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Piled Raft on Sandy Soil- An Extensive Study

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ABSTRACT: In recent years, designers have recognized that in addition to bearing capacity, settlement of foundations must be taken into account. To reduce settlement of buildings, piled raft appears to be a solution for structures found on soft ground. To investigate the performance of piled rafts, model tests have been conducted on circular, square and rectangular raft supported on piles with different spacings between piles. Numerical analyses were carried out to verify the results obtained in the model tests. The performance of a 14-story building was analysed to compare with the settlement readings obtained. The results of numerical analyses appear to be very encouraging as the results of the analyses well agree with the results of model tests, as well as the settlement readings collected in 790 days for this 14-story building. The value of numerical analyses in back analyses and in prediction of settlement of buildings has thus been confirmed.

KEYWORDS: Piled raft, ANSYS, Compressible layer

1. INTRODUCTION

The performance of a structure under serviceability conditions will depend upon the effectiveness of the design of the foundation system in controlling the settlement irrespective of the soil strata, be it sand or clay. Practically most of the international codes of practice quantitatively recommend the permissible settlement for all types of structures based on the performance requirement or what is known as serviceability requirements. Furthermore, the construction of the foundation system for any high-rise building takes nearly 30% to 50% of the total construction time, although the cost of the foundation may only be 15% to 20% of the total construction cost of the building. This makes the foundation system the most critical element from the point of view of risk assessment, optimization and assurance of the serviceability requirements.

By convention, for tall and heavily loaded structures resting on soft ground, deep piles are preferred to rafts because:

a) There is likely a risk of bearing capacity failure of the foundation systems without piles to transfer loads to competent soil strata,
b) The settlement under the applied load may be far in excess of the permissible value.

Traditionally, design of pile foundation and pile group focuses on bearing capacity of piles with little emphasis on settlements. This has changed in recent years as designers have recognized the importance of keeping settlement with tolerance and the modern computer technology has enabled settlements to be predicable.

Piled raft, i.e., raft supported on piles, offers the solution for buildings found on soft ground with settlements exceeding limits. It is traditionally assumed that the entire structural load would be taken by the piles. It has been reported that rafts shared 20% or even more of the applied loads. This phenomenon was observed in the case of PETRONAS twin towers. It is evident that ignoring the contribution of raft is inadequate from an engineering point of view. It is thus desirable to study the performance of piles and piled so the foundation design can be optimized.

2. 1-g MODEL TESTS

Tests were conducted on mini-size rafts, with and/or without piles, in a bin of 1000mm x 1000mm x 600mm in size. The typical configurations of the rafts and piles and the types of foundation soils are as follows, refer to Figure 1:

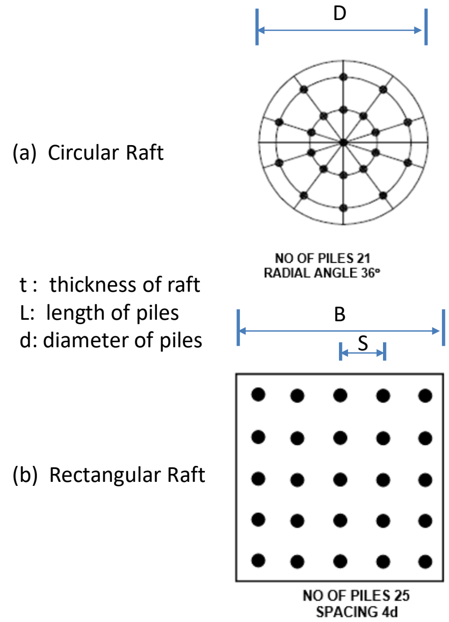


Figure 1 Layout of piles supporting the rafts

1) Piles
   d: diameter of piles = 10mm
   L: Length of piles = 160mm
   S: Center to center spacing of piles = 4d
   (unless specified otherwise)

2) Circular Raft
   D: diameter of the raft = 200mm
   t: Thickness of raft = 8mm

