model

The geotechnical model is based on the profiles presented by various authors (Oh etal, 2008; Moyes etal.,2006, Min.J.Huang 2006). The Soil profile in Surfers Paradise Gold Coast is carpetted with a layer of sand extending up to 13 m or more and is an ideal place to use piled raft foundation. Larich of PTY limited has discussed about the soul project in surfer's paradise QLD, Australia. This profile did not have peat in between. Table 1 presents the geotechnical model that has been used in the analysis. It is seen that, in this particular site, peat layer is absent indicating that the presence of peat layer varies from site to site. A typical profile is presented in Figures 1 to 3The geotechnical profile used for this analysis is given in Figure 4. The profile comprises of medium dense to dense sand with N values range from 10 to 40.This layer exists from ground level to 12.5m to 13m. Below this layer is the problematic peat layer which is compressible and its N-value ranges from 2to 5.Below this layer is stiff clay followed by weathered rock in gravel form Here the N –value is over 50. Pile load tests data are very scarce in Surfers Paradise. The Authors have done the analysis and will compare with available pile load tests data in the second phase.

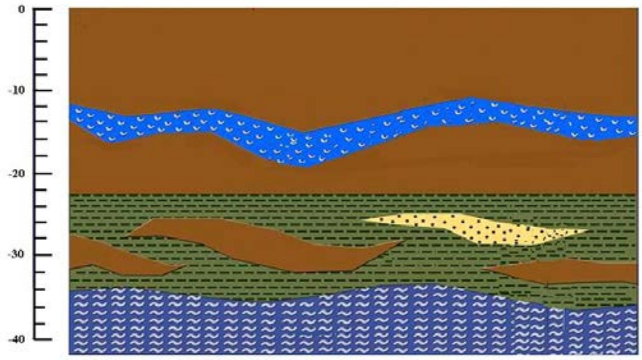

Figure 1 Typical Soil Profile in Surfers Paradise, Gold Coast

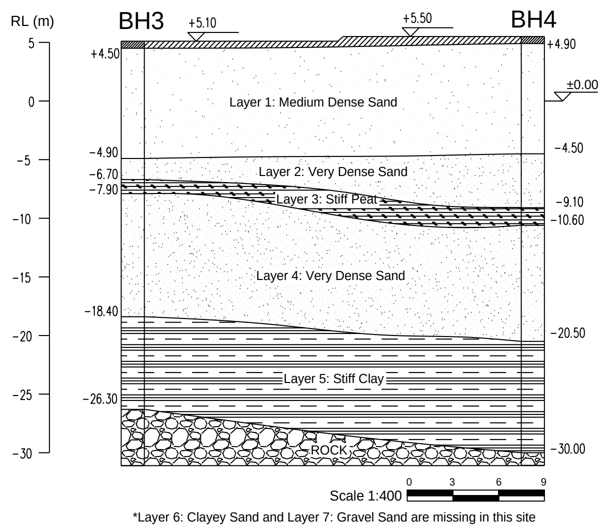

Figure 2 Artique Project- Soil Profile along Section (Huang, 2006)

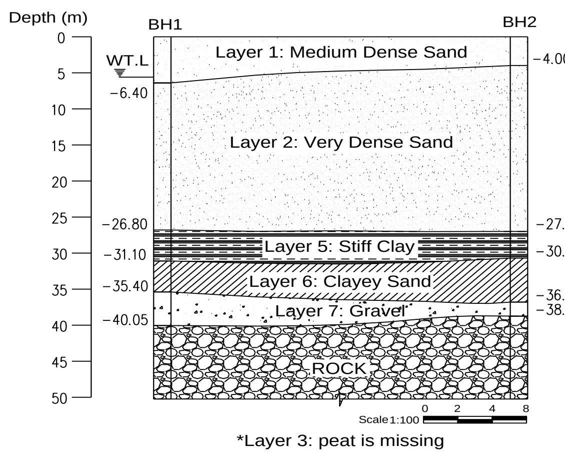

Figure 3 Q.1 Tower- Soil Profile (Huang, 2006)

4.3 Piled Raft Model

Figure 5 presents the model. The model comprises of 6 X 6 pile group with 4D spacing (D is the diameter of the pile) having an area ratio of 6.1%. The area ratio is defined as the ratio between the total cross sectional area of the piles provided to the plan area of the raft.

