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Piled Raft on Sandy Soil - An Observational Study

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ABSTRACT: The increasing recognition of the combined piled raft foundation system is mainly due to the economics and the savings that can be achieved in the foundation design without compromising the safety and serviceability requirements. While detailed investigations through field monitoring of the piled raft supporting several tall and heavily loaded structures have been reported (Hooper, 1974; Cooke et al., 1981; Poulos, 2008; Yamashita, 2012), it appears, not so many case histories exist on the applicability of piled raft in the case of moderately loaded structures. The present study is related to the monitoring of the piled raft supporting a 12 storied apartment building and the results have been subjected to validation through numerical analyses. The results have been compared with the published results for a similar structure. As a practical problem, the study also discusses the effect of a compressible layer sandwiched between two competent layers obtained from an analytical study.

KEYWORDS: Piled raft, ANSYS, Compressible layer.

1. INTRODUCTION

Deep piles installed up to refusal level had always been the foundation solution in the past, whenever either the bearing capacity became inadequate or the settlement was exceeding the permissible limit. While such a design could satisfy the safety and serviceability requirements of the structure, seldom could it have been economical, as the presence of pile cap/raft and its capability to transfer the applied load to the strata on which it was resting was completely ignored. In the last two or three decades there has been a noticeable increase in the use of combined piled raft foundation systems to support predominantly tall and super tall structures. Cunha and Poulos (2018) had pointed out that the combined piled raft foundation system is characterized by the raft connecting all the piles in the pile group and resting on a competent ground, positively contributes to the overall foundation behaviour as mentioned by many authors like Ta and Small (1996), Clancy and Randolph (1993, 1996), Mandolini and Viggiani (1997) and Katzenbach (2000a).

It had been established by Balakumar and Anirudhan (2010) and Long (2010) that a raft capping a closely spaced smaller diameter pile group could transfer nearly 20% of the total applied load, when the raft is seated on a competent ground. Further when the ground has adequate bearing capacity, but settlement alone is a problem, in providing a large group of piles, the number of piles is governed by the geometry of the foundation. This leads to an uneconomical design with a very high factor of safety and not justifiable from an engineering point of view for reducing the settlement. Therefore, 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.

1.1 The Piled Raft Foundation System

The combined piled raft foundation system is an intelligent and modern geotechnical engineering concept characterized by the design performed in the framework of well-developed theories. The combined piled raft foundation system distinguishes between the bearing capacity part of the problem and the settlement part of the problem in the sense that the settlement of the raft gets reduced by the introduction of piles in a strategic manner in the initial stages of loading, and at a higher load the added pile group enhances stiffness of the raft so that the combined system takes a much higher load than the un-piled raft at the same settlement level considered. Further neither the pile group nor the raft is singularly responsible for the safety of the structure, but it is the combined system of the pile group and the raft ensures the safety and serviceability of the structure. Therefore, it is the combined capacity of the system at any given settlement level required, that as a whole address the design requirement.

2. OBJECTIVE

The objective of this study emanates from the fact that the observational studies on piled rafts supporting lightly loaded structures with much lesser floors appear to be very scarce, whereas a larger volume of published results of the observational studies conducted on the piled raft supporting tall and super tall structures (Poulos, 2008; Poulos and Bunce, 2008; Poulos and Davids, 2005; Katzenbach et al., 2010) founded on large diameter bored piles capped with a thick raft are available. Such a condition may give an impression in the minds of structural designers that the piled raft is perhaps meant to support heavily loaded structures only. So it becomes essential to establish that the piled raft can effectively be used to support lightly loaded structures, with much less number of floors, adopting a thinner raft of uniform cross section provided over piles of relatively smaller diameter, such that the diameter to raft thickness ratio may be close to unity.

2.1 Need for Observational Studies

It is possible to achieve the above objective through numerical analyses also. However, there are certain limitations. An overview of the literature confirms that even by adopting the most rigorous methods of analysis, the results relating to the load sharing show wide variations as established by Russo and Viggiani (1997). Quoting Randolph (1994) for a group of more than 100 piles the accuracy of the available programmes is perhaps not more than ± 20%. This may be due to the fact that the evaluation of in situ subsoil properties is the most difficult part for almost all geotechnical problems; more so in the pile foundations as the properties are influenced to a significant extent by the methods of pile installations. Furthermore, the application of the superstructure load is time dependent and so the rate of settlement and the friction mobilised is governed by the properties of the soil surrounding the pile shaft. Franke (1991) had pointed out that the development of shaft stress from tip to top is caused by the movement of piles in the soil in between the pile group and the raft and hence the movement of the system as a whole is very important.

The installation effects are particularly significant for piles under vertical load, which is also the most common loading condition. In fact, the ultimate bearing capacity of a vertically loaded pile depends essentially on the characteristics of the soil immediately adjacent to the shaft and below the base of the pile; in these zones the installation produces significant variations of the state of stress and soil properties. These variations can influence the values of: (i) the ultimate bearing capacity and (ii) the load-settlement response or axial stiffness of the pile which might have been evaluated from theoretical considerations. These aspects may not get reflected in the case of analytical models and small scale model tests. Hence, to establish the applicability of the piled raft to support a moderately loaded structure in a more realistic and performance based, an observational method of study has been chosen.

The next issue is the monitoring of the piled raft during construction and after construction. In the experience of the authors, promoters of such commercial ventures seldom agree to provide support for costly instrumentation and hence it becomes necessary to prove that with least expenditure the settlement behavior can be monitored. Here, it is to be noted that Frank (1991) was of the opinion that the measurements taken through the strain gauges glued to the reinforcement bars could often be inaccurate and so only simple settlement markers were used.

2.2. 1g Model Tests

With reference to the present study discussion on 1g model tests may appear out of context, but the effect of pile configuration, pile surface roughness and pile raft area ratio (ratio of the sum of the pile cross sectional areas to the plan area of the raft) could not have been studied in a better manner than by conducting 1g model tests. These parameters have a lot of significance in the load sharing behaviour of the pile group of piled raft at any settlement reduction level. The layout of piles is important from the sequence of installation, the surface roughness can reflect the method of installation (smooth surface refers precast driven piles and rough surface represents driven cast in situ piles and bored piles), and the pile-raft area ratio reflects the economy of the system as the economics is governed by the number of piles and pile diameter, particularly when smaller diameter piles are used.

2.3. Comparison

Finally, comparisons between the measured and anticipated performance with experience gained in such comparisons and with other published results of observational studies on piled rafts supporting similar structures can be very valuable for future projects. Hence, the results of the present study are compared with the results of few selected case studies published. In this aspect, care has been taken to consider similar structures although such studies appear to be scarce

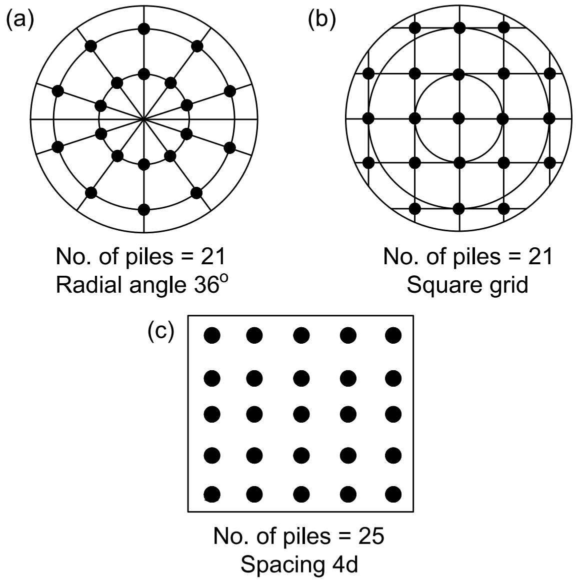
3. RESULTS, ANALYSES AND DISCUSSIONS

3.1. From 1g Model Tests

Although extensive studies have been conducted using 1g model tests, the discussion presented here is relevant to the prototype behavior of the piled raft. They are related to the effects of pile roughness (related to the installation procedure), grid pattern, and pile-raft area ratio A_R which is defined as the ratio of the total cross sectional area of the pile to the plan area of the raft.

3.1.1. Effect of Pile Roughness and Configuration from 1g Tests

Two important factors involved in a large pile group or piled raft are the grid pattern of the layout to in relation to the sequence of installation, and the installation methodology. Therefore, the initial study on the effect of pile layout and the roughness of pile surface has been done with 1g model tests. The details of the test set up, the properties of the bed materials, and the preparation of bed by sand raining process etc. are given elsewhere (Balakumar, 2008, 2018). The models taken typically for this presentation are shown in Figure 1(a) and Figure 1(b). Figure 1(c) presents the typical layout of square piled raft, which is discussed in a later part. The common feature here is that the pile raft area ratio (ratio of the sum of the pile cross sectional areas to the plan area of the raft) is close to 5%. As a part of the detailed study, the effect of pile roughness and the configuration typically in the case of circular piled raft were also studied. For the study the model shown in Figure 1(a) was taken with the pile group having piles with sand grains glued to them to represent rough piles and one with natural surface to represent piles with smooth surface were tested. Figure 2(a) presents the comparison of the load settlement response of piled raft with smooth piles and piled raft with rough piles. The piled raft with rough pile group took a load more than the model with smooth pile group by 8%. Similarly, two identical models of a piled raft, one with radial grid pile (1a) layout and the other with square grid (1b) were studied. Figure 2(b) presents the comparison of the load settlement response of piled raft with radial configuration (Model 1a) and square grid configuration (Model 1b). The model 1b was taking a load, 3% more than the radial grid (model 1a). In designing the layout of piled raft, the installation method and sequence of installation play a very important role and hence this study was done as the first step. Since most of the tank farm foundations were following a radial grid, the same was used in the studies (Balakumar, 2008). The models were 10 mm thick raft and 8 mm diameter piles made of Perspex sheet and rod respectively. The length of the piles varied from 200 mm to 100 mm.



No. of piles = 21
Radial angle 36°

No. of piles = 21
Square grid

No. of piles = 25
Spacing 4d

Figure 1 (a), (b) Circular piled raft, and (c) Square piled raft

3.1.2 Effect of Pile Raft Area Ratio

The load settlement response of the piled raft was studied by varying the pile-raft area ratio from 4.25% to 9.25%, and from the modelling comfort point of view, a circular piled raft was taken for the study. The radial angle corresponding to an area ratio of 4.25% was 45°, and for the maximum 9.25% the radial angle was 20°.160 mm long 10 mm diameter piles, and 8 mm thick raft (200 mm diameter) were maintained.

