Indian Geotechnical Journal, 37(2), 2007, 94-115

Performance Monitoring and Numerical Simulation of Piled Raft Foundation of a Twelve Storeyed Building

V. Balakumar* and K. Ilamparuthi**

Introduction

Piled raft foundation is a geo-technical compound construction, which comprises of three load bearing elements namely the raft, piles and the supporting soil. The aim of this system is to reduce the differential and overall settlement of the raft and enhance its load carrying capacity. The introduction of pile elements enhances the load bearing capacity of the raft for the given settlement of plain raft. By this, we look at the piles only as a reinforcing member in the soil to reduce the raft settlement. The strategic location of the piles are planned to reduce the bending moment in the raft and minimize the contact pressure. Contrary to the widely used traditional approach to the design of foundation system, wherein the structural loads are totally transferred by either raft alone or piles alone, piled raft is a fairly a recent approach in which the applied load is shared by the raft and pile through the interaction between them. The design of piled raft is based on complicated soil-structure interaction between the constituting elements as shown in Fig.1 and this is achieved through different methods (Reul 2000; Katzenbach et al. 2000, Polous and Davis 1980, Fleming et al. 1992; Randolph 1994; Franke 1991). In spite of the fact that this system of foundation has been in use, a commonly acceptable and standardized design method is yet to be formulated. For a successful design of a piled raft system, the knowledge on the interaction among the bearing elements is essential. This can be achieved only if such an understanding is available either in the form of published literature or design standards.

Recent developments in the laboratory testing and analytical modelling along with the field data available have enhanced the level of confidence in the use of piled raft, and quite a number of heavily loaded structures built in Germany have been supported on this foundation system. Their performances have been well documented. In spite of the documented information, the German code advocates the monitoring of the load settlement behaviour of piled raft as a mandatory requirement. This requirement gains more importance considering the following main advantages of this foundation system:

* Research Scholar, Division of Sol Mechanics and Foundation Engineering, Anna University, Chennai - 600 025, INDIA. Email: vb_kumar2002@yahoo.com

** Professor and Head, Division of Sol Mechanics and Foundation Engineering, Anna University, Chennai - 600 025, INDIA. Email: kanniilam@hotmail.com

1. Improvement in the serviceability of the foundation by the reduction in the settlement.
2. Improvement on the bearing capacity by the load sharing between the raft and the pile.
3. Reduction in internal stress level and bending moment of the raft by an optimal design of pile layout below the raft.

However this is yet to become a choice by default in the minds of designers for following reasons: (i) this involves complicated soil structure interaction studies which requires finite element analysis, (ii) evaluation of in situ soil properties like elastic modulus with a reasonable level of accuracy has always remained to be the difficult part of geotechnical investigation and (iii) lack of straight forward analytical methods for assuring the behaviour of this system even under elastic soil condition. Since this system is economical when the raft and piles are involved, such a data bank is essential for different soil conditions, so that this system of foundation can be adopted in any soil. This paper makes such an attempt, based on the observations made for a period of 790 days including a post construction period of 430 days on a piled raft supporting a twelve storeyed structure. The performance of piled raft was also studied through a numerically simulated model using FEM package ANSYS and compared with the observed results.

Earlier Works on Piled Raft

Review of the works reported in the literature reveals that these can be grouped under three heads, namely analytical modelling, experimental investigations on small scale laboratory models and performance study on instrumented prototype piled rafts. These are discussed in brief to explain the level of understanding at the moment in the subject and the necessity of the present study.

Analytical Modeling

Analytical model of piled raft foundation was initiated by Butterfield and Banerjee in the year 1971. Since then the attention of researchers working in the field of foundation engineering was drawn to model the three dimensional nature of piled raft-soil interaction problem. Powerful numerical approaches for understanding the complex behaviour of piled raft have been developed, for example, mixed technique wherein finite element and boundary element method are combined. Various analytical models reported in the literature can be grouped as detailed below:

(a) Methods employing strip on springs in which a series of strip footings represent the raft and springs of appropriate stiffness to represent the piles (Poulos 1991)

(b) Plate on spring approach in which the raft is represented by a plate and the piles by springs (Clancy and Randolph 1993; Poulos 1994; Yamashita et al. 1994)

(c) Boundary element method (Butterfield and Banerjee 1971; Kuwabara 1989; Sinha 1997)

(d) Methods combining boundary element for the piles and finite element for the raft (Hain and Lee 1978; Franke et al. 1994; Ta and Small 1996)

(e) Simplified finite element analysis involving a plane strain problem or axisymmetric problem (Hooper 1974; Prokoso and Kulhawy 2001)

(f) 3D finite element analysis. (Zhang et al. 1991; Lee 1993; Katzenbach et al. 1998; Reul, 2000).

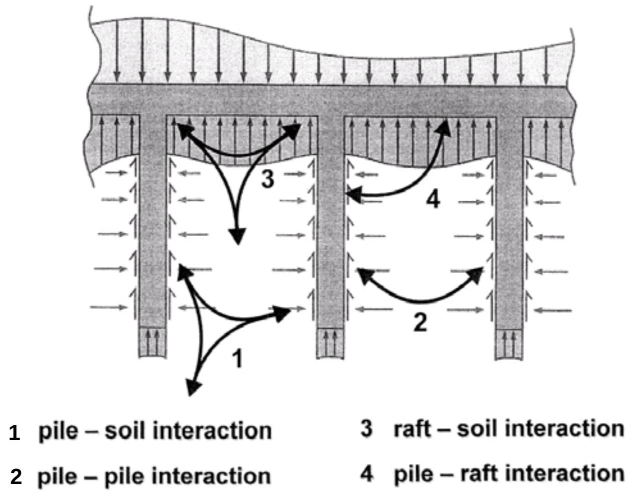

Fig. 1 General Principles of Piled Raft (Katzenbach 2001)

All the above models have been concentrating on specific aspects such as control of differential settlement, raft bending moment and effect of various parameters relating to the piles on them. Poulos (2001) has analysed some of the above methods critically. and has established that most of the methods tend to over predict the settlement even though the magnitude may be acceptable from design point of view. In the case of load shared by the piles, there is considerable variation among the different methods. The extent of scatter in the results of various analytical models indicates that the understanding of the behaviour of piled raft pertaining to settlement behaviour and load sharing have to be more clearly established. Also the models have not brought out so far to the best of our knowledge any specific design philosophy, perhaps due to the fact that the study has not been more comprehensive with adequate validation with the field data or small scale model studies. Some of the numerical models like plate on spring do not adequately represent the soil continuum. The three dimensional analysis requires considerable judgment in selecting the elements and boundary conditions particularly in handling large size problems. Also the computing capacity of the model chosen largely depends upon the mesh refinement even though coarser mesh provides fairly good results (Reul and Randolph 2002). Selection of the mesh type and the element need a lot of experience and judgment. Further modeling the interface behavior and non-linear pile response are not easy.

Experimental Studies on Model Piled Rafts

In spite of the fact that the use of pile foundations has been there in practice, the experimental work on piled raft behavior is not extensive. However experimental work on model piled raft with a rigid cap was reported as early as 1960 (Whitaker 1961). In the recent past centrifuge model tests were conducted to understand the behavior. The papers reported in the literature are put in two groups as indicated below:

1. 1g model studies on clay bed (Weisner and Brown 1978; Cooke 1986) and sand bed (Kim et al. 2001; Turek and Katzenbach 2003; Balakumar and Ilamparuthi 2004; Balakumar et al. 2005), and
2. Small scale model studies adopting centrifuge model on clay bed (Thaher and Jessberger 1991; Horikoshi and Randolph 1996).