It has been observed that the piled raft with an area ratio of around 6% produces the best performance (Balakumar, 2008).

Table 1 Geotechnical Model

Units	unit weight, γ' [kN/m³]	Friction angle, ϕ' [deg]	Drained cohesion, c' [kPa]	Undrained Shear strength, c_u [kPa]	Young's modulus, E[kN/m²]
Sand (L-MD)	19	30	0	-	44000
Sand (D)	20	38	0	-	129000
Peat	14	-	-	15	27000
Clay (ST)	18	-	-	140	48000
Bedrock	21	35	100	-	150E3

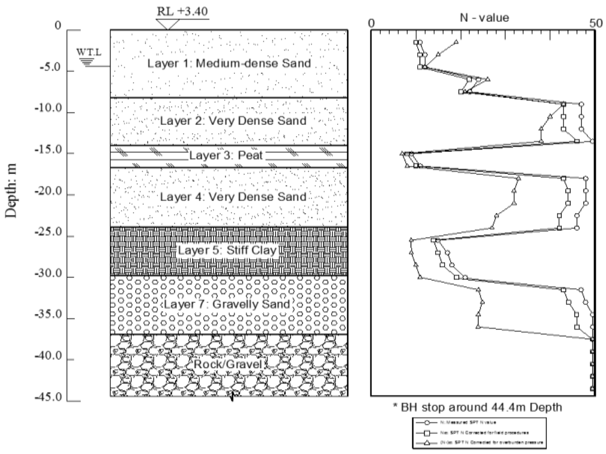

Figure 4 Geotechnical Parameters

The raft is 1m thick and the piles are 750 mm dia and 28 m long namely 1.5 times the raft width. The length of the pile has been taken on 28 m so that there will be sufficient length of pile available below the compressible layer. The piles are fully fixed to the base of the raft. Figure 6 a presents the finite element model and 6b the deformation contour. The various layers have been identified by the respective Es, density and Poisson's ratio etc have been derived from the correlations given by Poulos (1988). The parameters are presented in Table 1.No mesh refinement was needed. The piles have been modelled as beam elements.Four typical piles have been identified for the study. They are central pile (Pile 1), outer pile in line with the central pile on the X-axis (pile 2),corner pile as pile 3 and the peripheral pil below the central pile on Y-axis downwards.

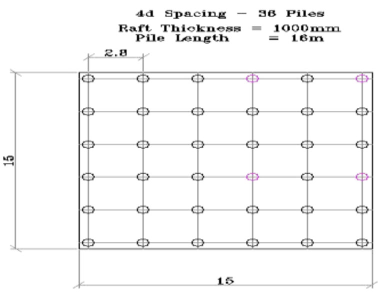

Figure 5 Piled raft model

4.4 Loading

In the present study the loading is restricted to vertical loading only. The loading was applied in the form of pressure load till the settlement reaches nearly 2% of the raft dimensions. The final loading was 645 kN /m2. The loading was applied in steps till the settlement of the piled raft reached 35mm in the case considering the intermediary compressible layer.