   For typical spacing between piles, S = 4d
   N: Number of piles = 21
   Area ratio (pile/raft) = 5.25%

3) Square Raft
   - B: with of the raft = 200mm
   - t: Thickness of raft = 8mm

   For typical spacing between piles, S = 4d
   N: Number of piles = 25
   Area ratio (pile/raft) = 4.91%

4) Foundation Soil
   - Loose sand, unit weight = 14.8 kN/m^3
   - Medium dense sand, unit weight = 15.5 kN/m^3
   - Dense sand, unit weight = 16.2 kN/m^3

There were 21 piles in two circles underneath the circular raft and 25 in a 5 x 5 grid underneath the square raft. The pile-to-raft area ratio is 5.25% for the former and 4.91% for the latter. Tests were carried out to a maximum settlement of 20mm which equal 10% of the size of the rafts. In all the cases, loads are uniformly distributed on the rafts.

2.1 Settlements of rafts with and without piles

Figure 2 compares the settlements of the circular raft, with and without piles, resting on medium sands. A similar comparison is given in Figure 3 for square raft resting on dense sand. For the same settlement, the rafts supported on piles did take larger loads than those without piles. In other words, for the same load, settlements of the raft with piles were smaller than those without piles. The effectiveness of piles in reducing the settlements of raft can readily be noted. The effects of the densities of foundation soils on the settlements of piles are illustrated in Figure 4. It is not a surprise that increase in soil densities, i.e., increase in strength and stiffness of soil, reduced settlements.

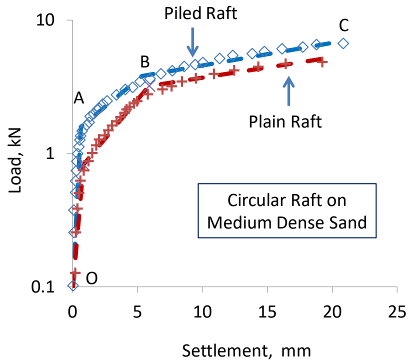


Figure 2 Settlements of circular raft, with and without piles, resting on medium dense sand

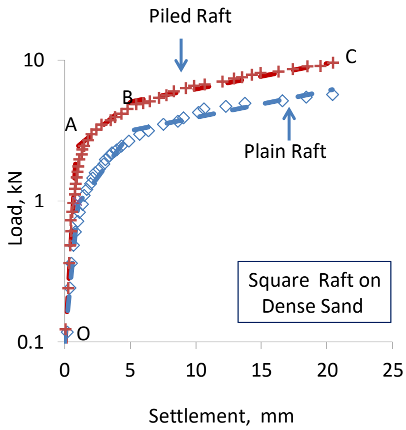


Figure 3 Settlements of square raft, with and without piles, resting on dense sand

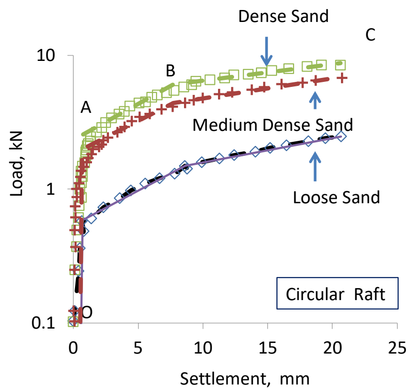


Figure 4 Effects of foundation soils on the settlements of piled rafts

As can be noted from these figures, the settlement curves can be divided into three segments, representing the settlements in three phases. The influence of raft and soil density on pile settlement can be quantified by using the indices of stiffness of the pile-raft setup, β, defined as follows:

$$\beta = \frac{\Delta P}{\Delta \delta} = \frac{P2-P1}{\delta 2-\delta 1} \tag{1}$$

where

- P1 = Load at the beginning of the phase
- P2 = Load at the end of the phase
- δ1 = settlement at the beginning of the phase
- δ2 = settlement at the end of phase

The indices of stiffness of the pile-raft setups for different cases are given in Table 1. It is readily apparent that the rafts increased the stiffness of the pile-raft systems. This is obviously due to the fact that the pressures acting on the bottom of rafts reduce the loads on piles. It is also apparent that as the stiffness of the foundation soil increased, the stiffness of the system increased, reducing settlements of the entire system.