These small scale model studies have brought out certain important conclusions like adopting linear elastic theory produce satisfactory results; also when piles are added as settlement reducer, increasing the number of piles do not produce any additional advantage (Cooke 1986). Horikoshi and Randolph (1998) showed that the addition of small group of piles in the center can reduce the differential settlement considerably. Thaher and Jessberger (1991) conducted centrifuge model tests on piled raft model in overconsolidated clay bed and established the effect of various piled raft parameters such as number of piles, pile length and pile diameter on the settlement. Balakumar and Ilamparuthi (2004) and Balakumar et al. (2005) conducted tests on piled raft models embedded in sand bed and examined the applicability of equivalent pier theory (Poulos 1980) and established the influence of various parameters on the load sharing and settlement reduction behavior of the piled raft. The work done on sand bed has proved that the load sharing between the raft and piles depends upon the settlement. However the 1g model studies have not been validated or compared with any behavioral trend of prototype piled raft. In most of the above studies the magnitude of settlement level for the study is very small and within the linear range.

Study on Prototype Piled Raft

As the analytical modeling and small scale model studies exhibit their own limitations, Eurocode has strongly recommended observational methods. The data collected by monitoring the instrumented piled raft over a period have to be used for back analysis in arriving at the initial assumption relating to the load sharing between the pile and the raft. It also warrants that the piled raft completed must be monitored during construction and as long as possible after construction. Katzenbazch et al. (2000) and Reul (2000) have reported the outcome of most of the works carried out on real size piled rafts supporting heavy structures on Frankfurt clay and some of the important data are given in Table 1. Monitoring of instrumented prototype piled raft have been performed right from 1973 wherein Hooper (1974) presented the load settlement behavior of a prototype piled raft supporting a tall structure namely Cavalry Barracks in London. The monitoring has been done according to the report for a period of six years and maximum settlement observed was 21.3 mm and also shown that most of the settlement took place during construction. It has also been presented that the load sharing has been of the order of 60% and 40% between the piles and raft respectively. Padfield and Sharrock (1983) suggested that the shaft resistance of the piles should nearly be fully mobilized to facilitate the role of settlement reducing pile. and suggested, stiff response in the central area of the raft and much softer response in the periphery. Franke (1991) from the review of the published results of three major buildings has concluded that the raft contact pressure would increase only when the base resistance of the piles is relatively smaller when compared to the shaft friction and suggested that a skillful layout of piles would reduce the raft bending moment and the internal stresses in the raft. Franke (1991) concluded that a balancing of load share must be done in such away that the raft shares a considerable quantum of load for a given settlement. This would warrant a trial and error analysis to fix the length of the pile after selecting the diameter. Frank further gave more importance for the load shared by the raft and indicated that finite element and boundary element methods must take into account the bilinear elastic / plastic shaft resistance behaviour, and simple design calculation must be developed for the design office. Schwab et al. (1991) used electronic devices for monitoring and measured raft contact pressure, settlement, pile head and tip loads. According to them the measurement of deformation below the raft has to be done for the assurance of structural safety and to serve as the basis of design for future projects. Yamashita et al. (1994) monitored a piled raft supporting a five storied structure and observed a load sharing ratio of 49% for piles and 51% for raft. Here the piles were steel piles inside the pre bored hole and grouted. Reul (2000) has conducted observational study on three different buildings and has analytically validated the behavior. His main observation includes the effect of mesh refinement on the results of analysis.

The overview of the work done as presented above indicate that invariably all the structures supported on piled raft studied so far are very tall and founded mostly on over consolidated clay. The piles are large diameter bored piles with raft thickness ranging from 1.5 to 3 m. Essentially, the concentration has been on the load sharing mechanism, in particular load taken by the piles. The overall settlement reduction aspect and the design methodology have not been discussed adequately. Also the contact stress distribution below the raft has not been discussed even though the main aim of providing piles with the raft is to change the contact pressure distribution and reduce the raft settlement. The factor of safety adopted on pile capacity or load for which pile has been designed, is not indicated, as the initial design needs this information. The studies do not discuss the nature of settlement and load settlement pattern. The analytical validation has been limited to the extent of establishing the load taken by the piles. Considering the aim of adding the pile to the raft, it is the change in the contact stress and the extent of settlement reduction that is more important than the load taken by the pile.

If the piled raft has to be used as a foundation system with more freedom and confidence, its suitability has to be established for medium sized structures also with relatively smaller diameter piles, and thinner raft and its effectiveness in overall settlement reduction must be adequately studied and validated. Any settlement oriented design will be more effective if it is based on observational data, duly validated by a suitable analytical test. For example the results of observations made on the piled raft of Eurotheum tower has been used to design the piled raft of the Max tower (Katzenbach et al. 2002). Similarly the data obtained from Max tower may be used as the basis for the design of subsequent project wherever it is applicable. This implies that adequate data based on the observations must be available along with analytical validation so that the results can be used as a base for the design. It is essential that such data bank must be available for every regional deposit. The present study has been done with the above as main objective and the paper presents the outcome of such a study.

Palace Regency Building, Chennai

The building taken for this study is located at Purasawakkam in Chennai, India. The structure is a twelve storeyed reinforced concrete construction with a basement floor. The weight of this concrete building on the raft is 99000 kN. The ground area of the building measures 32 m x 25 m. The height of the building is 36m and its slenderness ratio is 1.5 at the base of the building and in the base of the tower it is 3.0. The basement, ground floor and the first floor are for commercial use and the other upper floors are for residential requirement. The maximum and minimum loads on columns are 2870 kN and 1050 kN respectively. The structural design has been done in accordance with the provisions of the latest Indian Standard code of practice. The minimum grade of concrete is M20 and all the reinforcements were Fe 415 grade bars. The entire building was completed in 460 days and was fully occupied shortly thereafter. The structure was analysed assuming that it is resting on an unyielding support using STADD PRO, a versatile package for structural analysis and design. The support reactions from the analysis have been taken for the design of foundation.

TABLE 1: Some of Existing Structures on Piled Raft

Building data	Messe-Torhaus	Messeturm	DG-Bank (Westendstrasse I)	American Express	Taunustor Japan Centre	Forum (Kastor and Pollux)	Congress Centre Messe Frankfurt	Main Tower	Eurotheum	Frankfurter Welle.
Construction Period	1983-85	1988-91	1990-93	1991-92	1994-96	1994-97	1995-97	1996-99	1997-99	1998-2001
Max. Height above ground surface (m)	130	256.5	208	74.7	115.3	94/130	51.6	198	110	55
Floor above grade	22-30	64	53	16	29	22/32	13-14	57	31	13
Basement Floors	0	2	3	4	4	3	2	5	3	2
Thickness of raft (m)	2.5	3.0-6.0	3.0-4.5	2	1.0-3.5	1.0-3.0	0.8-2.7	3.0-3.8	1.0-2.5	1.0-2.2
Number of piles	2x42	64	40	35	25	26/22	141	112	25	102
Average pile spacing (m)	3.0-3.5 D	3.5-6.0 D	3.8-6.0 D	3.5 D	3.0-6.0 D	4.0-6.0 D	3.0-6.0 D	3.0-6.0 D	1.6-6.0 D	3.5 D
Pile Length l (m)	20	26.9-34.9	30	20	22	20.0 &30.0	12.5-34.5	20.0 & 30.0	25.0-30.0	20.0 & 25.0
Pile diameter D *(m)*	0.9	1.3	1.3	0.9	1.3	1.3	1.3	1.5	1.5	0.9
Observed piled raft coefficient apr	0.8	0.55	0.5	-	0.4	0.35/0.4	0.4	0.85	0.3	under construction
Observed max. settlement w (mm)	150	144	110	55	60	80	40-60	25	32	-

(After Katzenbach et al. 2000)

Soil Profiles of the Building Site

The soil profile at the site comprised of medium stiff sandy clay layer for the top 7m depth. The raft rests on this layer. From 7 m to 14 m the layer is silty sand with sand content more than 65% and the state of compaction is medium dense. Beyond 14 m the percentage of sand content increases with depth and so the state of compaction. This layer extends up to 24 m. The stratum beyond 24 m is disintegrated rock. The bore hole was terminated in this layer, after ascertaining that the rock extends for a larger depth. Figure 2 presents the sectional elevation of the structure with the soil profile and the essential soil parameters.