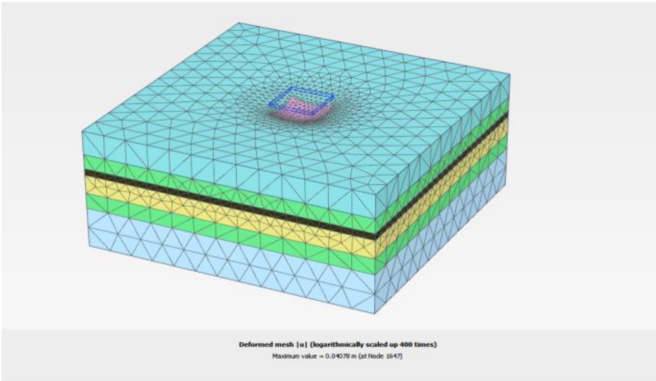

Figure 6(a) FEA model

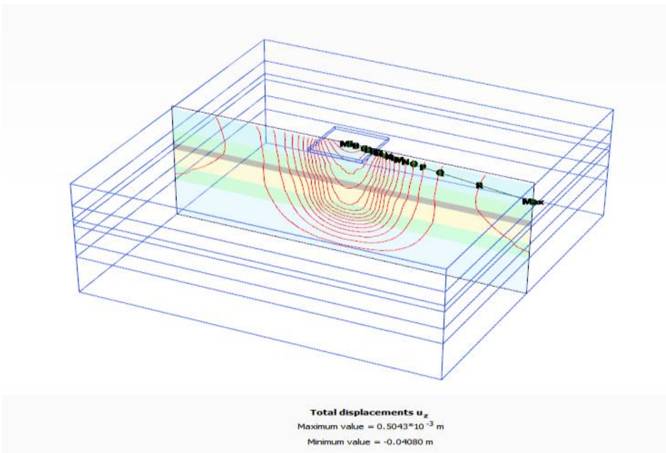

Figure 6(b) Deformation contour

5. LOAD SETTLEMENT RESPONSE

In general in the case of homogeneous layer the applied pressure from the raft enhances the confining pressure below the pile group by the inter -granular friction. This enables the pile group to take a higher load by friction and once the friction is overcome the system loses its stiffness gradually and then rapidly.(Balakumar , 2008) as shown in Figure 7.

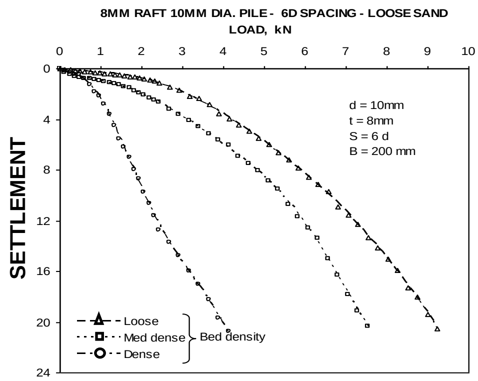

Figure 7 Load Settlement Response of Piled Raft on Homogeneous Layer

In order to understand the effect of intermediary compressible layer on the behaviour of piled raft, the load settlement response of piled raft on layered soil with intermediary peat layer is compared with the load settlement response of the piled raft on a homogeneous layer. The load settlement response of piled raft on a homogeneous layer is taken from 1g tests conducted on a square piled raft (with a pile- raft area ratio of total cross sectional area to the area of the raft) of 5% which is close to the area ratio of the model studied now namely 6% The details of the 1g model tests on square piled raft with 4D pile spacing on a poorly graded sand bed is discussed in detail elsewhere (Balakumar and Ilamparuthi,2005). It is assumed that this small variation may not affect the comparison of load settlement response. Figure 6 presents the load settlement response of piled raft on a homogeneous layer and Figure 8 presents the load settlement responseof piled raft of the present study. of piled raft of the present study.