Table 1 Indices of stiffness of circular raft, with or without piles, on soil with different densities

Soil Density	Indices of Stiffness of Pile, β, N/mm					
	Phase OA		Phase AB		Phase BC	
	Plain	Piled	Plain	Piled	Plain	Piled
Loose	195	380	137	197	98	130
Medium Dense	600	1100	467	633	255	345
Dense	800	1700	617	800	314	410

2.2 Settlements of piles with and without raft

Figure 5 presents the comparisons the settlements of pile groups with or without raft (i.e. the raft was not in contact with foundation soil) for the case of circular raft and the square raft. In the latter, the spacing of piles was increased to S = 6d, instead of the typical spacing of S = 4d. The effects of raft-soil interaction on the settlements of piles are evident.

In the case without raft, it is seen that once the friction is overcome, the pile group settles instantaneously; whereas in the case with raft, the pile group continues to take further load even after the friction is overcome. The settlement level at which the friction is overcome is termed as critical settlement and the critical settlements are far higher for piles with raft than piles without raft.

Figure 6 shows the settlements of the square raft on piles with different spacings. Both settlements and loads were normalized to their values at the end of the test.

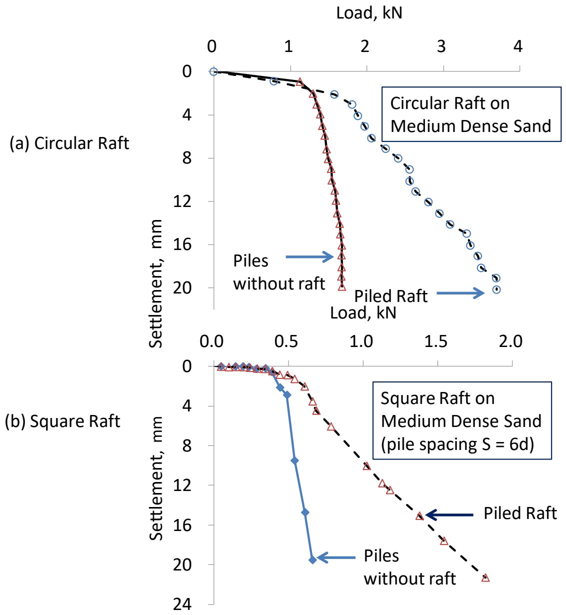


Figure 5 Settlements of piles with and without raft

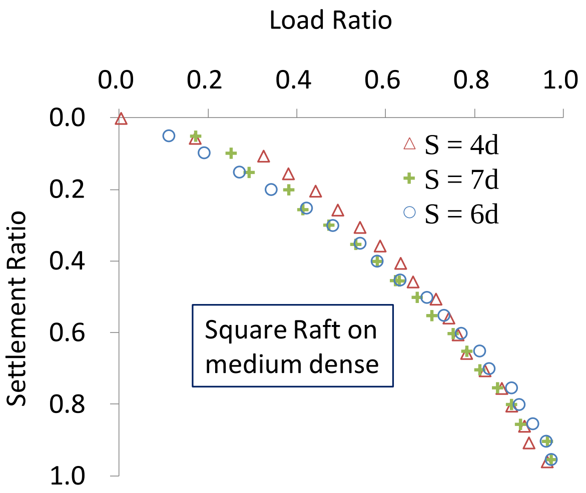


Figure 6 Settlements of square piled raft with different pile spacings

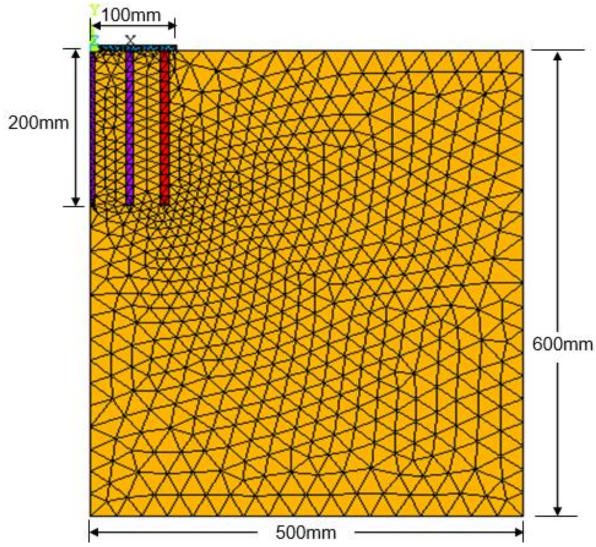


Figure 7 Axisymmetric model and mesh used in

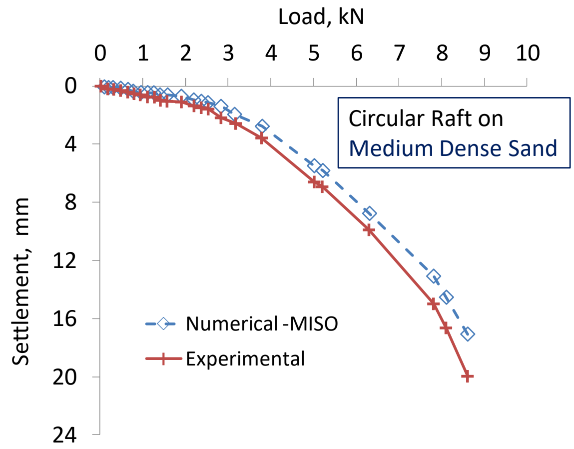


Figure 8 Comparison of load-settlement behaviour in numerical analyses and in model test

3. NUMERICAL ANALYSES ON MODEL TESTS

Analyses have been performed by using the software package ANSYS-3D on rafts of various shapes for obtaining the contact pressures acting on the base of the rafts and the loads taken by the piles. Multi-linear isotropic hardening model was adopted to simulate the no-linearity of soils. The results are compared with the results obtained in the model tests. In all the cases analyzed, the loading was applied in the form of uniformly distributed load as done in the case of model tests.