Selection of Design Parameters and Design of Foundation System

Since the structure has basement it was proposed initially to support it either on raft or on deep piles. Computations showed that the raft will undergo a total settlement of 300 mm including long term settlement which is more than the permissible value as per the code (IS1904-1986). Also the structure has a central courtyard and at this place the column loads are relatively low, which could have resulted in further differential settlement. Hence keeping the variations of column loads and the magnitude of differential settlement in mind it was decided to support the structure on deep piles. Further few structures in the neighboring area within 100 m carrying load lesser than this structure are supported on deep piles. However at this stage the option of piled raft was thought of and the design was made based on the procedure out lined by Poulos (1994). Moreover no standard design procedure or guide lines for load sharing between the piles and raft are available for soil conditions of this site. Hence the existing principle outlined by Burland et al. (1977), Padfield and Sharock (1983), and Franke (1991) were taken as the basic guidelines. According to Burland (1977) the piles have to be ductile. Franke (1991) had indicated that the base resistance of the pile has to be much smaller than the friction and the load sharing by the raft has to be considerable. Padfield and Sharock (1983) suggested that shaft friction has to be fully mobilized for settlement reducing piles. Accordingly the main principles considered in the design are:

i. the raft must have an equal share of the load as piles.
ii. the piles have to be floating and
iii. the settlement level must be such that the pile must mobilize friction entirely.

While the first two aspects could be taken care of, the movement required for the mobilization of the entire friction could not be assumed. Hence it was considered that the piled raft settlement shall be more than 12mm for the complete mobilization of frictional resistance, which is the limiting settlement for individual piles as per IS 2911 (Part IV)-1985.

As large diameter bored piles were becoming uneconomical for the intensities of column load, smaller diameter piles were used. The layout of piles was made in such a way that it follows a known pattern. Among the various patterns, it was decided to locate the piles below the column as adopted by Yamshita et al. (1994). It was also decided to adopt the load sharing data available under identical circumstances. To the best of our knowledge no published data was available to establish the load settlement or load sharing behavior of piled raft in Indian conditions, particularly for relatively medium sized building with flexible raft. Yamashita et al. (1994) have established the load sharing behavior by adopting thinner raft and showed that the load sharing between raft and the pile was in the ratio of 49% and 51% respectively for the raft with piles below the column. Based on this, the load shared by the piles and the raft was assumed as 50% of the total load in the design. The piles were designed to have a factor of safety of 1.75, keeping in mind the likely variations of the loading in the commercial floors. The raft was designed as a flat slab treating the piles as columns; 600mm was the raft thickness required from the bending moment and shear considerations. The layout of piles is given in the Figure 3.

The most important parameter in the design of piled raft is the E_s value of the supporting strata. When the stratum becomes cohesionless the most reliable method to assess the soil parameters at its in-situ conditions is the N value. While a lot of empirical expressions are available to relate N and E_s, the charts published by Mori (1965) for clay and Schultz (1966) for sand were used in this study to obtain the E_s values of various layers of the deposits of this area. The other important factor is the load sharing ratio between the piles and the raft which was taken as 50% as stated earlier. In designing the pile group the factor of safety against block failure was computed as given by Poulos (2001)

$$F = \frac{P_w + Np_i\eta}{P} \tag{1}$$

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, and
P =total structural load.

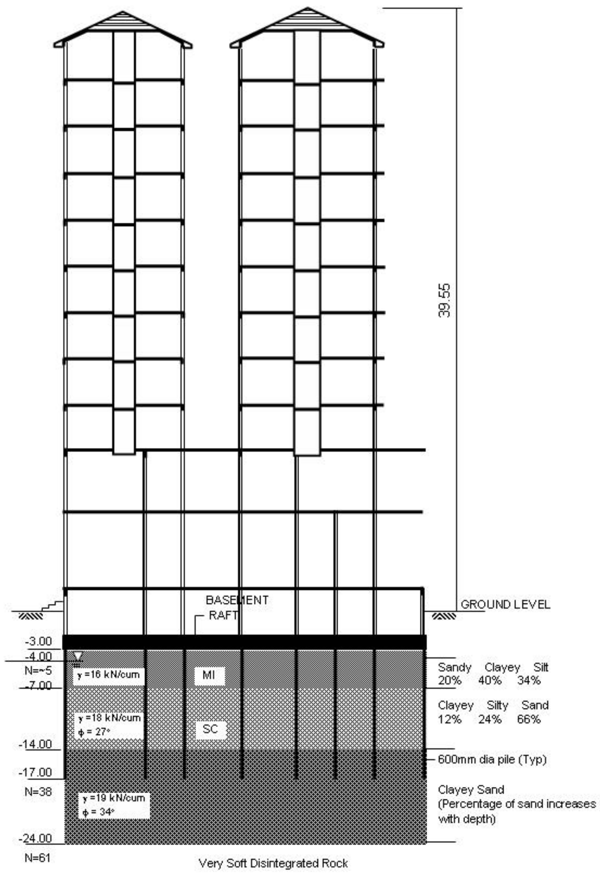

Fig. 2 Sectional Elevation with Geotechnical Data

Accordingly the number of piles required were computed as 86 and from symmetry point of view 93 piles were installed as shown in the layout. The piles provided were of 600 mm diameter under each column. Under many columns two piles were installed. The piles were installed adopting the rotary drilling equipment and were terminated in sand layer at a depth of 17 m below the existing ground level. It was ensured that the bottom of the bore was clean so that the seating of the pile would be done on the natural soil. The piles were terminated in sand layer where the observed N-value was around 40.

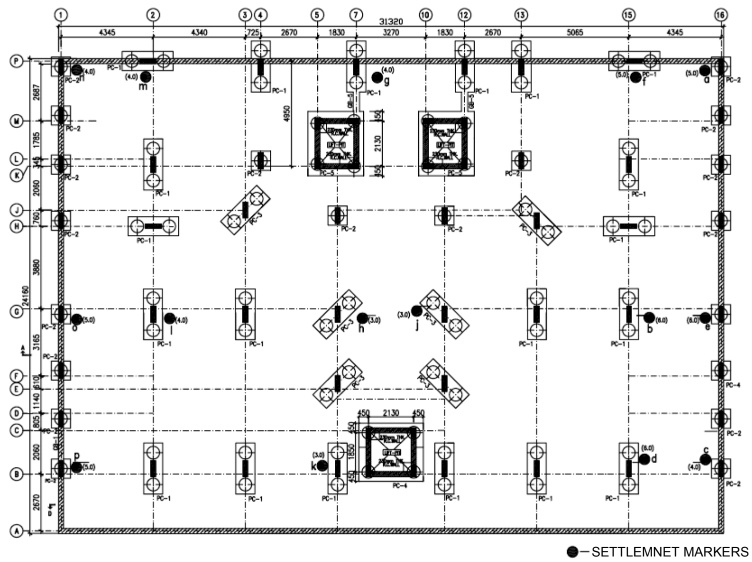

Fig. 3 Layout of Piles and Columns Position

Instrumentation of the Piled Raft and Measurements

Since the primary aim was to study the load settlement characteristics 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 14 points as given in Figure 3. The settlement markers comprised of 75 mm × 75 mm × 6 mm plate two numbers separated by a distance of 600 mm and form an open box by welding the plates with 4 bars of 12 mm diameter. This box was welded to the bottom layer of reinforcement. The verticality of the marker and the level of the top surface were checked using mercury level and plumb bob. The selection of the location for the settlement markers was done in such a way that the settlement profile can be plotted in both the directions at various sections. In order to measure the settlement a standard bench mark was established such that it can be viewed from any point and will not undergo any movement.