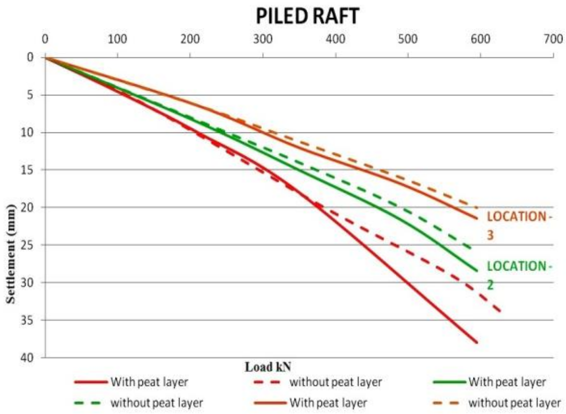

Figure 8 Load Settlement Response of Piled Raft

It can be seen that in the case of piled raft on a homogeneous bed the response is well defined. In this case, till the load reaches 25% of the final load the stiffness exhibited is very high and then as the load increases the rate of reduction rapidly increases. But in the case of the layered soil with peat almost upto 40% of the applied load the stiffness of the piled raft is high and when the load further increases the rate of reduction of the stiffness increases. When the load level increases beyond 60 to 65% the rate of reduction of stiffness is rapid. Although the behaviour is not as well defined as in the case of homogeneous layer, the response is similar and the effect of the compressible layer gets pronounced only after the load reaches beyond 60% of the maximum load applied. The top sand layer whose state of compaction increases with depth offers adequate frictional resistance preventing the additional stresses generated by the compressible clay affecting the load settlement response. This amounts to the fact that when the upper layers are competent the compressible layer does not appreciably influence the load settlement response. It can also be seen that at the final load the piled raft with peat layer settles more by 20.5% at the centre, 23% in the periphery and in the corner the percentage variation is 24.6%. Although the variation appears to be small it indicates that there will be an increased differential settlement when there is an intermediary compressible layer.

6. AXIAL LOAD DISTRIBUTION IN THE PILE

The axial stress distribution which is an important parameter in the design of piles from the capacity point of view, and together with the distribution of bending moment will influence the structural design provisions. These two aspects are studied in comparison with the data obtained by Min Huang(2006).The load sharing behaviour of a typical square piled raft obtained through the 1g model tests is also considered. Figure 9 and Figure 10 presents a typical axial stress distribution in the pile without a compressible layer and a typical distribution considering the compressible layer. In the case of the pile group passing through a homogeneous layer the shaft stress distribution indicates a gradual reduction in the stress upto 0.6L and then a rapid reduction beyond 0,8L, where the axial stress reduces to a negligible level The ratio of the tip stress to head stress is of the order of 20% confirming that maximum part of the load is transferred by friction. Min J. Huang,s analyses (Balakumar etal.,2008) also presents the similar behaviour as seen in the Figure 11. Upto a depth of 0.8L the reduction in axial stress is gradual and thereafter the fall is rapid. But it can be seen that the behaviour is more uniform and the ratio of axial stress to tip stress works out to 20%.