Figure 2(c) presents the load settlement response and Figure 2(d) presents the effect of area ratio A_R on the load sharing ratio α_{pr} (α_{pr} is defined as the ratio between the amount of load 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}).

$$\propto_{pr} = \frac{Q_p}{Q_{pr}} \tag{1}$$

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

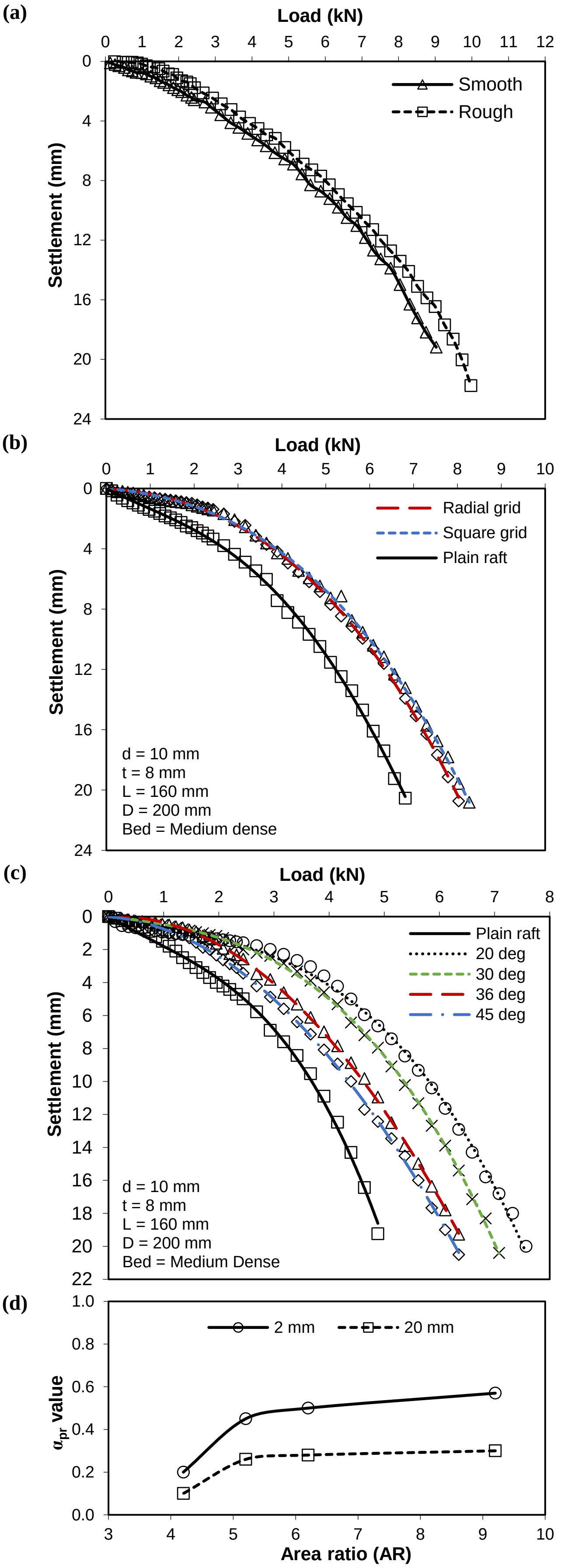


Figure 2 (a) Effect of roughness on load-settlement response of piled raft in dense sand, (b) Comparison of load settlement response of plain and piled raft-Radial and square grid, (c) The Load Settlement response-Area ratios, and (d) 2D Variation of αpr with Area ratio

It can be seen that the α_{pr} value is much higher at the settlement level of 2 mm indicating that the load shared by the pile group in the initial stages is far higher than the values at higher settlement. It can also be seen that the optimum benefit can be obtained when the pile raft area ratio is around 5%, when the raft is closer to the ground level. When there is a deeper excavation this percentage may have to be decided based on the load sharing and the corresponding settlement reduction required.

4. ISSUES ON ANALYSES AND DESIGN

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. As Russo (1998) has pointed out to move from the traditional capacity based design to settlement based design the main requirement in the method of analyses is that it must be capable of taking into account properly the soil structure interaction within the foundation (Balakumar et al., 2005; Katzenbach, 2005) had observed that the implementation of linear and nonlinear soil modulus depends upon cases under study as the results can vary to an extent of 20% to 30%.

In most of the cases, for the initial stages of analyses and design the required parameters are obtained either from laboratory tests or from standard correlations between tests like SPT and E_s values before the installation of piles. It is also to be noted here that many such correlations are site specific and using such correlations without proper validation may not be advisable and very careful consideration is required on the applicability of such correlations to the specific site under consideration. This can affect the accuracy of results. Therefore, for the validation of the design, parameters have to be evaluated after the piles are installed.

However, over the past few years there has been 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 which appear to be a very reliable procedure.

5. FINITE ELEMENT ANALYSES

The design of piled raft has three stages (Poulos, 2008), but the role of detailed analyses comes only in the third stage. For the initial stage and preliminary design either axisymmetric or plane strain modelling may be adequate as both methods can predict the load settlement response and the overall settlement reduction behaviour based on the pile layout, diameter and length can be predicted. In an earlier publication (Balakumar et al., 2018) it was shown that the two methods may predict a stiffer response compared to the actual load settlement response obtained from a 1g model test which can be taken to represent site behaviour.

5.1 Non Linear 3D Analyses of 1g Model Tested

For the three dimensional analyses, the model shown in Figure 1(c) was chosen to keep in line with the shape of the piled raft in the present observational study. The nonlinear behaviour of the soil was 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. The soil was idealized as an isotropic homogenous half-space. The soil medium below the raft was modeled using an eight-noded brick element (SOLID 45). Solid 45 is used for the 3D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node. They are translations in the nodal x, y, and z directions. The elements have plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities.

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 15.5 kN/m^3 (15.5 $\pm$ 0.1 kN/m^3) under different confining pressures. A value of 0.35 was used in computation for Poisson's ratio.

In the analysis the bed dimensions were kept the 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 properties given below in Table 1 were evaluated from the laboratory tests on the samples as said earlier.

Table 1 Material properties used in the analyses

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

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 a uniformly distributed load in small increments till the load on the raft was equal to the final test load. Figure 3 shows the quarter model including finite element meshing adopted in the analysis.

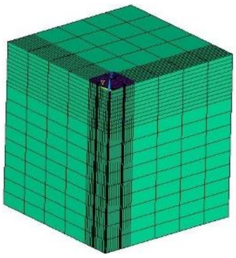


Figure 3 Quarter model and finite element mesh adopted for square piled raft in ANSYS nonlinear analysis

At the maximum load of 8.7 kN the settlement was found to be 18.9 mm. Figure 4 presents the settlement contours. From the contours, it can be seen that, the piles had settled uniformly and the settlement was 15 mm. 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 5 presents the comparison of the load settlement response obtained from the 1g model tests and the nonlinear 3D analyses. It can be seen that the analytical model predicts a slightly stiffer response compared to the response produced by the 1g model test.

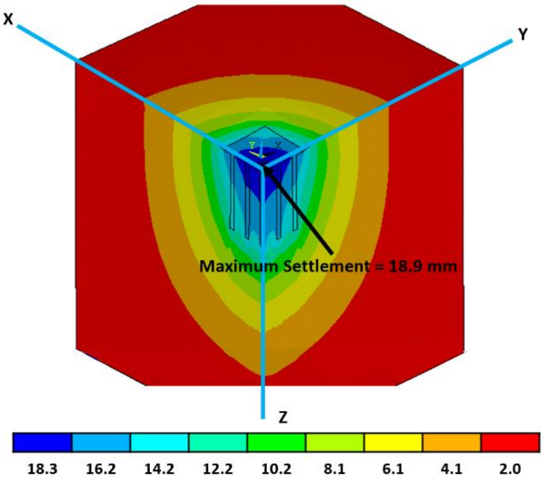


Figure 4 Settlement contour for the load of 8.70 kN

Figure 5 confirms that the three dimensional analyses give a closer response to the actual behaviour obtained from the 1g tests. Figure 6(a) and Figure 6(b) present the raft stress distribution under a loading corresponding to 2 mm settlement and 18.9 mm settlement at the maximum load. It can be seen that in both cases, the stress distribution is reasonably uniform; at 2 mm settlement, the contact stress was found to vary from 0.02 N/mm^2 to 0.04 N/mm^2. At the maximum loading, the stress variation is greater. On the raft the contact stress varies from 0.132 N/mm^2 to 0.139 N/mm^2 but closer to the pile positions the stress varies from 1.7 N/mm^2 to 1.93 N/mm^2.

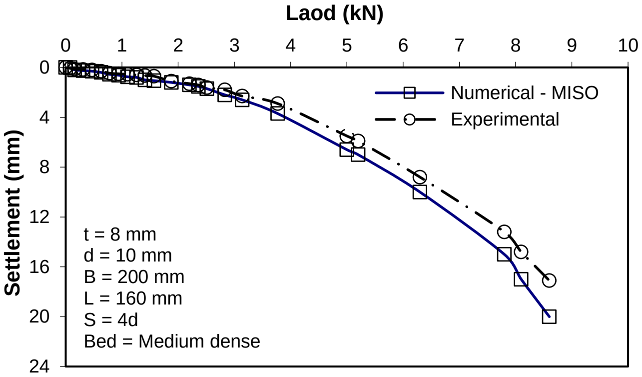


Figure 5 Comparison of load-settlement response between ANSYS and test data for square piled raft with 6d pile spacing