3.1 Axisymmetric analyses on the circular raft

Axisymmetric analyses practically retain the essential features of the three dimensional analyses. Analyses were carried out on the circular raft, refer to Figure 1. Figure 7 presents the finite element model adopted in the analyses. The soil was idealized by adopting the Multiple-input-single-output (MISO) model. The analyses were carried out with the pressure load applied in steps of small increments. Figure 8 presents the comparison of the load settlement response obtained from the model tests and the axisymmetric analyses. The two sets of readings agree reasonably well.

3.2 Plane Strain Analyses on rectangular raft

Model tests were carried out on a rectangular piled raft resting on medium dense sand. The raft was 70mm x 200mm in size. There were two rows of piles at 4d apart. Figure 9 depicts the finite element model adopted. The settlement contour given in Figure 10 indicates a maximum settlement of 12.5 mm and 11.4mm at its center and the edges of the raft, respectively.

Figure 11 presents the comparison of the load settlement response obtained from the model tests and the numerical analyses.

3.3 Non-Linear 3D Analyses on square raft

Three dimensional analyses were conducted on the square raft mentioned above, refer to Figure 1. Figure 12 shows the finite element mesh adopted in the analysis. Because of symmetry, only a quadrant of the system is model. At the maximum load of 8.7 kN the settlement was found to be 18.9mm as depicted in Figure 13 with an average 15mm for the entire raft. Figure 14 presents the comparison of the load settlement response obtained from the model tests and the nonlinear 3D analyses

Figure 15 presents the stress distribution at the bottom of raft. The load shared by the raft was of the order of 35% of the applied load. Figure 16 and Figure 17 represent the stresses at the top and at tip of piles, respectively. It can be noted that the stresses at the tips are very small. The ratios of the stress at the tip to the stress at the pile head were of the order of 11% for central piles, 9% to 10% for the inner piles and 17% to 19% for the outer piles.