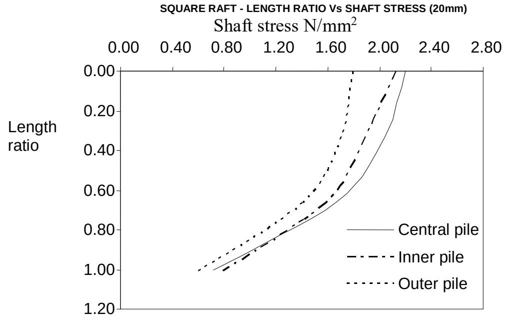

Figure 9 Axial Stress Distribution in the Pile without Peat Layer

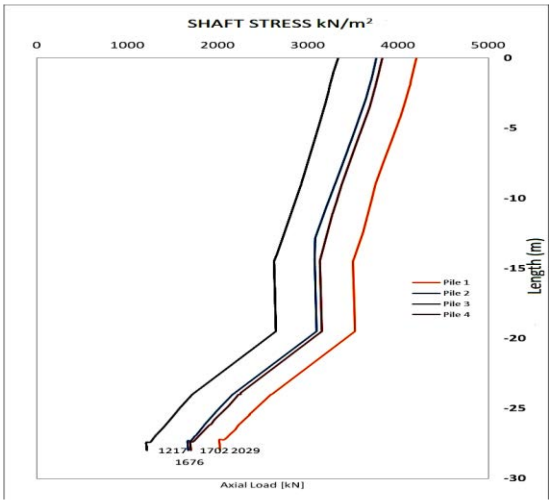

Figure 10 Axial Stress Distribution in the Pile with Peat Layer

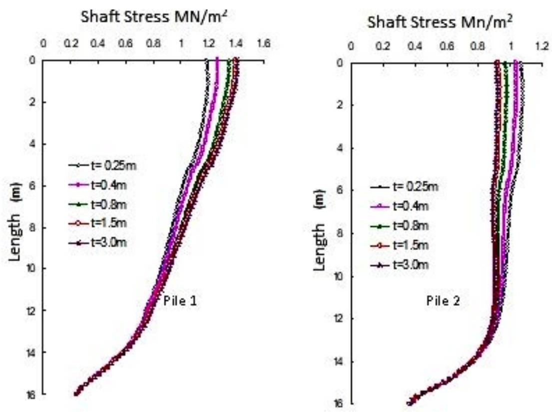

Figure 11 Axial Stress Distribution

Comparing the above behaviour with axial stress distribution in the piles passing through the compressible layer the axial stress distribution exhibits a non-uniform reduction with the depth as in the Figure 11. There are three stages of stress variation. The variation between top to 13m is treated as stage 1, from 13m to around 20m as stage 2 and 20m to 28 m as stage 3. The shaft stress is evaluated in four piles of the group namely central pile, corner pile, one peripheral pile on the X –axis, and one peripheral pile on the Y axis. The reduction in the shaft stress reduces gradually. But the rate of reduction reduces from 12.5 to 13 m level from the top and extends upto 23m (from 0.47L upto 0.8L)Beyond 0.8L as in the previous cases the rate of the drop is more rapid. But the ratio of the tip stress to the head stress to works out to 45% to 53% the maximum being at the central pile and the minimum being at the corner pile. The reduction ratio works out to 85 % upto 13 m level; from 13m to 22.5m the reduction in stress with reference to the head stress is 71% which reduces to around 45%. The trend remains same although the magnitude may vary. This indicates that the frictional resistance of the weaker layer is enhanced by the stronger layers above and below the compressible layer.

6.1 Discussion

In the case of load transfer mechanism there are three types of interaction namely raft - soil soil-pile, pile –pile and raft- pile,and raft -raft When there is an intermediary compressible layer there appears to be an interaction between the upper layer (medium dense to dense sand) and the lower layer namely stiff clay which causes perhaps an enhancement of the frictional resistance of the weaker layer in between. There is always a confusion particularly when the soft layer is found below a denser layer in computing the negative friction in the sense that when the compressible layer reference to the pile the upper layer also settles down and hence the upper sand layer also can contribute for additional drag load. This behaviour is very evident from the shaft stress distribution from the rate of reduction in the axial stress with depth. Although the pile group in a piled raft is intended to be primarily a settlement reducer the pile design has to recognize this excess load. It is also to be noted here that the ratio of tip stress to head stress varies from 40% to 45% caused by perhaps the increased frictional resistance of the compressible layer due to the stronger upper and lower sand layers.

7. BENDING MOMENT BEHAVIOUR

In general the piles are always designed for combined axial load and bending moment due to the lateral loads. The bending moment due to axial load is very small, but when the pile passes through compressible layer this section is subjected to higher bending moment, which is not so in the case of pile group passing through homogeneous layer. Care has to be taken to consider the bending moment value at the section passing through compressible layer. It is seen from the Figure 12 that the bending moment exhibits both positive and negative bending moment unlike in the of pile group through uniform homogeneous layer as presented by Min. Huang (2006), and shown in Figure 13.This variation in bending moment is mainly due the differential settlement as seen in the settlement profile. Further the value of bending moments in the pile sections is far higher and hence the piled raft design with pile group passing through compressible layer has to be analysed for all the conditions of loading so that the pile element can be designed for axial stress and the bending moment. Once the peat layer is crossed the structural provisions can be reduced to the extent of the axial force requirement.

The maximum positive bending moment as can be seen at 14m is of the order of 200 kNm which is not seen in Figure 8.Keeping the axial stress distribution and bending moment together it can be said that as pile is subjected to a higher bending moment in the section inside the compressible layer. Hence the structural provision can become higher than the conventional requirement in particular the corner and the peripheral piles. In such cases it appears that higher diameter pile may have to be used.