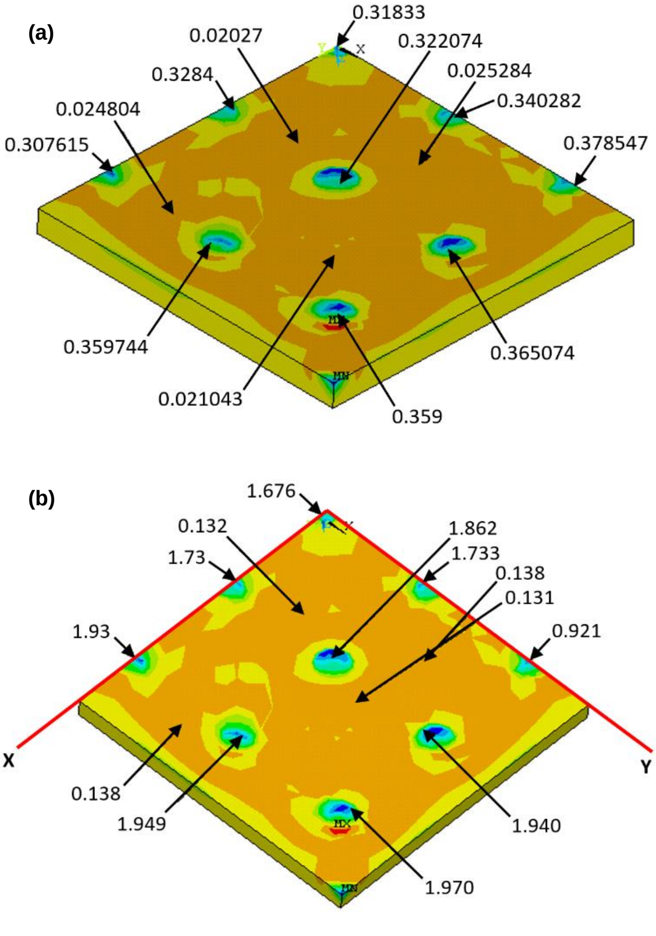


Figure 6 (a) Vertical stress in the square piled raft for the load of 2.8 kN and 4d pile spacing and (b) Vertical stress in the square piled raft with piles at 4d spacing for the load of 8.7 kN

It was found that the load shared by the raft was 35% of the applied load at 2 mm settlement level, but at the final settlement the load shared by the raft had increased to 64%. These results establish that at lower load levels the pile group provides the stiffness for the system to take higher load, and at higher load the pile group enhances the stiffness of the raft. It can also be seen that near the piles there is a concentration of stress, whereas, further away in the case of raft there was no such concentration of stress.

Figures 7 and 8 represent the pile head stress and the tip stress at the maximum load. 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.

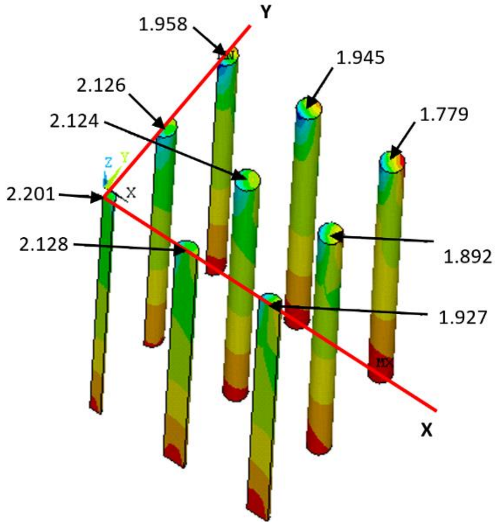


Figure 7 Pile head stress for 8.70 kN load (4d pile spacing)

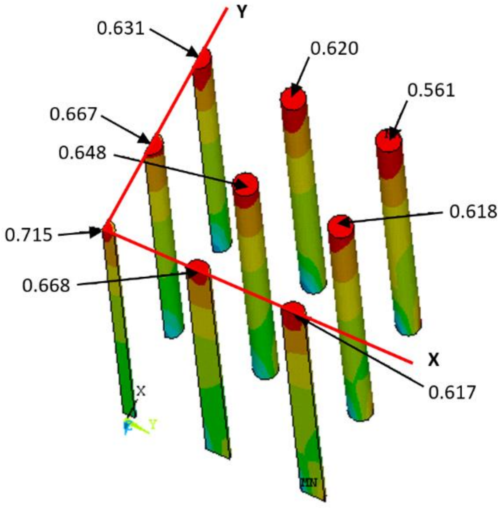


Figure 8 Pile tip stress for 8.7 kN load (4d pile spacing)

Figure 9 indicates the shaft stress distribution and the variation in the shaft stress distribution. 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 the circular raft also, establishing the ductile nature of the pile group. Figure 10 presents the distribution of pile head load, tip load and the load shared by the raft.

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 be predicted in 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.

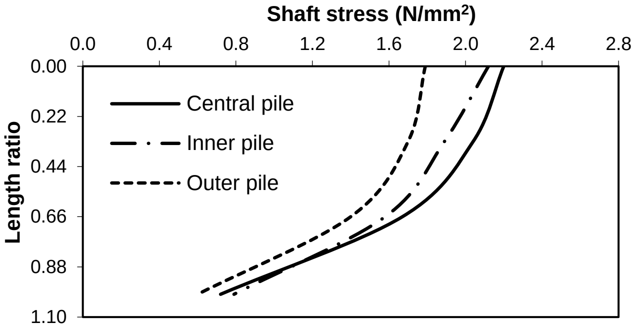


Figure 9 Variation of stress over the length of pile of square piled raft for the load of 8.7 kN (No. of piles 25 at 4d spacing)

Hence, it can be concluded that adopting plane strain and axisymmetric analyses is acceptable for the initial analyses for the initial 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 10 (block diagram) presents the load shared by the raft, load on the pile head and tip.

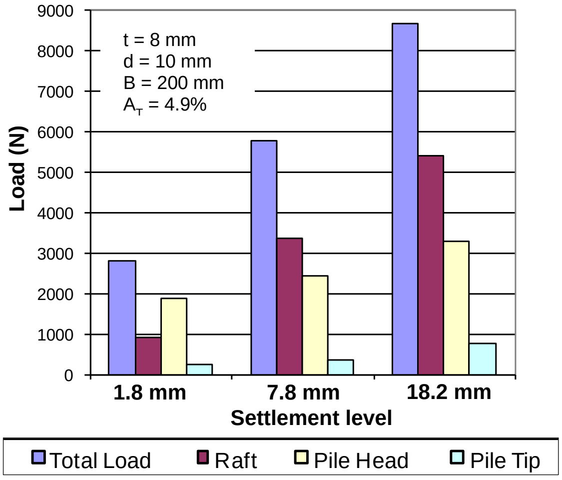


Figure 10 Load shared between raft and piles of square piled raft

6. OBSERVATIONAL CASE STUDY

6.1 Introduction

The increasing recognition of the combined piled raft foundation system has generated a need for the accumulation of field experience in the case of piled raft supporting moderately (or relatively smaller loadings) loaded structures, similar to what is available in the case of tall and heavily loaded structure, so that the piled raft foundation system can become an alternate system by default for all types of structures. Such a case history presented here is based on the observations made on the performance of piled raft supporting a 12 storeyed residential apartment designed with a floor live load of 2.0 kN/m^2 is presented the construction period was 12 months and observational period was 25 months including construction period.

6.2 The Structure - "Palace Regency"

The structure studied has a plan measurement of 32 m by 25 m with the height being 36 m. The structure was comprised of a basement and ground + 10 upper floors; the first two floors would be commercial and the upper floors were residential. The structure has four towers from second floor level, with a central podium being terminated at 2nd floor level.

The structure is RCC framed and the entire design was carried out for loadings outlined in the national standards namely IS 875-part3 for loading data and IS 456/ 2000 for the general RCC design and construction. The maximum and minimum column loads are 2870 kN in the tower area and 1350 kN in the peripheral area.

The frame was analysed with STAAD-PRO and the support reactions were taken to design the piled raft foundation system. The column layout at the foundation level and the sectional elevation are given in Figure 11 and Figure 12, respectively. The enlarged version of Figures 11 and 12 have been appended in the Appendix for clarity.

6.3. Geotechnical Investigation and the Soil Profile

The structure is located in a 4000 m^2 plot located in one of the busy commercial hubs in Chennai which is known for the dense traffic and closely spaced structures. The geotechnical investigation of the site was done with 3 numbers deep boreholes. Standard penetration tests were conducted at regular but close intervals; the strata were primarily non cohesive and undisturbed samples could not be collected in an effective manner, and so values of SPT has to be relied upon to evaluate the in-situ parameters. The disturbed samples collected separately and from the SPT spoon were used to determine parameters like grain size analyses, natural moisture content, density etc. They are presented in Figure 12, which is appended in the Appendix for clarity. Dense clayey sand with N-value 40 was the layer where the piles were terminated.

6.4 Design Parameters and Foundation Design

Since the structure had a basement, the initial thought was to provide a raft for the foundation but the computed settlement was nearly 300 mm which is far beyond the permissible settlement as per Indian standards (IS 1904-1986).

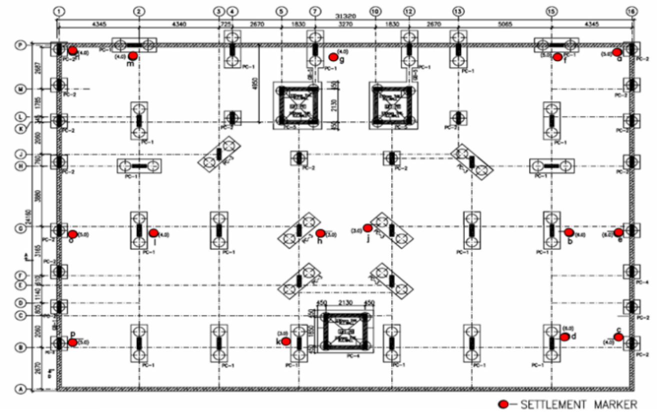


Figure 11 Pile layout with settlement markers itself *(Refer to Appendix for the enlarged figure)*

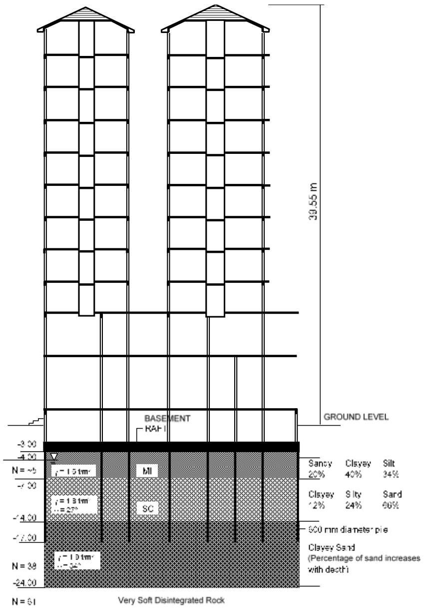


Figure 12 Section with geotechnical data *(Refer to Appendix for the enlarged figure)*

Keeping in mind the variation in the column load due to the presence of shallow courtyard, it was decided to support the structure on deep piles. However, giving due considerations to the N-values increasing with depth, it was decided to support the structure on a piled raft, from the available data (Yamashita, 1994) for a similar structure of moderate column load, the load sharing between the raft and the pile group was assumed to be equal for the initial design. 600 mm diameter piles whose axial capacity was designed based on N-values, with a factor of safety of 1.75, which was considered suitable. The factor of safety was decided keeping in mind the likely variations in the column load as the 2 floors (1st and the 2nd). The raft was designed as a flat slab. 600 mm was the thickness of the raft satisfying the bending and shear considerations. As no initial pile load test could be conducted due to paucity of time, in designing the pile group the factor of safety against block failure was computed as given by Poulos (2001).

$$F = \frac{P_w + NP_i\,\eta}{P} \tag{2}$$

where,

F = Factor of safety against block failure
P_w = bearing capacity of raft
N = number of piles
p_i = individual pile capacity
ή = group efficiency
P = total structural load

The piles were provided below the columns. The column layout and the optimisation of the column load for the pile grouping necessitated the provision of 93 piles as given in the layout. The length of the piles was 14 m below the raft bottom. The strata at the pile termination level had an N-value of 40. The pile raft area ratio here was 2%.