The initial reading was taken as soon as the raft was cast. Subsequent readings were taken each time the slab was cast (i.e. immediately after the deshuttering of the slab was done). The settlement of all markers was monitored for the entire construction period of 360 days. The last slab namely the Lift Machine Room was cast after 402 days pointing the completion of the structure, and by the time 50% of the brick work and partition along with the flooring was completed. Subsequently every three months readings were taken for the next one year. During this period the rate of increase of the settlement was very small and gradual. Thereafter the balance work relating to other interior and occupational loadings were completed. The observations were continued and completed on 796th day from the date of commencement of construction. The period from 360th day and 796th day has been termed here as post construction period. The increase in the settlement was recorded at various locations regularly as far as possible, even though the construction procedure and interior work caused a lot of disturbances in the observations of few gauges. The settlement readings were recorded with a high precision leveling instrument. The settlements recorded at various locations during the entire construction and post construction period are presented in Table 2.

TABLE 2: Settlement Observations - at Various Locations

(P. C. = Post construction)

	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	P.C.
796	12	14	9	12	12	10	11	13	13	P. C.

Load-Settlement and Load Sharing Behavior

The readings recorded at the locations of settlement gauges are reduced corresponding to the level of permanent bench mark and the difference in level between the initial and subsequent readings are reported as settlement. Figure 4 indicates the sequence of loading with time and observed settlement pattern in gauges b, e and c representing inner, outer and corner locations respectively of one of the four tower areas which are almost identical.

As stated earlier the construction was completed in 360 days, and whatever settlements recorded within this period was due to self weight of the structure inclusive of construction load. The settlement recorded after this period was post construction settlement which includes the effect of all the loads existed at that point of time.

During the initial sixty days practically there was no settlement or the magnitude was not measurable. This can be due to the fact that the intensity of loading was small to cause any measurable movement. But when the third floor slab was cast and deshuttered the settlement at various gauges varied from 1 mm to 3 mm. Measurable variation in settlement occurred after the completion of the sixth floor. The corresponding load on the foundation system was around 45% of the total load. Thereafter the settlement rate was more with load and at the time of completion of structure the maximum settlement in the tower area was 11 mm. The gauges b, e, c and d representing one of the tower areas showed a settlement of 11 mm, 10 mm, 9 mm and 10 mm respectively, indicating almost uniform settlement. In the central courtyard represented by the gauges the “h, j and g” the recorded settlements were 6 mm, 8 mm, and 8 mm respectively. However a gradual increase in settlement was observed and recorded after the construction period of 360 days at all the locations. The maximum and minimum settlement recorded is 11 mm and 6 mm at the end of construction, which are at locations b and h. The gauge b represents the centre of the tower area whereas the gauge h which is the least loaded, located in the courtyard area of the structure. Moreover piles provided in this area are identical to the piles provided at other areas of the raft, which apparently has reduced the settlement. Study on settlement profile showed that the settlement at center part of the raft in each of the tower area is higher than at the edges. The higher settlement at the middle portion is attributed to heavier column loads and the flexible nature of the raft. Measurement of settlement was continued after the completion of building. The maximum increase in settlement during the post construction period of 436 days was 3 mm. The rate of increase in the settlement during post construction period is very small and gradual.

Figure4 presents the sequence of construction loading and measured settlement with time. It can be seen that the rate of settlement increased during the construction period between 200 to 360 days, where the percentage of loading increased steadily from 45% to 95%. In other words we can infer that only after 50% of the structural load acted on the piled raft, the total friction got mobilized causing a larger movement of the system. This increase in the settlement indicates that the load shed by the piles is taken by the raft. It is at this stage the piles take up the role as settlement reducer.

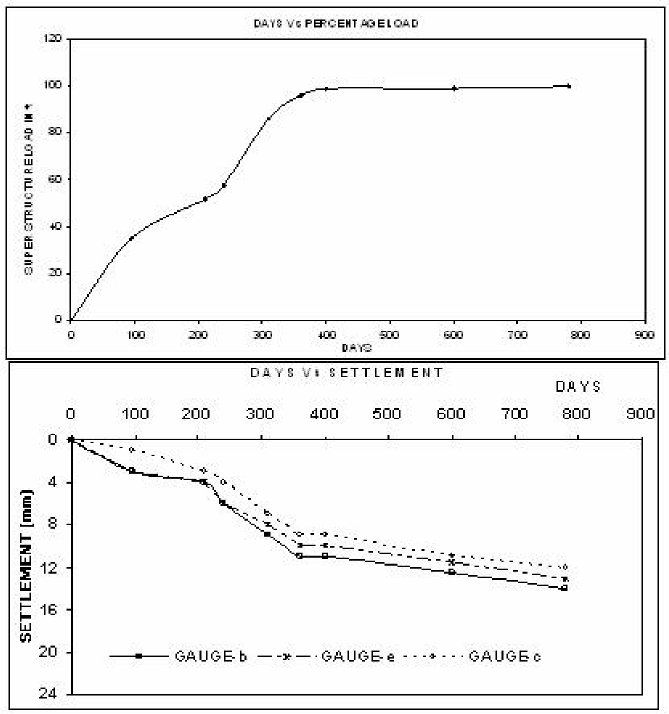

Fig. 4 Loading and Settlement Sequence with Time

Figure 5 presents the load taken by the raft at various stages of construction. Even though no instrumentation could be done for measuring the load, the load taken by the raft could be computed from the settlement observed during various stages of construction. The load shared by the raft was back calculated from the settlements measured using elastic equations (Hemsley 2000). The radius of influence of the load was computed and the stresses were calculated using observed settlement. For an average settlement of 3mm the load taken by the raft is of the order of 7.6%. At 50% and 80% of the total load the raft was found to share 17.5% and 33% of the total load. At the final loading the raft takes 43% of the applied load.

During the initial stages of loading, most part of the load has been taken by the piles, but as loading increased the raft started sharing the load. This is clearly seen from the Figure 5. Load sharing by the raft increases with increase in settlement of the piled raft system. When the load is 80%, the raft shared around 33% of the total load. However at the final load, the load taken by the raft was 43%, which is close to the assumed load share of 50% considered in the design of piled raft. Yamashita et al. (1994) have also reported that the raft carry 49% of the total load which is in close agreement with the observations made in this study.