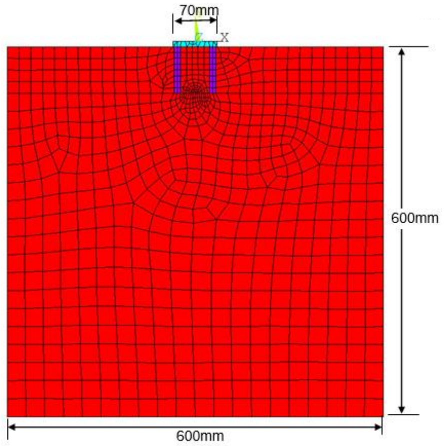


Figure 9 Finite element mesh used for rectangular pile raft in plane strain analysis using ANSYS

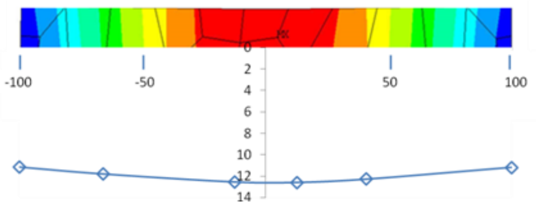
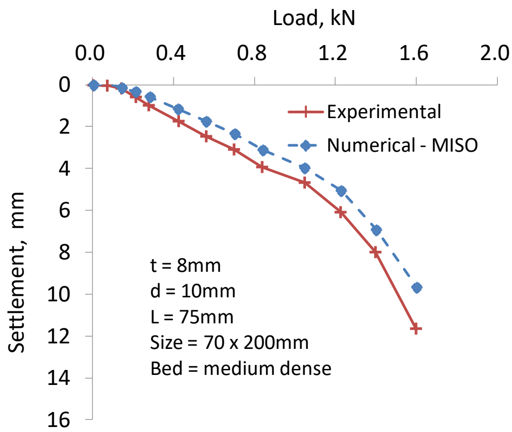


Figure 10 Settlement of piled raft at the load of 1.55 kN



Fgure 11 Comparison of load-settlement response between ANSYS and test data for rectangular piled raft

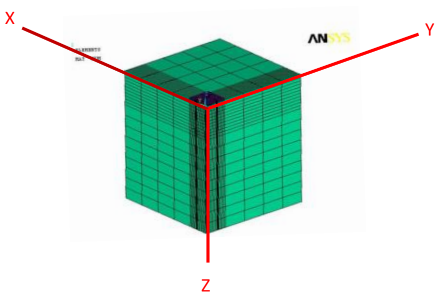


Figure 12 Finite element mesh of a quadrant of the system adopted for square piled raft in ANSYS analysis

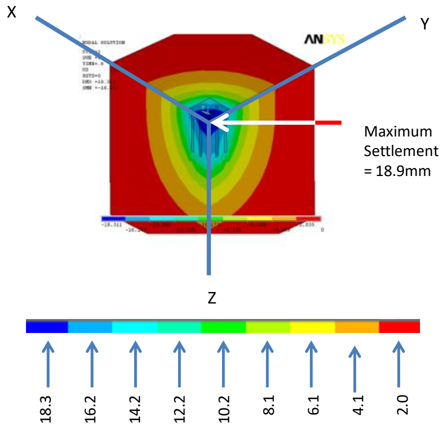


Figure 13 Settlement contour for the load of 8.70kN (settlement 18.90mm)

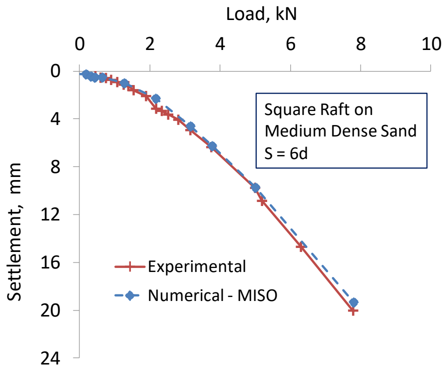


Figure 14 Comparison of load -settlement response between ANSYS and test data for square piled raft with 6d pile spacing