6.6 Instrumentation of the Piled Raft and Measurements

As stated earlier, monitoring of the piled raft during construction and after construction became important. In the experience of the authors in the case of such commercial ventures, the promoters seldom agree to provide support for costly instrumentation and hence it becomes necessary to prove that with least expenditure the settlement behavior at least can be monitored. Since the primary aim was to study the load settlement behaviour of the piled raft, importance was given to obtain the settlement values at various locations at every stage of loading. Hence, settlement markers were placed at 15 points as shown in Figure 11.

The settlement markers comprised of 75 mm × 75 mm × 6 mm plate two numbers, separated by a distance of 600 mm, and were made to form an open box by welding the plates with 4 bars of 12 mm diameter. This box was welded to the bottom layer of the raft reinforcement. The verticality of the marker and the level of the top surface were checked using mercury levels and a plumb bob. The selection of the location for the settlement markers was done in such a way that the settlement profile of the raft could be plotted in both the directions at various sections. In order to measure the settlement a standard benchmark was established such that it could be viewed from any point and would not undergo any movement. Figure 13 shows the sequence of construction loading and the measured settlement profile with time, as observed from the three of the settlement markers. Soil inhomogeneity can cause a small variability of the settlement also.

These inhomogeneities cannot be identified even by the best possible method of investigation. Hence the pile installation record becomes very important information and cannot be ignored. The maximum settlement varied from 12 mm to 14 mm. The total time the settlement pattern monitored was 720 days, of which 360 days was the construction time, which accounted for 90% of the total loading. Table 2 given below presents the observed settlement at various stages of construction.

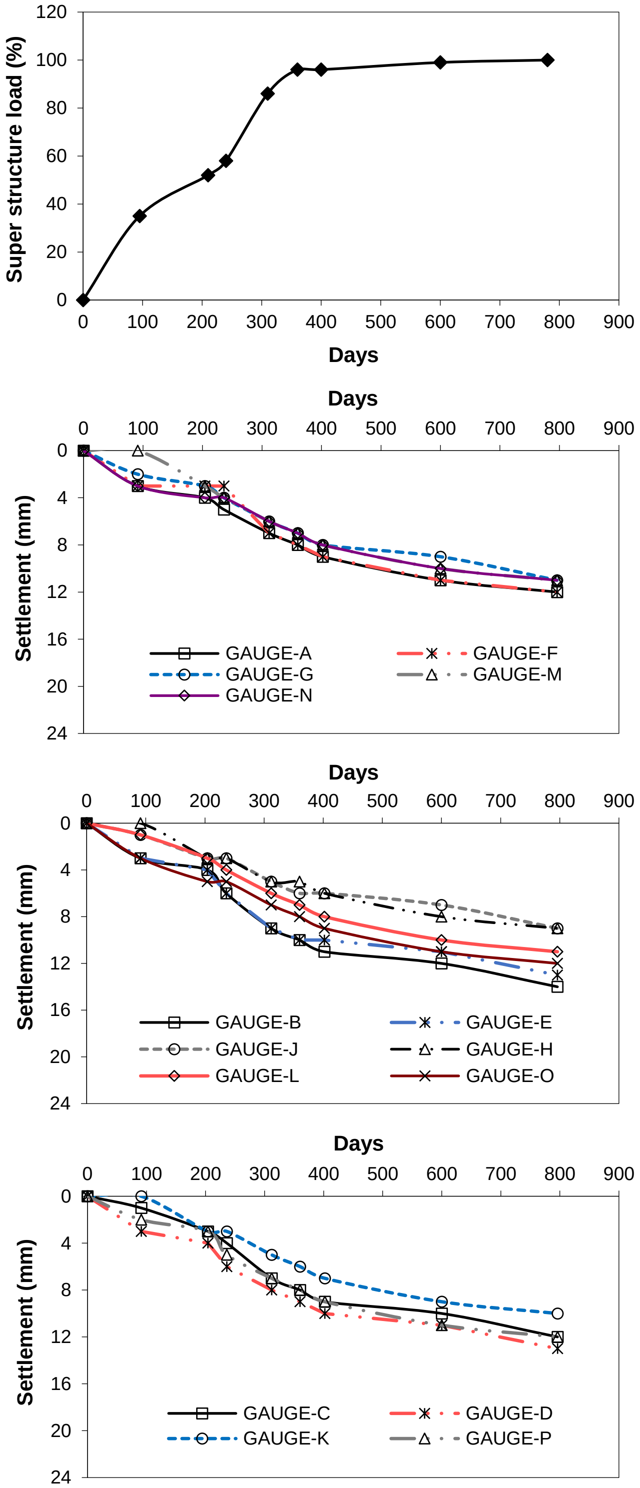


Figure 13 Rate of construction loading and settlement with time (observed values)

As can be seen in the initial 90 days the settlement was 0 mm to 3 mm. From 90 days onwards the settlement started increasing gradually and at the end of 400 days the settlement reached 8 mm to 12 mm. Then the settlement gradually increased to the final value of 12 mm to 14 mm.

The progress of construction loading and the settlement pattern matched to a very reasonable extent. Figure 14 presents the mobilisation of the raft stress and pile head load (in the form of stress) which also follow the same trend. It is seen that the rate of increase in the raft stress is relatively smaller in the first 200 days till the sixth floor is cast. Thereafter there was a rapid increase in the rate of mobilisation of raft stress in the next 200 days by which time 90% of the total load had been applied.

Table 2 Observed settlement

	Settlement in mm									
Days	**A**	**B**	**H**	**C**	**G**	**K**	**J**	**E**	**D**	**Stages of construction**
91	3	3	0	1	2	0	1	3	3	III Floor
143	3	3	2	2	2	2	2	3	3	VI Floor
204	4	4	3	3	3	3	2	4	4	VII Floor
236	5	6	3	4	4	3	3	6	6	VIII Floor
312	7	9	5	7	6	5	4	9	8	X Floor
360	9	11	6	9	8	7	5	10	10	Completion
402	9	11	6	9	9	7	8	10	10	Post construction
796	12	14	9	12	12	10	11	13	13	Post construction

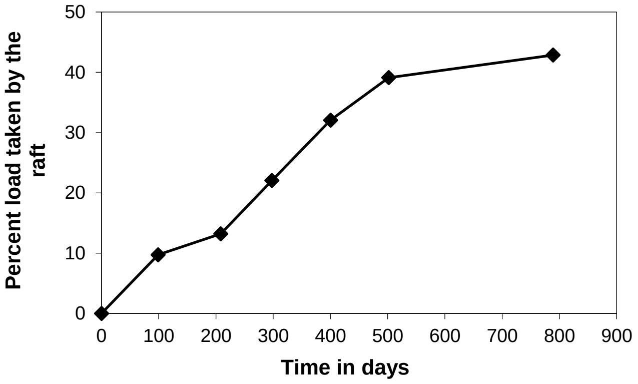


Figure 14 Load shared by raft and pile with time (computed)

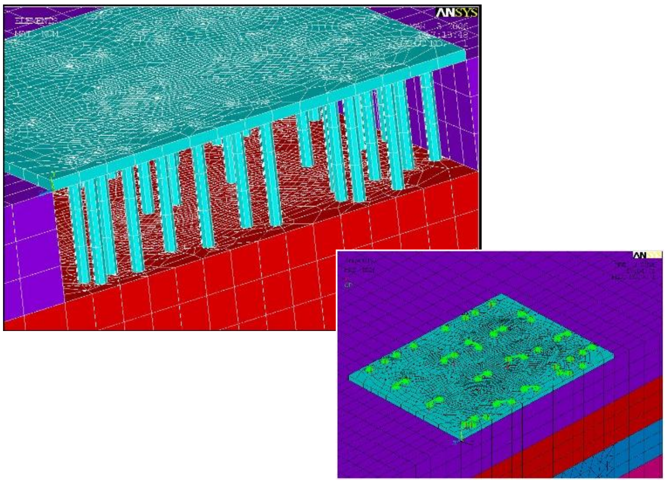
6.7 Numerical Analyses - Palace Regency

The numerical analysis of the piled raft under study was carried out adopting ANSYS - FEA code. For practical consideration elastic analyses were carried out. In generating the model, solid modelling was used. The soil was modelled using eight noded brick elements (solid 45) having 3 degrees of freedom at each node. The model had 93000 elements and 108761 nodes. The Poisson's ratio for soil was taken as 0.35 and for raft it was 0.20.

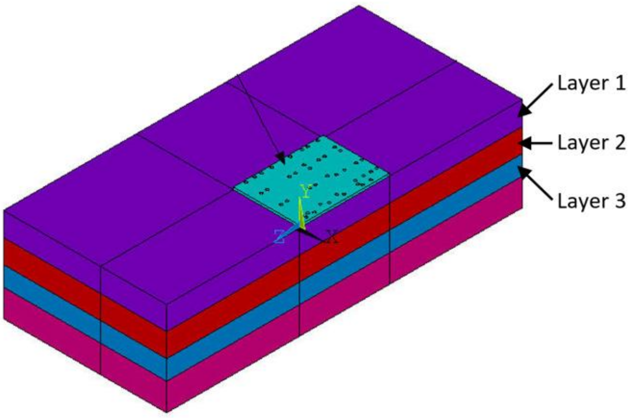
The most important parameter for the numerical modelling of the piled raft is the E_s, namely the elastic modulus of the various layers through which the pile group passes through. Since the strata were predominantly non cohesive, the most reliable method to arrive at these in situ parameters is through a reliable correlation between N-values (Figure 15(c)) and E_s. Accordingly, the chart published by Mori (1965) was used to arrive at the elastic modulus of various layers. The values are presented in Figure 12 and also separately in Figure 15(b) and in the Appendix placed after References.