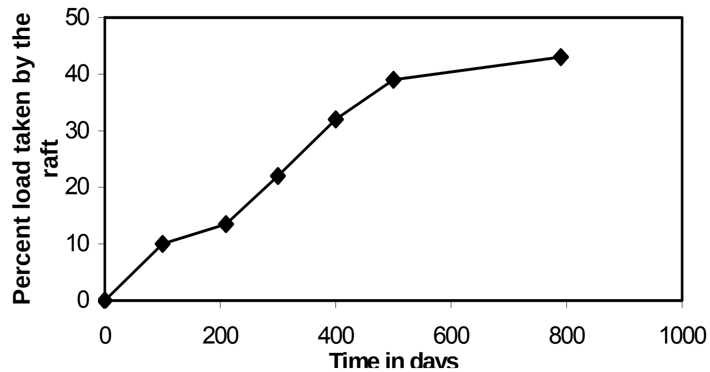

Fig. 5 Percentage Load Taken by the Raft at Various Stages of Construction

Numerical Analysis

The piled raft foundation system adapted for the building was modelled numerically, so that results of numerical analysis can be compared with real time performance. A commonly available finite element code namely ANSYS was chosen for this purpose. In order to generate the model, the principles of solid modelling have been used. The soil has been modelled with eight noded brick elements with each node having three degrees of freedom. The raft and the piles were modelled with Solid45, which is a eight nodded brick element having three degrees of freedom at each node. They are nodal translations in the x, y and z directions. Half model has been taken to reduce the computing time. Certain amount of marginal variation found during the idealization has been ignored while generating the model, as this will not affect the performance of the model during the analysis and accuracy of the results. Appropriate boundary condition has been imposed on the edges of the model. In order to generate the mesh, map meshing technique has been adopted. Reul and Randolph (2002) have studied the effect of mesh refinement on the quality and accuracy of the results and have proved that mesh refinement beyond a certain extent does not enhance the quality of the results. However, in the present analysis the maximum aspect ratio adopted was 5. The extent of soil medium and element sizes were chosen by trial and error to suit the required accuracy and computing time. The model has 93,000 elements and 108761 nodes. The simulated finite element model of piled raft is shown in Figure 6.

Material Property

There are only two materials namely concrete and the soil. The property of the concrete namely the elastic modulus was taken as per the recommendation of IS 456-2000. In the case of soil the elastic modulus of the soil E_s was found from the N values. The properties of materials used in the ANSYS analysis are as presented in Figure 7. The Poisson's ratio of 0.35 was used in the analysis for all the soil layers and for the concrete, the value adopted is 0.20.

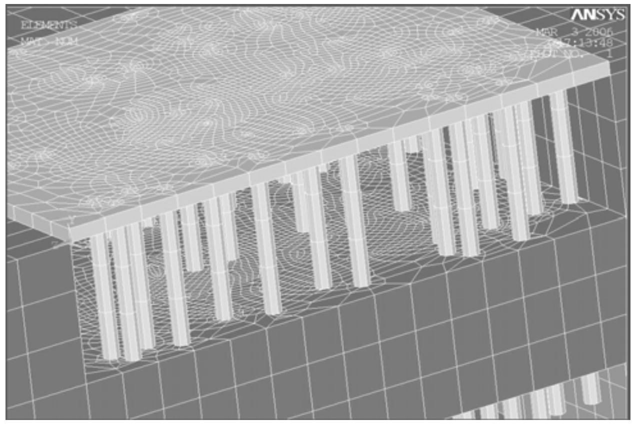

Fig. 6 Finite Element Simulation and Meshing of Piled Raft

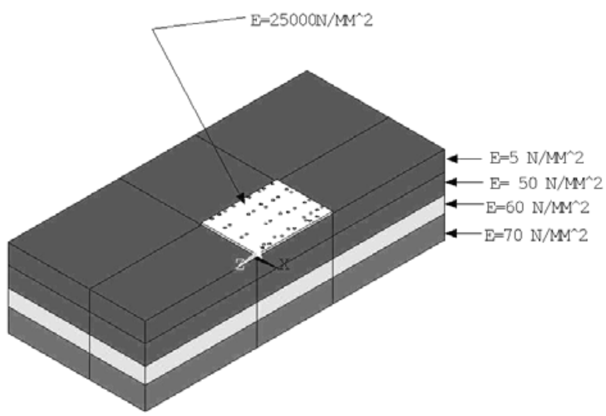

Fig. 7 Elastic Modulus of Various Layers

Application of Loading

Since the structure is a tall frame, a three dimensional frame analysis was performed for various load combinations and support reactions at column points were arrived at. For the foundation design these support reactions were taken. The column forces (axial, lateral and moment) computed from the three dimensional frame analysis in the form of support reactions, were applied at the respective column locations. Since the contribution of transient loading namely wind and earthquake in the form of horizontal loads are beyond the scope of present study, these forces were not accounted for in the analysis. Even though the raft was placed at a depth of 3m below the original ground level, the change in the in situ stresses due to excavation was not simulated in the present study.

Settlement Behavior

The output from the analysis pertaining to the settlement behavior was studied from the settlement contour and the results are shown in Figure 8. The nodes representing each settlement marker was located and the magnitude of settlement was picked up. These values were compared with the final settlement measured along the longitudinal (grids P, B, and G) and transverse sections (B14 - P14). Since the structure has symmetry in transverse direction one section was considered adequate to represent the transverse behavior.
The measured settlement along any section shows that the settlement at edges is more than the centre and the maximum difference is around 4mm. This indicates that the differential settlement is far less than the permissible value. Further the settlement at the edge and center of the piled raft are 6% and 7% respectively of the plain raft elastic settlement (computed). Thus the piled raft reduced the settlement effectively despite adopting a raft of 600 mm thick (flexible raft).

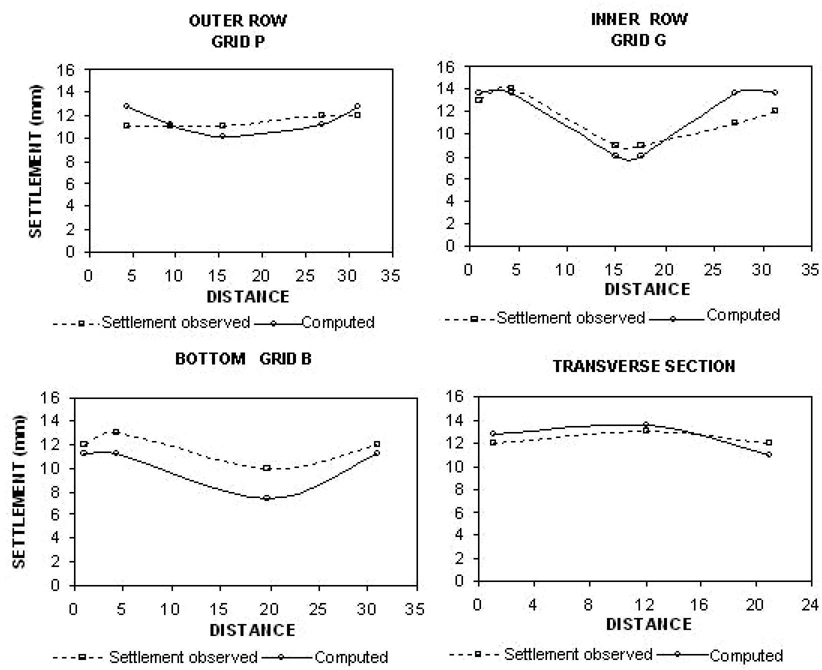

Fig. 8 Observed Settlement Vs. Computed Value at Various Sections

A comparison of the observed and computed settlement profile indicates that the results agree well. However, the computed values are marginally higher in general. The computed settlement is higher by 2.5 mm than the observed values in the edges and the same is lesser by 3.5 mm in the mid portion of the raft. But this difference reduces the central grid B. In grid G the computed values are lower than the observed value. The difference in settlement may be attributed to (i) in the measured settlement, the stiffness of the super structure is included automatically where as in the numerical model the presence of super structure is ignored i.e. interaction between the structure and foundation is ignored and (ii) in elastic analysis irrespective of the relative stiffness of soil-foundation system and types of soil, the contact pressure is always higher at the edges than at central part of the raft.