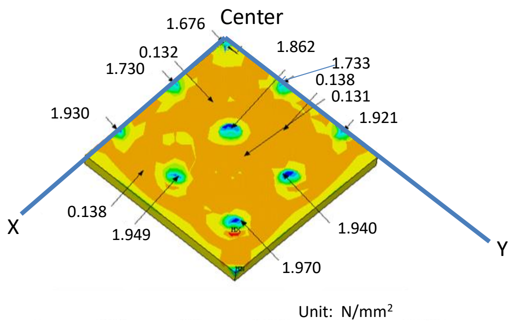


Figure 15 Vertical stress under the square piled raft with piles for the load of 8.7kN

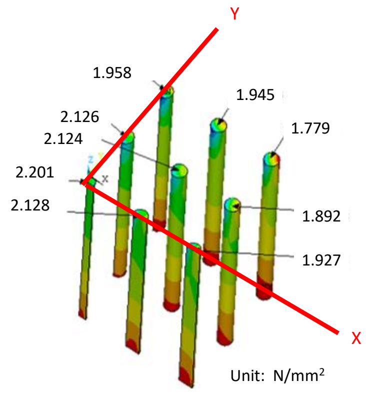


Figure 16 Stresses on pile heads for 8.70kN load

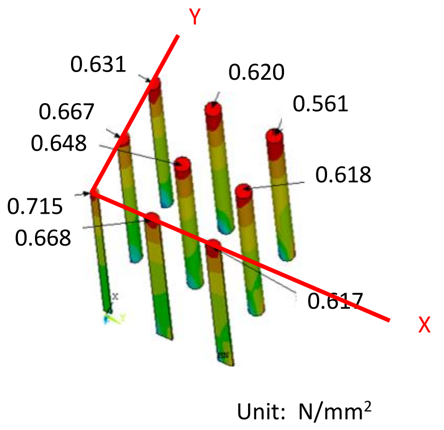


Figure 17 Stresses at tips of piles for 8.7kN load

Figure 18 depicts the variation of axial stresses along the shafts of piles under the circular raft. A similar plot is given in Figure 19 for the square raft.

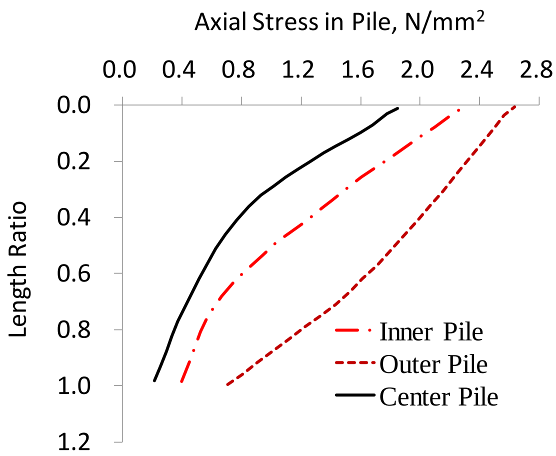


Figure 18 Variation of axial stress along the shaft of typical piles under the circular piled raft for a load of 8.10kN

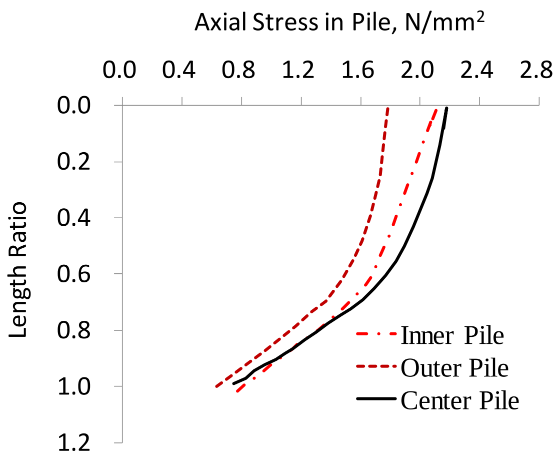


Figure 19 Variation of axial stress along the shaft of typical piles under the square piled raft for a load of 8.10kN