Figure 15(a) presents the model with meshing. Figure 15(b) presents the E_s values adopted for analyses. The column loads were applied in the respective column locations. The interface characteristics between the raft and the soil were represented by Targe 170 and conta 174. In the analyses perfect contact between the raft and the soil ensured through default option available in the program. The interface characteristics between the raft and the soil were represented by the element Targe 170 used in the pair based contact, the target surface is defined by 3D target element Targe 170. Conta 174 is used to represent contact and sliding between 3-D target surfaces and a deformable surface defined by this element. In the analyses, perfect contact between the raft and the soil was ensured through the default option available in the software.

Figure 16 presents a comparison of the observed settlements and computed settlements. It is seen that that settlement profile matches very closely with the observed settlement profile. More details of this work are presented in another publication (Balakumar and Ilamparuthy, 2007). Figure 17 presents the raft stress distribution. It is seen that the stress close to the pile locations is more intense than the stress between the pile groups.

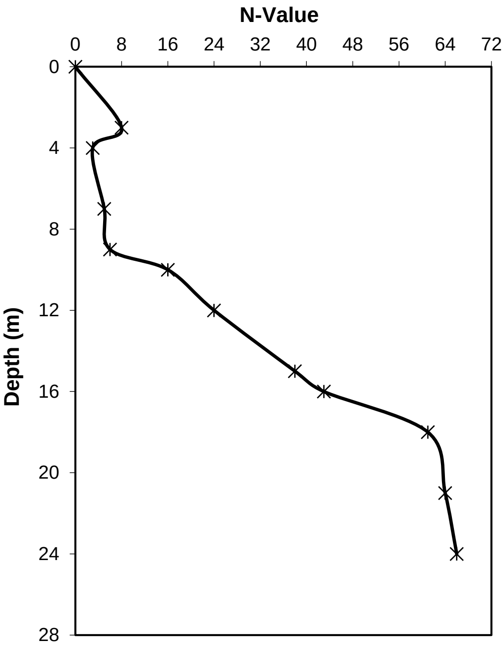


(a)



Layer	Description	E_s value (N/mm^2)
1	Sandy clayey silt	5
2	Silty clayey sand	50
3	Clayey sand	60

(b)



(c)

Figure 15 (a) Finite Element Simulation and Meshing of Piled Raft, (b) Values of ES for various layers, and (c) Variation of N-Values with depth

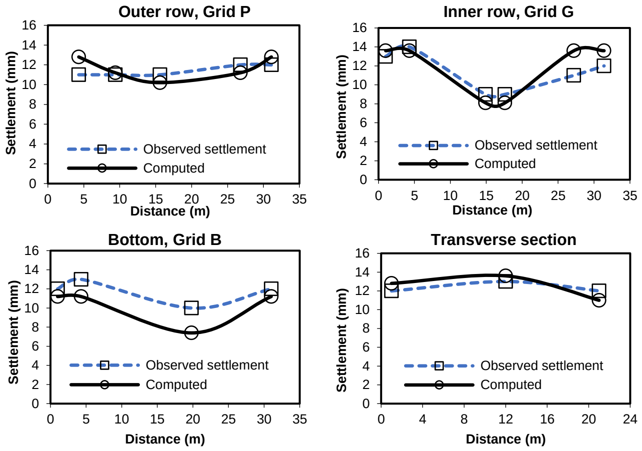


Figure 16 Observed settlement vs. computed value at various sections

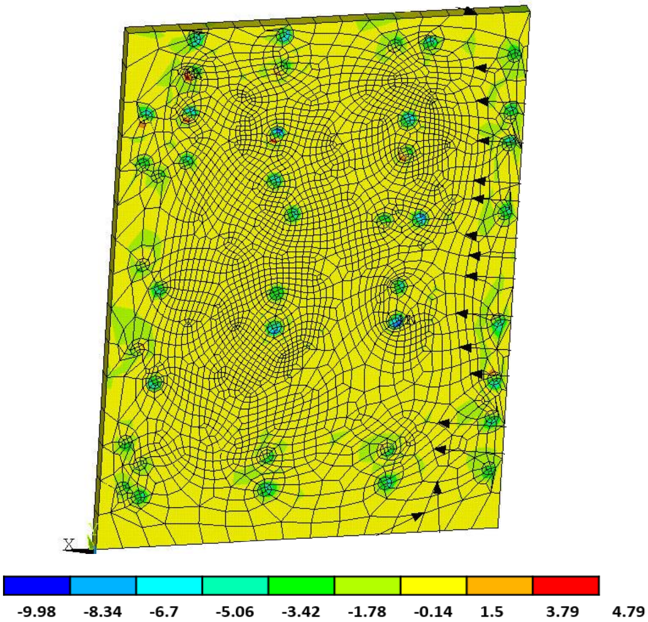


Figure 17 Raft contact stress along grid P

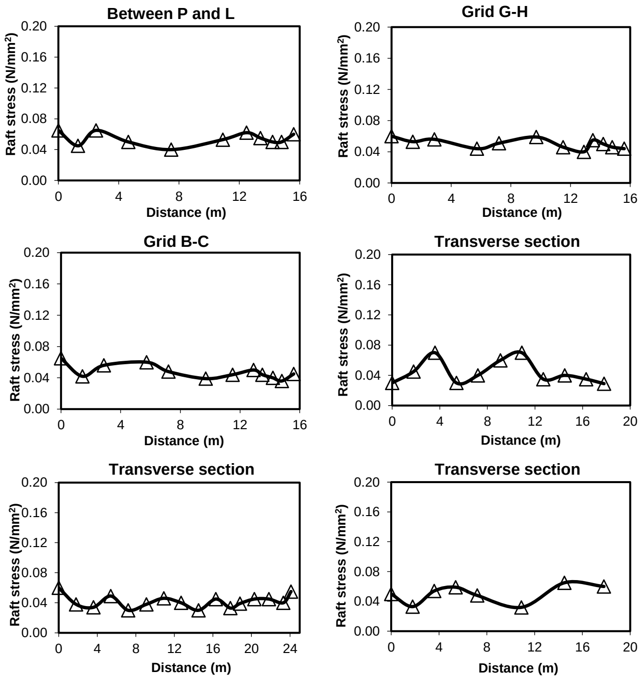


Figure 18 Contact stress in transverse sections (between Piles)

Figure 18 presents the contact stress distribution between rows of piles in transverse section also, between grid 1 and 2, 2 and 3, and 12 and 13, respectively.

Although there is some variation in the contact pressure, this can be attributed partly to the marginal variation in the nature of the soil. Otherwise practically the contact stress is uniform. Figure 19 presents the contact stresses at various points close to the pile location and in between the pile location. The stresses are maximum close to the pile locations and reduce as at points away from the pile locations. The reduction is gradual.

Figure 20(a) and Figure 20(b) present the computed head stress and tip stress values, and it was found that the tip stress was much smaller than the head stress indicating that the major part of the load taken by piles was through the shaft friction. This is in agreement with the shaft stress distribution through the numerical analyses of the 1g model tested. Figure 21 presents the block diagram of load applied, pile head load and the tip load. It can be seen that the tip load is only 30% of the head load, indicating that major part of the load is taken by friction.

In the case of Palace Regency, the total settlement was 14 mm and nearly 75% of the settlement was mobilised at the end of 400 days and thereafter the increase was gradual. Similarly, the load sharing between the raft and the pile group was 43% and 57%. The maximum pile head load was mobilised after 400 days, and the small increase took place in a very gradual manner.