The results in the central portion where the courtyard has been located agree very closely. Here the loadings are relatively smaller, indicating that at lower level of load the analytical and the observed values agree very well. The computed and the observed results agree to a reasonable extent in the transverse sections also. Looking at the degree of agreement it can be stated that the numerical and prototype results compare closely for linear elastic condition of soil. Since most of the settlement has taken place during the construction and after construction increase in settlement is very less, we can say that under working load the load settlement relation is close to elastic behavior of soil.

Load Sharing Behavior

In Figure 9 the contact stress at selected points are presented. The stress thus obtained along specific sections are presented and discussed below. Figures 10 and 11 present the raft soil contact pressure distribution over the length of the raft. Figure 10 presents the contact pressure along the grids P, G and B. These are typical grids having the piles. The sections represent half raft as the either half is symmetrical to this. The peak values indicate the stress near the piles and the lower values indicate the stress in between the piles. In the case of grid P the raft stress is maximum at the edge; the magnitude being 0.12 N/mm^2. The peak value varies from 0.10 N/mm^2 to 0.12 N/mm^2. In the grid G the edge stress is 0.07 N/mm^2 and the peak values varies from 0.09 N/mm^2 to 0.10 N/mm^2. In grid B the edge and the peak value are more or less uniform with the magnitude being 0.1 N/mm^2. The low values which are in between the pile group indicate an average value of 0.05 N/mm^2 to 0.06 N/mm^2. The grid P as can be seen from the pile lay out has a tributary area of raft much lesser compared to the other two grids. This is the outer most grid having a higher load due to the presence of the wall for the entire height and RCC retaining wall from the ground to the basement level. Hence with a higher loading and lesser raft tributary area, higher percentage of load gets transferred to the piles and the load taken by the raft becomes less. In the case of grid G and grid B, the tributary area of the raft is higher and the raft shares a higher amount of load.

Figure 11 presents the raft – soil contact stress variation in other raft sections, which are between the pile grids. The first section marked, is section between grids P and L taken approximately at a distance of 1.5 m down from the grid P. The raft has an edge stress of 0.06 N/mm^2. The average contact stress on the raft found to be 0.06 N/mm^2, with a variation being from 0.04 N/mm^2 to 0.07 N/mm^2. The second section marked between grid G and H lies exactly in the middle of grid G and H. In this case the edge stress is of the order of 0.055 N/mm^2. The third section is between B and C grids which is located at a distance of around 1.4 m from the grid B appears towards C. Here the edge stress is higher of the order of 0.061N/mm2 and the average stress is 0.055 N/mm^2. The transverse section taken in between the grids 13 and 15 indicates a similar trend with relatively uniform stress of 0.045 N/mm^2, amounting to 31% of the total applied load. As can be seen in all these grids, the raft contact stress is fairly uniform and of the order of 0.055 N/mm^2 which is 38% of the applied load.

Head Load and Tip Load Distribution

The load shared by the pile group has been picked up as shown from the nodal stress value as an average of all the nodes. Very small areas of stress concentrations have been ignored. The average of remaining values of stress multiplied by the area has been taken as head load and tip load. These have been presented in Figure 12. The head load – tip load distribution with the column load has been plotted in the form bar chart as shown in Figure 13. In general the percentage of tip load varies from 20% to 40% but in majority of the cases the variation is 20% to 30%. Further it is noticed that the tip resistance of piles in the central part of tower sections is more. It is because of more confinement to these piles than at the edges. This is also quite evident from the section B, where the tip resistance of the piles are the lowest. The magnitude of the tip load clearly indicates the ductile behavior of the piles as expected. Accordingly, the raft has taken a reasonable share of the load.

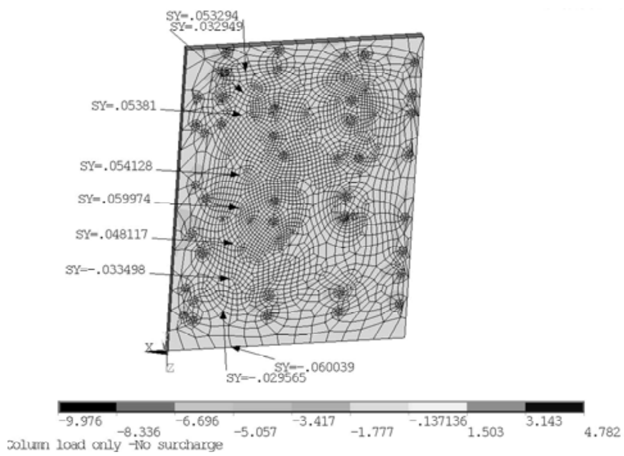

Fig. 9 Contact Stress at Specific Points of the Raft

Hence it can be conclusively said that the behavior of the foundation system has been as expected with the piles behaving as a flexible group and settlement reducer. Even though the piles have been located below the columns, the load sharing of the raft has been 43% from the observed settlement value and 37% as per the numerical modeling with the piles behaving as a settlement reducer sharing 57% to 63% of the total applied load.

Conclusions

Based on the response analysis of piled raft of the 12 storeyed structure on sand, the following conclusions are drawn:

1. The maximum settlements at the end of the post construction period and immediately after construction indicate that the majority of settlement takes place during construction.
2. The total settlement is mostly elastic in nature as the pressure at the base of the raft is close to the pre-consolidation pressure.

3. The settlement predicted by numerical simulation using ANSYS compares well with the observed values indicating that linear modelling is adequate and accurate enough to predict the settlement and load sharing between the piles and raft.