8. PARAMETRIC STUDY

In the present study, the influence of two important factors relating to the compressible layer, namely the thickness and the consistency on the behavior of the pile group of piled raft need to be considered. The effect of the layer thickness was studied by repeating the analyses for three different thicknesses of the layers namely 2.5m, 5m, and 8m. The shaft stress distribution over the length of the piles is plotted as typically shown in Figure 10. The stress reduction ratio **α** which is the ratio of the variation in the stress between two successive points (eg : stress at pile head – stress at 0.25L / stress at pile head , stress at 0.5 L – stress at 0.25L/ stress at 0.25L and so on) is plotted against length ratio to study the effect of layer thickness. Similarly to study the effect of layer consistency the analyses was repeated for three different N-values namely N=4, N=8 and N=12. In the same manner as said earlier the stress reduction ratios are tabulated and for one typical pile a plot is made between the stress reduction ratio and length ratio for discussion.

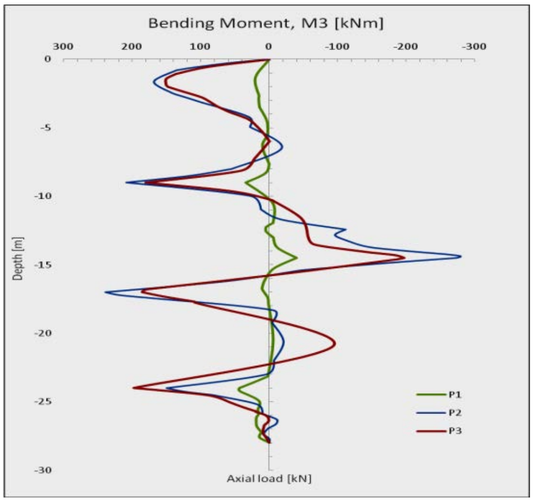

Figure 12 Bending Moment Distribution with compressible Layer

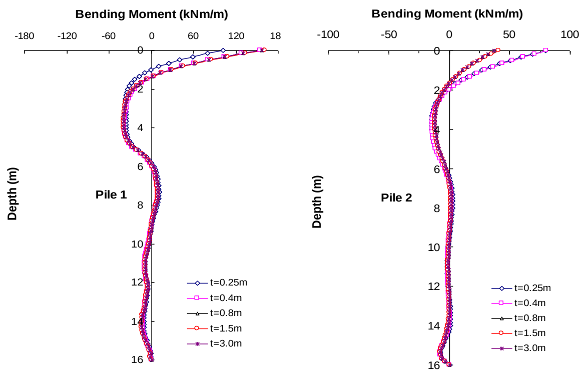

Figure 13 Bending Moment Distribution without compressible Layer

8.1 Variation of Layer Thickness

Table 2 presents the variation of stress reduction ratio **α** with pile length ratio for the various thickness of the compressible layers namely t = 2.5m , t=5m and t=8m.The table presents the variation for four different selected piles.

Table 2 Variation in the Shaft Stress reduction ratio(%) at various layer thickness

L	t=2.5				t=5				t=8			
	1	2	3	4	1	2	3	4	1	2	3	4
0.2 L	5.6	6.6	24	6.3	6.2	7.4	7.3	6.8	7.1	8.6	8.7	8
0.5 L	19.2	19.9	15.8	15.8	19.5	21.3	27.3	20.2	21.6	22.1	24.24	23.7
0.75 L	41.1	43.7	43	45.1	24.3	34.2	38	29.97	25	26.8	31.66	27.5
1 L	67.7	69.7	77.3	71.7	56.6	60.9	70	60.2	47.5	49.2	86.3	51.5

To discuss the results, the variation of the stress reduction ratio to the length ratio is presented for the central pile in Figure 14.