4. CASE STUDY

The structure under study has a plan measurement of 32m x 25m with the height being 36m, refer to Figures 20 and 21. The frame was analysed with STAAD-PRO and the support reactions were taken to design the piled raft foundation system. The piles, a total of 93 in number, are 14 m deep from the raft bottom and the tips of piles were embedded in medium dense to dense sand with the N value of the order of 45. The maximum column load was 2,700kN and the minimum load was 1,100kN. The column loads were applied as point loads at the column locations.

The raft is 600mm in thickness and is found at GL-3m. The performance of the piled raft was monitored for a period of 790 days including the post construction period. The maximum settlement was 14mm. The loading was within the elastic limits and hence linear analyses were fully justified. The analyses were conducted by using ANSYS.

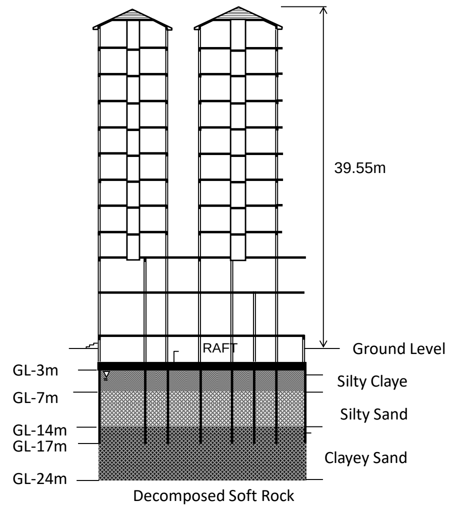


Figure 20 Elevation of the case analyzed

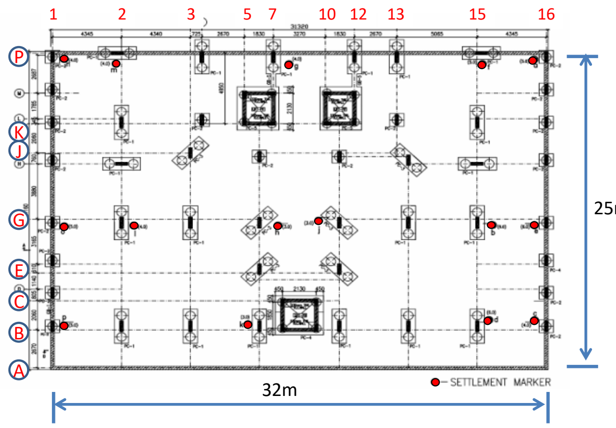


Figure 21 Plan and layout of piles

Figure 22 presents the finite element model adopted. The column loads were applied in the respective column locations. Figure 23 presents a comparison of the observed settlements and computed settlements. It is noted that the two sets of readings agree very well. More details of this work is available in Balakumar and Ilamparuthy, (2007). The distribution of stresses on the raft is given in Figure 24. Stress concentration at the locations of piles is evident.

Figures 25 depicts the stresses at the heads of piles.

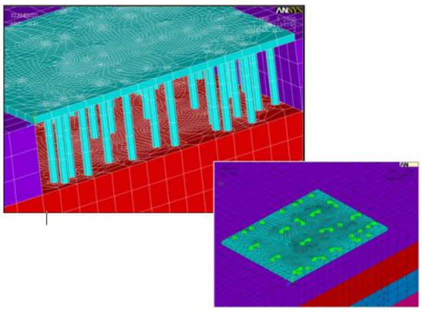
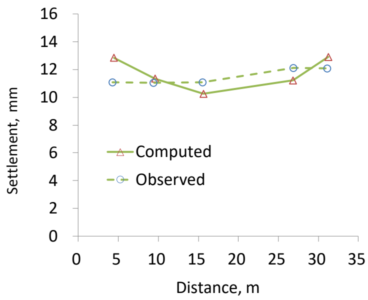
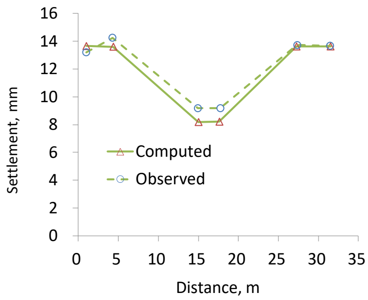