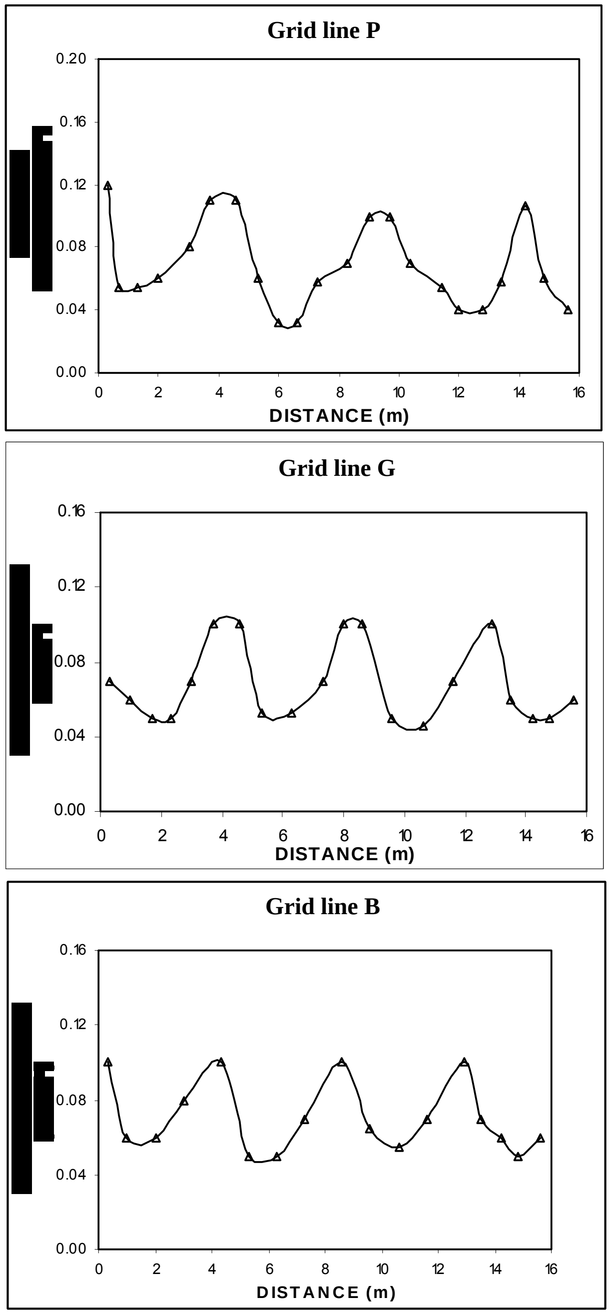

Fig. 10 Raft Stress

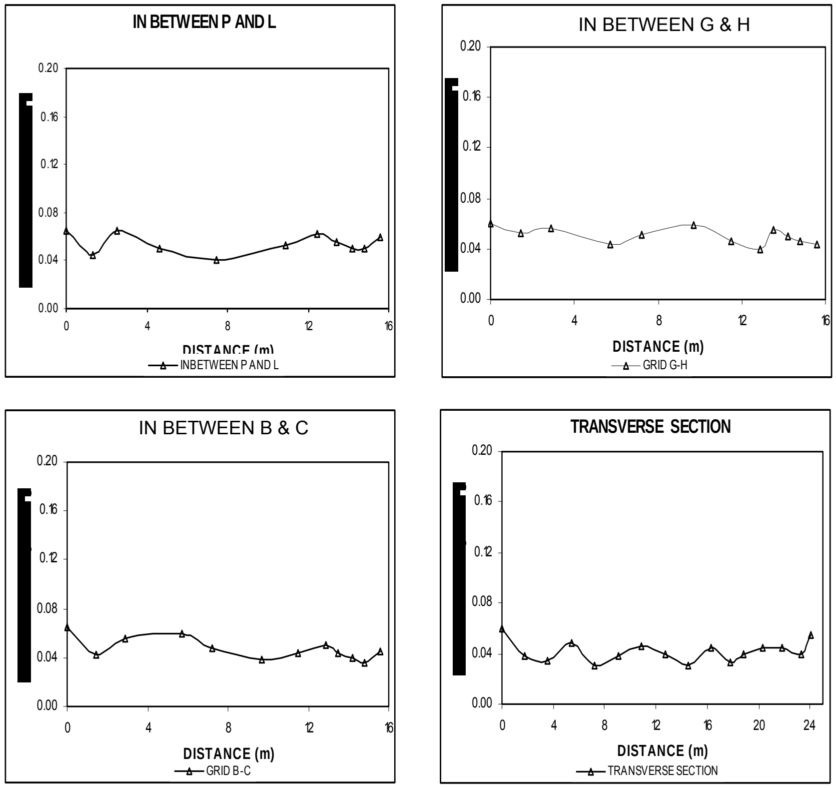

Fig. 11 Raft Stress Profile between Pile rows

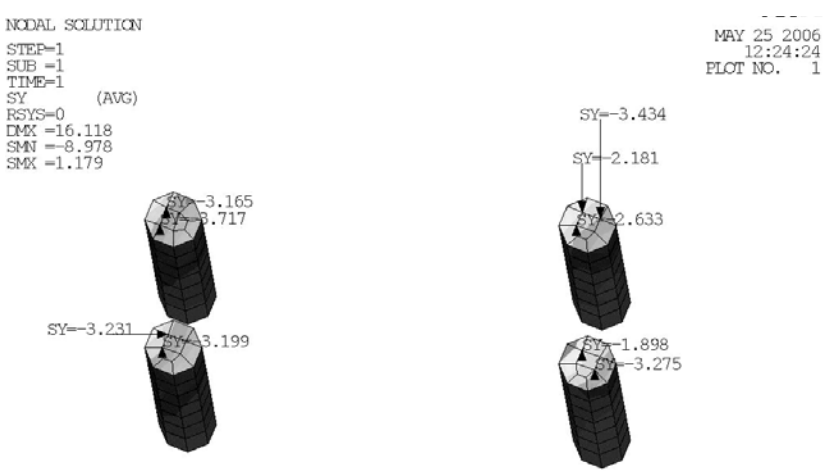

Fig. 12 Typical Nodal Stress on Pile Head

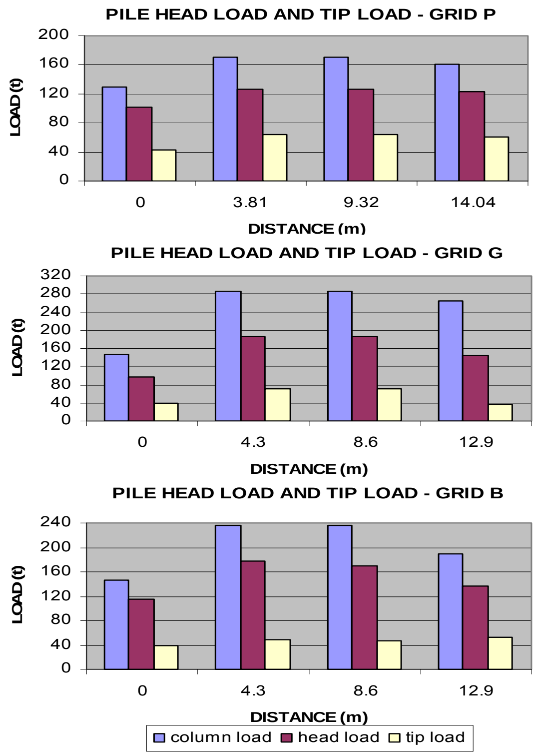

Fig. 13 The Head Load – Tip Load Distribution with the Column Load

4. The load sharing behaviour as predicted by the numerical analysis indicates that the raft stress at the edges is higher than that in the center but the raft settlement is restricted.
5. On an average the load sharing is of the order of 62% and 38% for pile and raft respectively. The actual observation indicates that the raft takes 43% and the pile takes 57%. However in the central portion where the raft area between the piles is larger the raft share increases, which is about 41% of the total load and the piles share 59%. The numerical model predicts a higher load sharing for piles and lower for raft, as compared to what has been based on this tributary area.

References

Balakumar, V. and Ilamparuthi, K. (2004): “Laboratory Study on the Behavior of Piled Raft on Granular Soils”, 15th *South East Asian Geotechnical Society Conf.,* Bangkok, Thailand, pp. 293 – 298.

Balakumar V., Kalaiarasi V. and Ilamparuthi K. (2005): “Experimental and Analytical Study on the Behavior of Circular Piled Raft on Sand”, *Proc. 16th Int. Conf. Soil Mech. Geotech. Engg.,* Osaka, 4, pp. 1943-1947.

Burland, J. B., Broms, B. B. and de Mello, V. F. B. (1977): "Behavior of Foundations and Structures", *Proc. 9th Int. Conf. Soil Mech. Found. Engg.,* Tokyo, 2, pp. 495 – 546.

Butterfield, R. and Banerjee, P. K. (1971): "The Problem of Pile Group – Pile Cap Interaction", *Geotechnique*, 21(2), pp. 135 – 142.

Clancy, P. and Randolph, M. F. (1992): "Analysis and Design of Piled Raft Foundations", *Research Report No. G 1062*, Department of Civil Engineering, The University of Western Australia, Perth, Australia.

Clancy, P. and Randolph, M. F. (1993): "Simple Design Tests for Piled Raft Foundations", *Geotechnique*, 46(2), pp. 313-328.

Cooke, R. W. (1986): "Piled Raft Foundation on Stiff Clays – A Contribution to Design Philosophy", *Geotechnique*, 36(2), pp. 169 -203.

Fleming, W. G. K., Weltman, A .J., Randolph, M. F. and Elson, W. K. (1992): *Piling Engineering,* 2nd Edition, John Wiley and Sons, New York.