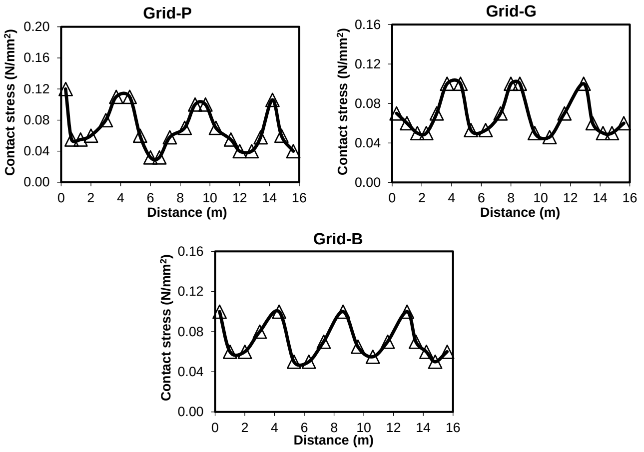


Figure 19 Contact stress at specific points of the raft

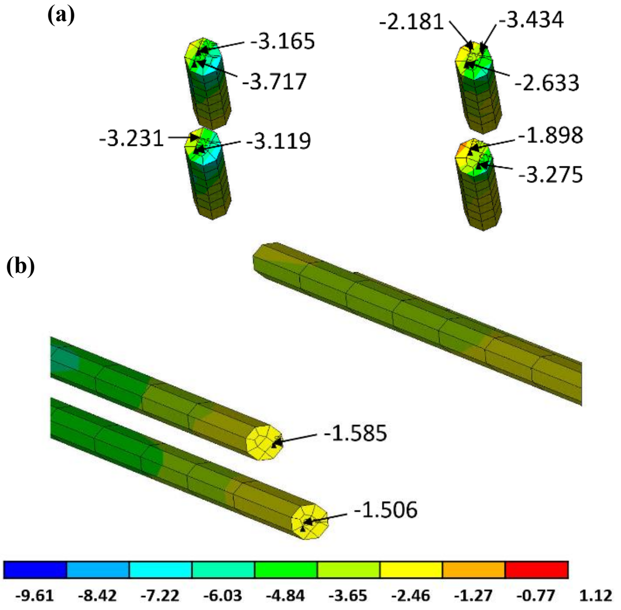


Figure 20 (a) Typical head stress values and (b) Typical tip stress values

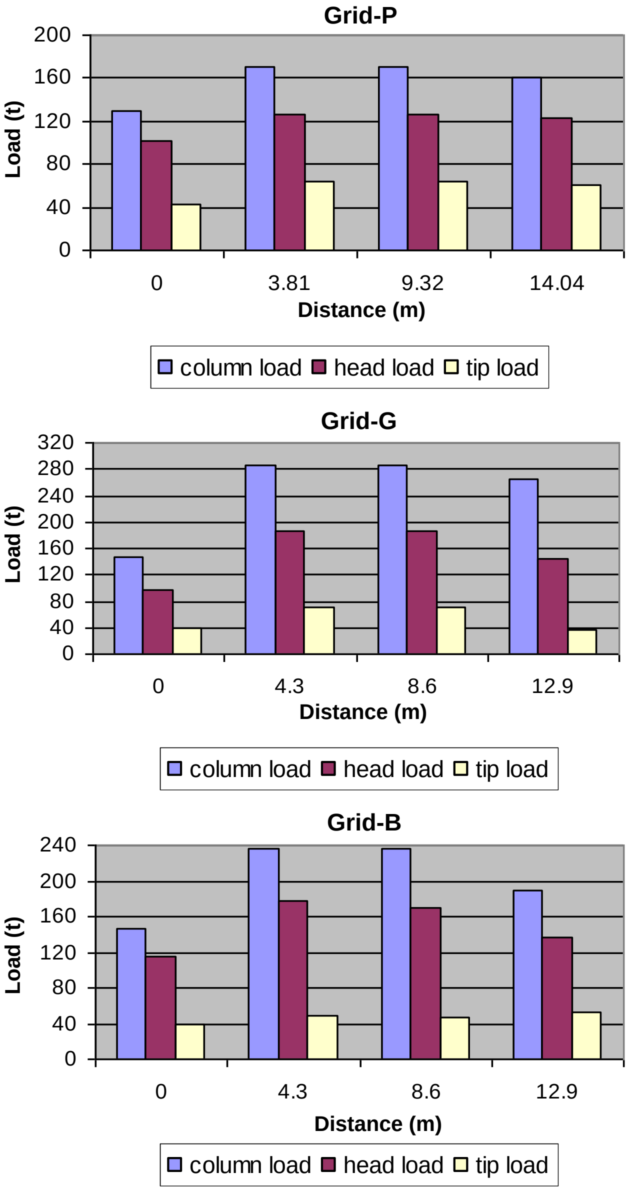


Figure 21 The block diagram of load applied, pile head load and the tip load

7. COMPARITIVE STUDY

As stated earlier in section 1.2, comparison of the results from the present study with other published results of similar studies on piled rafts can form a data base which can be very useful for designing piled rafts for similar projects in the future. So for the comparison purposes, piled rafts supporting three structures are considered, namely a circular silo, a five storeyed office building, and a 12 storeyed hospital building which have been monitored and the results have been documented and published.

Yamashita (2012) had pointed out that although detailed investigations of several high rise load sharing behaviour buildings have been carried out in Germany (Katzenbach et al., 2000b), not so many case histories exist on the monitoring of the load sharing behaviour in relation with the settlement reduction.

7.1 Piled Raft Supporting a Silo

The initial studies on a small piled raft having 5 piles in a circular layout supporting a silo showed that 43% of the total load was shared by the pile group (Yamashita, 2012). The strata were silty and normally consolidated up to 15 m depth, from 9 m level. Beyond this layer upto 44 m depth was alluvial silty sand. The pile length was 24 m, and at the tip, the undrained cohesion was 240 kPa. The load shared by the raft was 57%. Figure 22 shows the loading and settlement with time. It is interesting to see that the pile-raft area ratio was around 3% only.

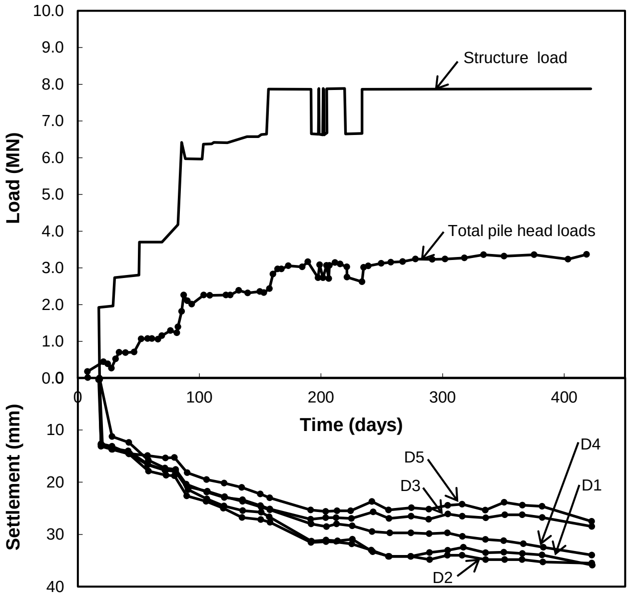


Figure 22 Increase in total load, total pile load and foundation settlement with time (From Yamashita, 2012)

It can be seen that even in the case of a small structure the settlement behaviour is similar to what had been observed in the case of the 12 storied Palace Regency.

7.2 Five Storeyed Office Complex

The structure had a plan dimension of 24 m by 23 m. The foundation system comprised of four types H piles lowered into bore holes of 700 mm diameter and 800 mm diameter grouted with site manufactured sand cement grout. The pile raft area ratio was found to be 1.7% only, considering the bore diameter as the pile diameter. In this case the piles were kept below the column. Here also, a similar time rate of settlement was observed following the loading trend with time. The load shared by the pile group was 49% of the building load on the tributary area, and the settlement was only 12 mm. The initial design of the pile group disposition in the case of the Palace Regency was done following the above pattern.

7.3 Hospital Building (Yamashita et al., 2011; Yamashita, 2012)

The comparison is further extended with observational data obtained by monitoring the piled raft supporting a thirteen story hospital building on clay deposits. Here, the strata consist of predominantly loose sand and silty sand up to 8 m from ground level, followed by soft sandy silt and silty clay up to 21 m depth. The structure was supported on seventeen numbers, 19 m long PHC piles (pre-tensioned spun high strength concrete) inserted inside the pre-bored holes and grouted. On the perimeter 198 steel H-piles were provided inside a soil cement diaphragm wall. In this case the pile-raft area ratio was around 4% only. The total settlement was 20.6 mm 52 months after construction. There was a negligible angular rotation of 1/1440 radians at the edge of the high rise section. Figure 23 presents the settlement with time, Figure 24 and Figure 25 present axial load mobilisation with time, and load sharing between raft and the piles in the tributary area.

Comparing the behaviour of piled raft supporting the hospital building and Palace Regency, it can be seen that the maximum settlement of 20.6 mm was reached after 1600 days approximately, but nearly 80% to 85 % of the settlement had occurred after 400 days. This would mean that nearly 20% was long term consolidation settlement. The measurement of axial load on the two instrumented piles indicated that the rate of mobilisation was rapid till 400 days and then it gradually increased up to 800 days. The load shared by the piles was 45% to 46% of the total load. In the case of a 47 storeyed building also the behaviour was similar with settlements between 12 mm and 29 mm.

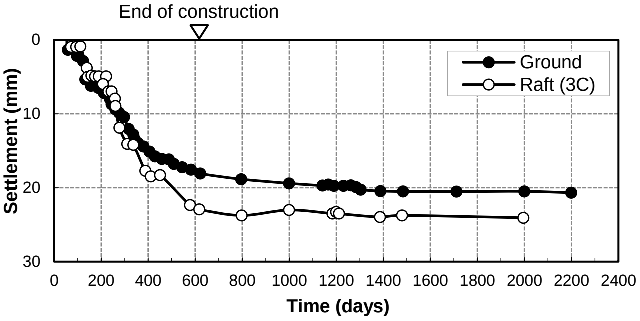


Figure 23 Measured settlement of ground and raft (From Yamashita, 2012)

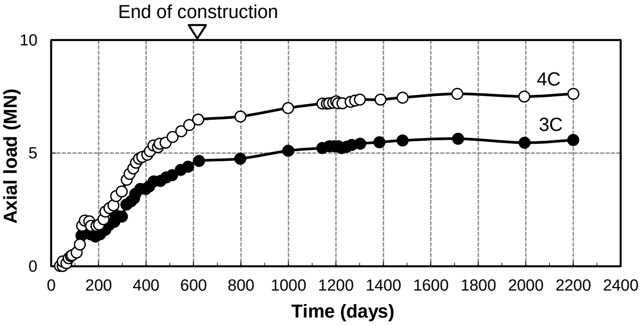


Figure 24 Measured axial loads of piles 3C and 4C (From Yamashita, 2012)

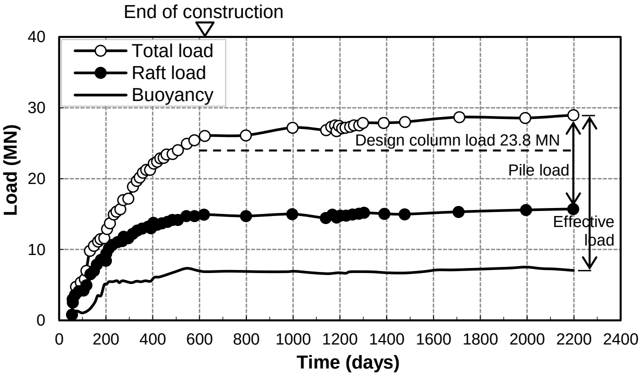


Figure 25 Load sharing between raft and piles in tributary area (From Yamashita, 2012)