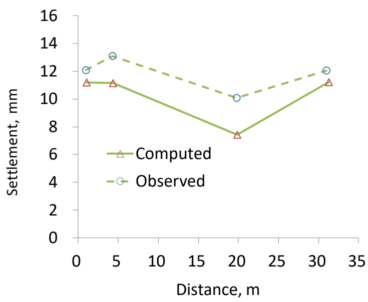
Figure 22 Finite Element Simulation and Meshing of Piled Raft



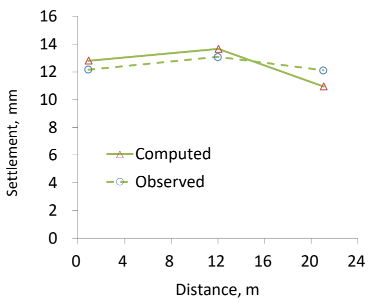
(a) Outer Row: Grid P



(b) Inner Row: Grid G



(c) Bottom Grid B



(d) Transverse

Figure 23 Observed Settlement Vs Computed Value at Various Sections

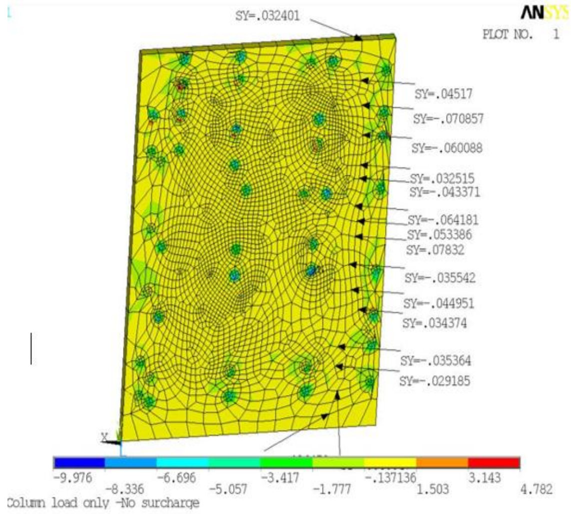


Figure 24 Distribution of stresses at raft-pile interface

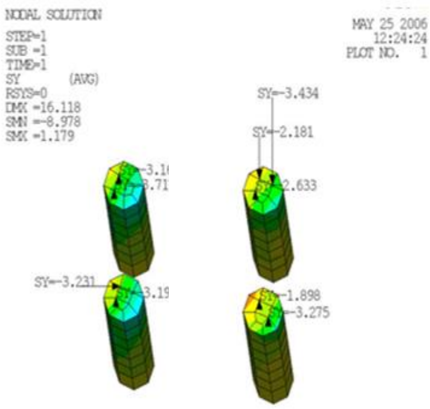


Figure 25 Typical head stress values

6. CONCLUSION

The foregoing discussions lead to the following conclusions:

1) Piled rafts are effective in reducing settlements of buildings
2) Raft share nearly 40% of the load the plane strain analyses for the rectangular raft and axisymmetric analyses for the circular raft. In the three-dimensional analyses for square raft, the load shared by the raft was about 35 to 40% of the total.
3) The results obtained in numerical analyses are in good agreement with the results obtained from model tests.
4) The results of numerical analyses also well agree with the long term settlement record of the building analyzed.
5) Accordingly, numerial analyses are proved to be a useful tool for predicting settlements of buildings.

7. ACKNOWLEDGEMENT

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