Franke, E. (1991): "Measurements Beneath Piled Rafts", Keynote Lecture, *ENPC Conf.,* Paris, pp. 1 -21.

Franke, E., Lutz, B. and El-Mossallamy, Y. (1994): "Measurements and Numerical Modeling of High Rise Building Foundations on Frankfurt Clay", *Geotechnical Special Publication*, ASCE, 40, pp. 1325 – 1336.

Hain, S. J. (1975): "Analysis of Rafts and Raft-Pile Foundations", *Proc. Symp. on Recent Development In Soil Mechanics,* The Univ. New South Wales, Sydney, Australia, pp. 213 – 253.

Hain, S. J. and Lee, I. K. (1978): "The Analysis of Flexible Pile Raft Systems", *Geotechnique*, 28(1), pp. 65-83.

Hemsley, J. A. (2000): *Design Applications of Raft Foundations*, Thomas Telford, London.

Hooper, J. A. (1974): "Observations on the Behavior of a Piled Raft Foundation on London Clay", *Proc. Institution of Civil Engineers,* Part 2, 55, pp. 855-877.

Horikoshi, K. and Randolph, M. F. (1996): "Centrifuge Modeling of Piled Raft Foundations on Clay", *Geotechnique,* 46(4), pp. 741-752.

Horikoshi, K. and Randolph. M. F. (1998): "A Contribution to Optimal Design of Piled Raft", *Geotechnique,* 48(3), pp. 301 – 317.

IS1904-1986 (1986): *Code of Practice for Design and Construction of Foundations in Soils: General Requirements*, Bureau of Indian Standards, New Delhi.

IS 2911-1979 (1979): (Part 1-Section2) *Code of Practice for Design and Construction of Bored Cast in situ Piles*, Bureau of Indian Standards, New Delhi.

IS 2911-1985 (1985): (Part 4) *Code of Practice for Design and Construction of Pile Foundations, Load Test on Piles*, Bureau of Indian Standards, New Delhi.
Katzenbach, R., Arslan, V. and Moorman, Ch. (1998): *Deep Foundations on Bored and Augured piles*, (Eds.) Van Impe and Haegman, Balkema pp. 439 – 448.

Katzenbach R., Arslan V. and Moorman, Ch. (2000): "Piled Raft Foundation Projects in Germany", *Design Application of Raft Foundations,* (Ed.) J. A. Hemsley, Thomas Telford, London, pp. 323 – 391.

Katzenbach, R., Schmitt, A. and Turek, J. (2002): "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*, Zurich, 1, pp. 02 – 07.

Kim, H.T., Yoo, H. K. and Kang, I. K. (2002): "Genetic Algorithm Optimum Design of Piled Raft Foundations with Model Tests", *Journal of South East Asian Geotechnical Society,* 33, pp. 1 - 9.

Kim, K. N., Lee, S. K., Chung, C. K., Kim, M. N. and Lee, H. (2001): "Optimal Pile Arrangement for Minimizing Differential Settlements in Piled Raft Foundations", *Computers and Geotechnics*, 28, pp. 235–253.

Kuwabara, F. (1989): "An Elastic Analysis for a Piled Raft Foundation in a Homogeneous Soil", *Soils and Foundations*, 28(1), pp. 82-92.

Lee, I. K. (1993): "Analysis and Performance of Raft and Raft – Pile Systems", Keynote Lecture, *3rd Int. Conf. on Case Histories in Geotech. Engg.,* St Louis ADFA, The Univ. New South Wales, Sydney, Australia.

Mori, (1965): "Discussion", *Proc. 6th Int. Conf. Soil Mech. Found. Engg.*, Montreal, 3, pp. 501-504.

Padfield, C. J. and Sharrock, M. J. (1983): "Settlement of Structures on Clay Soils", *Construction Industry Research and Information Institute, Special Publication*, 27.

Poulos, H. G. (1991): "Analysis of Piled Strip Foundations", *Computer Methods and Advances in Geomechanics,* (Eds.) Beer, G., Booker, J. R. and Carter, J. P., Balkema, Rotterdam, pp. 153–191.

Poulos, H. G. (1994): "An Approximate Numerical Analysis Pile Raft Interaction", *International Journal for Numerical and Analytical Methods in Geomechanics,* 18, pp. 73-92.

Poulos, H. G. (2001): "Piled Raft Foundation: Design and Application", *Geotechnique*, 51(2), pp. 95-113.

Poulos, H. G. and Davis, E. H. (1974): *Elastic Solutions for Soil and Rock Mechanics*, John Wiley and Sons, New York.

Poulos, H. G. and Davis, E. H. (1980): *Pile Foundation Analysis and Design*, John Wiley and Sons, New York.

Prokoso, W. A. and Kulhawy, F. H. (2001): “Contribution to Piled Raft Foundation Design”, *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, 127(1), pp. 17-24.

Randolph, M. F. (1994): “Design Methods for Pile Group and Piled Rafts”, *Proc. 13th Int. Conf. on Soil Mech. Found. Engg.,* New Delhi, pp. 61-81.

Reul, O. (2000): “In-Situ Messungen Und Numerische Studien Zum Tragverhalten Der Kombinierten Pfahl-Plattngrundung”, *Mitteillungen Desinstituts Und Der Versuchanstilt Fur Geotechnique Der Technischen Universitadt. Darmstadt. Heft*, 53.

Reul, O. and Randolph. M. F. (2002): “Study on the Influence of Finite Element Mesh Refinement on the Calculated Behavior of Piled Raft”, *Proc. of 8th Int. Symp. Numer. Models* Geomech. Rome, pp. 259 – 264.

Schultz, E. and Muhs, H. (1966): “Bouden under Suchungen Fur Ingenieur Bauten“, Springer, Berlin.

Schwab, H., Gundling, N. and Lutz, B. (1991): *Field Measurements in Geotechnique*, (Ed). Sorum, Balkema, Rotterdam.

Sinha, J. (1997): *Piled Raft Foundations Subjected to Swelling and Shrinking Soils*, Ph. D. Thesis, University of Sydney, Australia.

Ta, L. D. and Small, J. C. (1996): “Analysis of Piled Raft System in Layered Soil”, *International Journal for Numerical and Analytical Methods in Geomechanics*, 20, pp. 57-72.

Thaher, M. and Jessberger, H. L. (1991): “The Behavior of Pile-Raft Foundations, Investigated in Centrifuge Model Tests”, *Proc. Centrifuge 91,* Colorado, Balkema, pp. 225-234.

Turek, J. and Katzenbach, R. (2003): “Small Scale Model Tests with Combined Piled Raft Foundations”, *Proc. of the 4th Int. Seminar on Deep Foundations on Bored and Augured Piles*, Ghent, Belgium, pp. 409 – 413.

Wiesner, J. and Brown, P. T. (1978): “Laboratory Tests on Model Piled Raft Foundations”, *Research Report* 318, University of Sydney, Australia.

Whitaker, V. (1961): “Some Experiments on Model Piled Foundations in Clay”, *Proc. Symp. Pile foundations, 6th Int. Congress of the International Association for Bridge and Structural Engg.*, Stockholm, pp. 124 – 139.

Yamashita, K., Kakurai, M. and Yamada, T. (1994): “Investigation of a Piled Raft Foundation on Stiff Clay”, *Proc. of 13th Int. Conf. on Soil Mech. and Found. Engg.,* New Delhi, pp. 543-546.

Zhang, G. M., Lee, I. K. and Zhao, X. H. (1991): “Interactive Analysis Behavior of Raft- Pile Foundations”, *Proc. of Geo coast, 91*, Yokahama, pp 719–764.