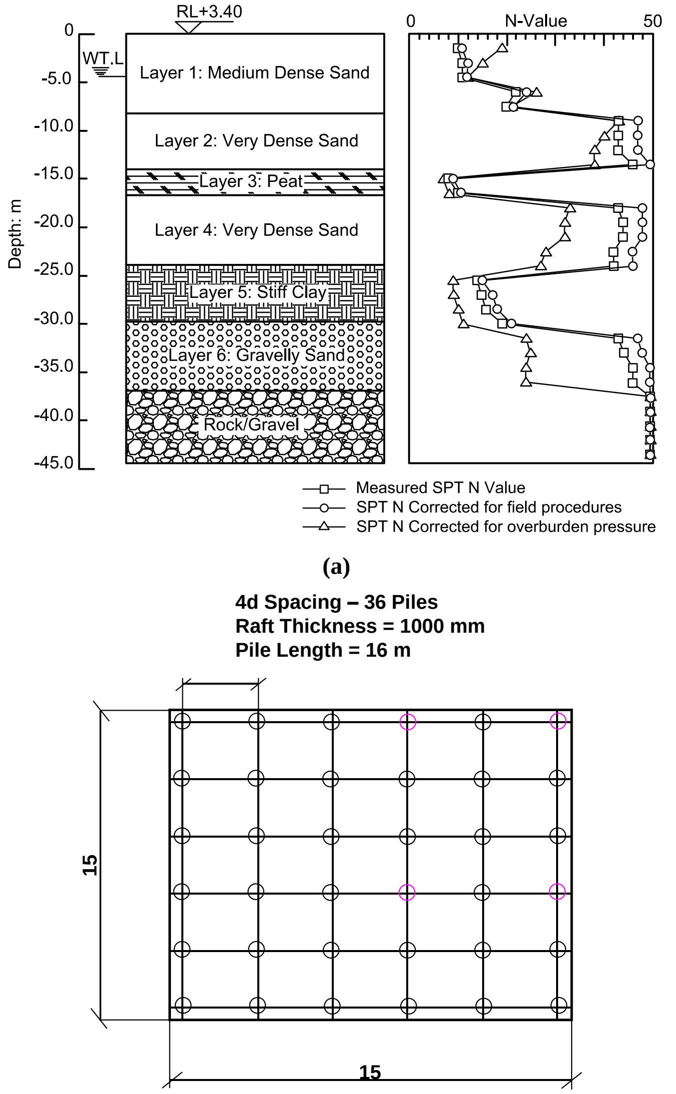
8. EFFECT OF INTERMEDIATE COMPRESSIBLE LAYER

Although the above study establishes the successful adoption of piled raft even for a moderately loaded structure, one very important practical problem that needs attention is discussed below. The problem is the presence of a compressible clay layer sandwiched between two competent strata which cannot be ignored in the analyses. The piled raft problem by itself is complex and the problem gets further complicated due to the presence of such a layer which can influence the pile soil interaction process and affect the load sharing behavior.

Typically, such layers are present in the Brisbane-Gold Coast area wherein number of structures had been supported on piled raft (Oh et al., 2008; Moyes et al., 2006; Min. J. Huang, 2006). In this study, the shaft stress distribution alone is discussed as the load settlement response and other aspects have been presented in detail in an earlier publication (Balakumar et al., 2018).

Table 3 Geotechnical properties

Units	Unit weight, γ' [kN/ m^3]	Friction angle, ϕ' [deg]	Drained cohesion, c' [kPa]	Undrained Shear strength, c_u [kPa]	Young's modulus, E, [kN/ m^2]
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	-	150E+3

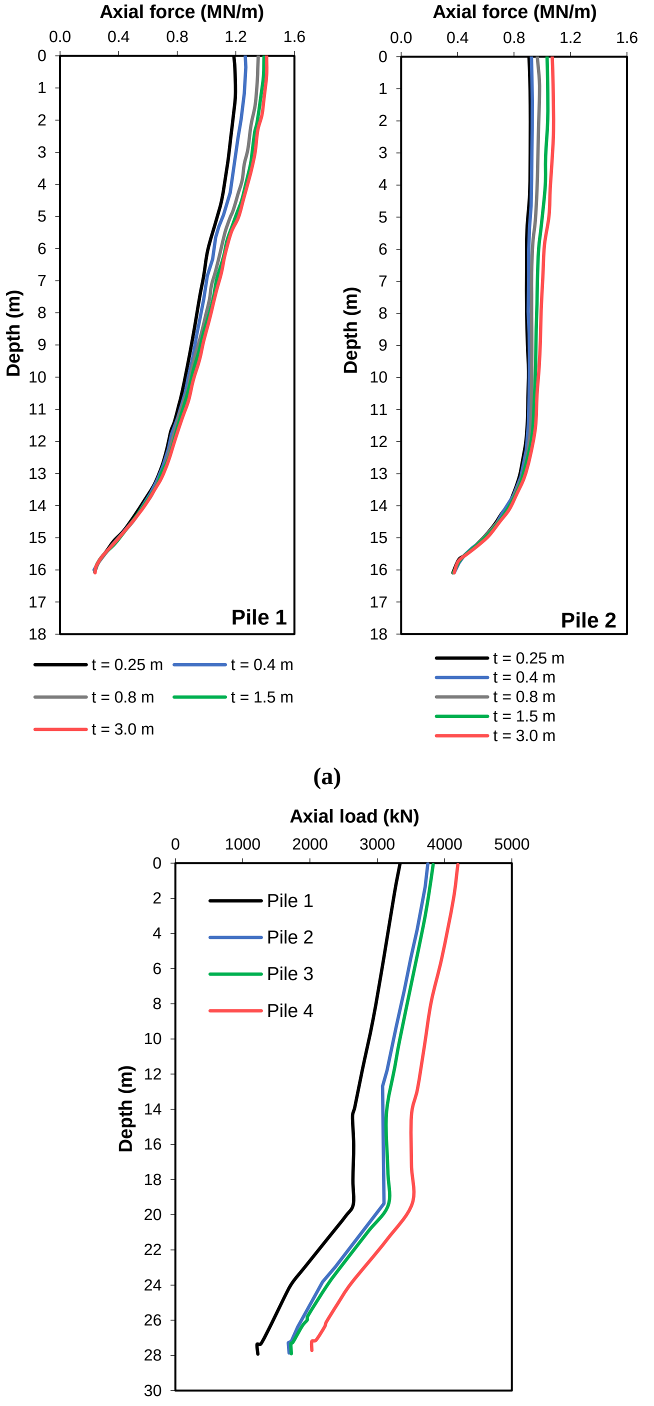


(a)

(b)

Figure 26 (a) Soil profile and (b) Piled raft model studied

The geotechnical model and the parameters considered for the various layers are presented in Figure 26(a) and Table 3, and Figure 26(b) presents the piled raft model. Figures 27(a) and 27(b) present a comparison between the axial stress distribution on the piles passing through a homogeneous layer and the pile group passing through a compressible sandwich layer. It can be seen that in the homogeneous case the axial stress reduction is gradual up to a depth of 0.6L and then there is a rapid reduction. In the case of pile group passing through compressible layer there is an increase in shaft stress in the pile section passing through the compressible sandwich layer. This increases the tip stress compared to the homogeneous soil condition.



(a)

(b)

Figure 27 (a) Axial stress distribution piles through uniform strata and (b) Axial load distribution in the pile with peat layer

The study conducted so far has indicated that the effect of intermediate compressible layer is such that it increases the settlement by 20.5% in the center, 23% in the periphery and 24.6% in the corner (Balakumar et al., 2018). It was also observed that the ratio of tip stress to head stress increases more than what was observed when the compressible layer was absent (Balakumar et al., 2018).

A study was conducted by varying the state of compaction through the N-values. Three different N-values were considered, namely 4, 8, 12, representing soft, on the lower side of medium stiff, and on the high side of medium stiff. Also, the study was done by varying the layer thickness. The thickness considered was 2.5 m, 5 m, and 8 m. Figures 28(a) and 28(b) present the variation of shaft stress for a typical central pile under different layer thickness and N-Values.

The following Table 4 presents the ratio of tip stress to head stress. In the case of homogeneous bed condition this ratio will be of the order 15% to 20% but in the case of the pile group passing through compressible layer this ratio is as high as 30% to 40%. It can also be seen that the variation in the layer thickness has a greater influence than the state of compaction.

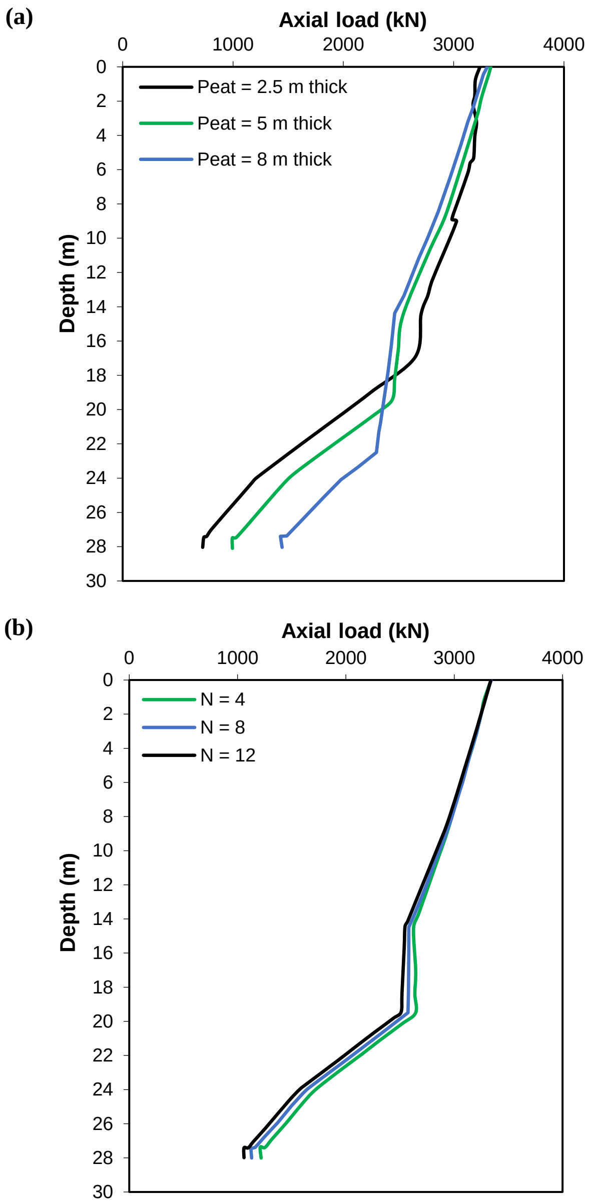


Figure 28 (a) Variation of shaft stress for a typical central pile under different thickness and (b) Variation of shaft stress for a typical central pile under different N values

Table 4 Effect of thickness and N value on shaft stress ratio

Effect of Thickness on Shaft Stress Ratio				
Thickness (m)	**Head Stress to Tip Stress Ratio**			
	P1	**P2**	**P3**	**P4**
t = 2.5	0.2	0.3	0.25	0.28
t = 5	0.43	0.39	0.3	0.397
t = 8	0.53	0.5	0.37	0.48
Effect of State of Compaction				
N Value	**Head Stress to Tip Stress Ratio**			
	P1	**P2**	**P3**	**P4**
N = 4	0.48	0.44	0.36	0.44
N = 8	0.47	0.43	0.34	0.43
N = 12	0.46	0.4	0.32	0.415

Hence, in designing the piled raft with the pile group passing through an intermediate compressible layer there will be an increase in the stress at the section passing through the compressible layer. This has to be accounted for in the pile design.