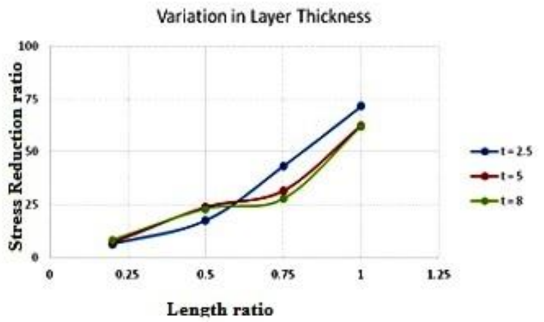

Figure 14 variation of the stress reduction ratio to the length ratio

It can be seen that the rate of increase in the stress reduction ratio is rapid as the length ratio of the pile increases when the layer thickness is 2.5m. As the thickness increases, the rate of increase in the stress reduction ratio reduces between the length ratio 0.5 and 0.75 and then it increases. This indicates that the compressible layer present in this region settles, generating the negative friction which causes an increase in the shaft stress locally. In all the other piles also the same trend exists. It can be said that as the thickness of the layer increases, the compressible layer contributes for the negative skin friction locally, increasing the shaft stress at that section.

8.2 Effect of Variation in the State of Compaction

In the same manner as in the previous case, the analyses was repeated for three different cases of N-Values namely N=4 (soft), N=8 (medium stiff) N=12 (stiff) representing three different consistencies of the compressible layer. The rate of variation of the shaft stress reduction ratio **α** is presented in the cases of four selected piles in Table 3.

Table 3 The rate of variation of the shaft stress reduction ratio α(%)

L		0.2 L	0.5 L	0.75 L	1 L
N = 4	1	6.2	16.7	26.6	51.7
	2	7.2	18.1	27.7	55.3
	3	7.4	21.2	31.6	63.5
	4	6.7	18.14	30.1	55.2
N = 8	1	6.22	17.8	28.5	53.5
	2	7.5	19.4	29.8	57.3
	3	7.5	22.9	34.1	66.1
	4	6.8	19	31.8	57.3
N = 12	1	6.3	18.2	29.5	54.4
	2	7.5	20.5	31.6	32.3 (59.1)
	3	7.5	23.6	35.8	67.9
	4	6.9	19.6	33.16	38.46

For the sake of discussion and better understanding, the rate of variation of the shaft stress reduction ratio **α** (%) is plotted against the length ratio and is presented in Figure 15

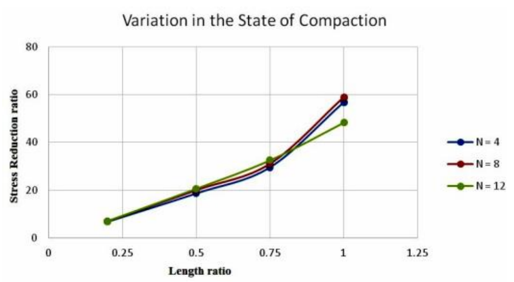

Figure 15 variation of the shaft stress reduction ratio to length ratio

It can be seen that the variation in the shaft stress reduction ratio is gradual and uniform indicating that N- Value has no significant influence the shaft stress reduction and the variation is as per the general behavior. In other words the shaft stress reduces over the length uniformly unlike in the case of variation in the layer thickness.

9. CONCLUSION

In order to study the applicability of piled raft under any practical geotechnical conditions the effect of intermediary peat or compressible layer was studied. Such profiles are widely seen in the Gold Coast area as furnished by various authors mentioned in Table. Accordingly the study was carried out numerically using PLAXIS 3-D considering a general soil profile. A parametric study was also conducted by varying the thickness of the compressible layer and its consistency. The conclusions are as follows:

1. The presence of peat layer induces a higher differential settlement. The settlement varies by 20 to 25% from the centre to the edge.
2. From the study of axial stress and bending moment variation in the vicinity of the compressible layer, the fall in the axial stress distribution is influenced by the drag force developed by the peat layer. The drag force adds an additional load on the pile irrespective of its location. In other words the piles are subjected to additional axial load in the section of the pile passing through the compressible layer.
3. It is seen from the ratio of tip stress to head stress; the ductile behaviour of the pile group is affected by the presence of the peat layer.
4. From the parametric study it is seen that the thickness of the compressible layer has a higher influence on the behaviour than the state of compaction.

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