9. CONCLUSIONS

1. The observational study conducted by monitoring the piled raft supporting a 12 storied residential apartment has established that the combined piled raft foundation system can prove to be an economical foundation system to support even a moderate to lightly loaded structure when settlement governs the design of the foundation under favorable ground conditions. It can be seen that the results of the present study are in line with results of similar studies, and hence piled raft foundation system can be considered as a viable alternative to deep piles to support any type of structure, so long as there is no imminent possibility of bearing capacity failure.
2. It is seen that most of the settlement occurs during the construction period itself. The rate of mobilization of raft stress is slow in the initial stages of construction, and this may be due to the uplift forces generated by the water table; as the loading increases the rate of raft stress mobilization increases in line with the rate of increase in the loading as the construction progresses.
3. The results of 1g model tests presented show that an optimum performance of piled raft foundation system can be achieved with a pile-raft area ratio of maximum around 5%. Higher percentages may lead the system to behave as fully piled as the load shared by the raft may become very small.
4. The 1g model test conducted on the square piled raft with a pile-raft area ratio of around 5% showed the raft sharing 63% of the applied load, whereas in the case of the Palace Regency the raft shared 43% of the applied load. The difference may be due to the monitoring methods, the real ground conditions, and the pile installation process.
5. In general, most of the piled raft foundations designed and constructed in recent times appear to have the raft sharing nearly 45 to 55% of the applied load, and the balance by the pile group.
6. The presence of an intermediate compressible layer affects the shaft stress distribution in the piles and the overall settlement and can cause some differential settlement also. In the section of the pile passing through the compressible layer, there is an increase in the stress caused possibly by the drag force or perhaps an increase in the stress at the particular section. The ratio of head stress to tip stress is more than that observed under normal conditions, and so the pile length may have to be increased more than that which would have been otherwise required.

10. ACKNOWLEDGEMENTS

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Many thanks for Prof. Yamashita for his permission to use Figures 22 to 25 and Mrs. Abhirami. B. (former graduate student and presently research scholar at Anna University, Chennai, India) for all the support given in preparing this paper.

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12. APPENDIX

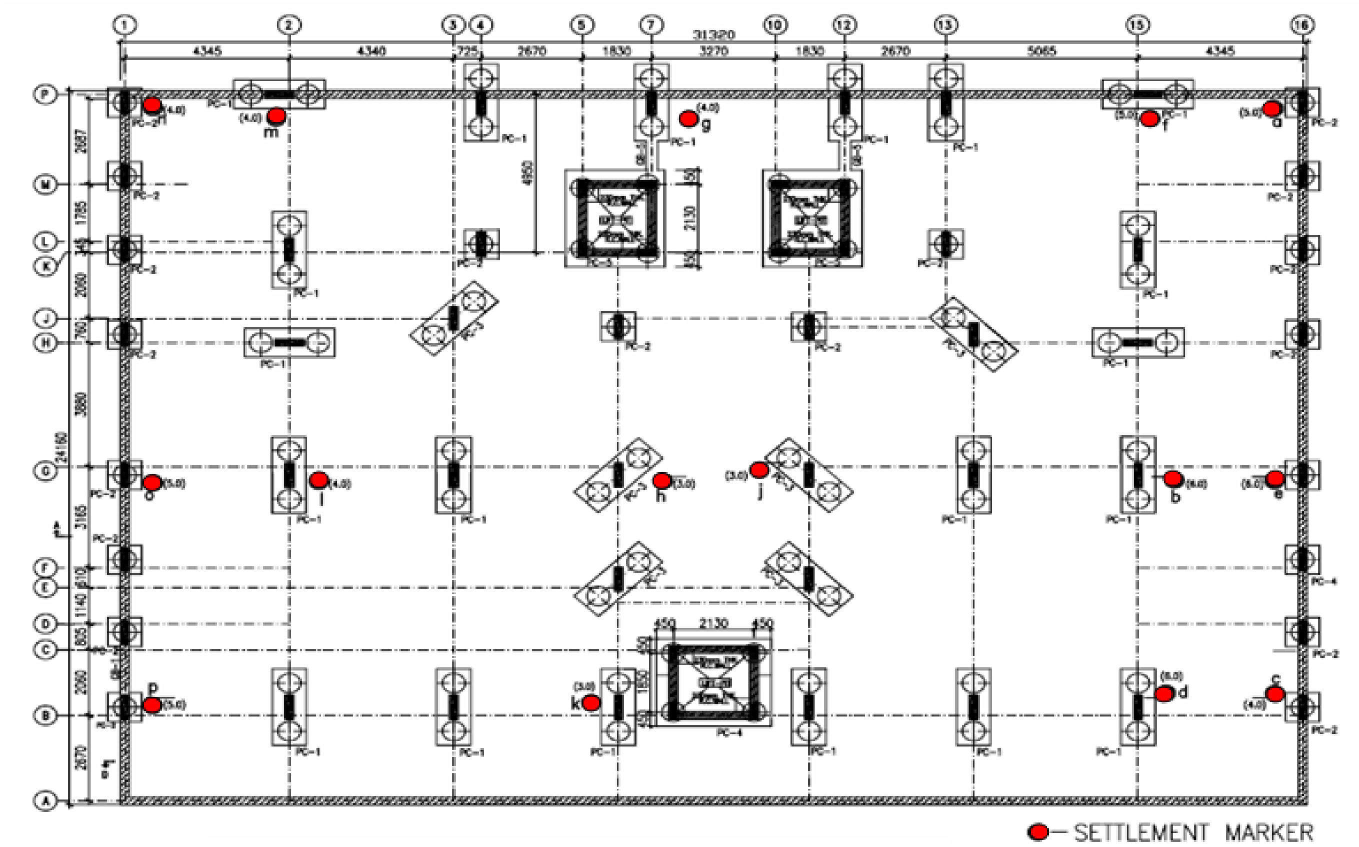

Figure A.1 Enlarged view of Figure 11

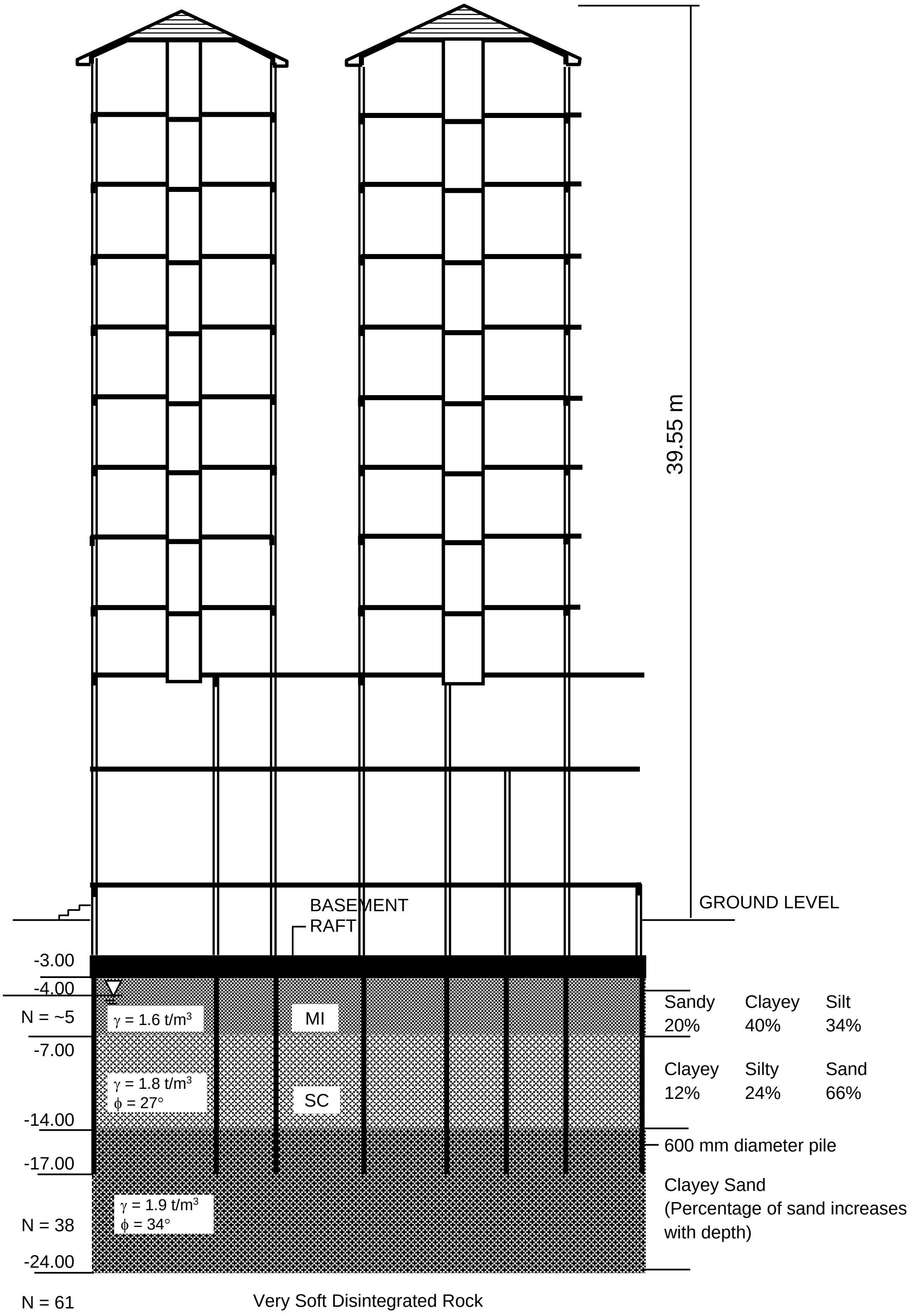

Figure A.2 Enlarged view of Figure 12