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FINITE ELEMENT MODELING FOR PILED RAFT FOUNDATION IN SAND

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ABSTRACT : This study relates to the analysis of un-piled and piled raft foundations with sandy soil conditions similar to those found in Surfers Paradise of Australia. The subsoil layer model was established for Surfers Paradise from 25 boreholes data at four different sites. The boreholes extend to 50m from ground surface to the rock stratum. A seven layer subsoil model was established and the geotechnical parameters for these layers are estimated from SPT tests. Based on these geotechnical parameters, a finite element analysis was conducted on un-piled and piled raft foundations. For the un-piled raft, the normalized settlement parameter (IR) for the raft sizes of 8m×8m and 15m×15m ranged as 1.02-1.15, and 0.64-0.81 respectively. In the case of the piled raft with raft thicknesses of 0.25, 0.4, 0.8, 1.5 and 3m, the corresponding maximum settlements are 64, 63.3, 62.6, 62.3 and 62.2 mm, and the bending moment values are 107, 160, 321, 446 and 485 kNm. The piles are 0.7m diameter and 16m length. Three values of intensity of loading as 215, 430 and 645kN/m^2 are studied. The suitability of piled raft foundation in sandy subsoil is assessed and general conclusions are made.

KEYWORDS: Sand, Settlement, Piled Raft, PLAXIS.

1. INTRODUCTION

Many tall buildings at Surfers Paradise along the coastal strip of Gold Coast involve piles as well as raft and piled raft foundations. As such this paper is devoted to the analysis of rafts and piled raft foundations for typical sub-surface soil profiles at Surfers Paradise using PLAXIS (software based on Finite Element Method). The subsoil conditions at Surfers Paradise is an estuarine deposit and typically consist of an upper layer of medium dense sand (Layer 1), followed by very dense sand (Layer 2). Below this layer of very dense sand, there is a layer of peat (Layer 3). At some locations the Layer 3 is missing. Below the peat layer is a very dense sand layer (Layer 4) followed by sandy clay (Layer 5). This in turn is underlain by clayey sand (Layer 6) which overlies a layer of gravely sand (Layer 7).

Outstanding contributions on piled foundations and piled raft foundations were also made by pioneering workers such as Berezantzev et al [1], Vesic [2], Burland [3], Meyerhof [4], Semple and Rigden []5, Poulos [6], Fleming et al. [7] among a very large number of researchers. Further, various computer softwares are now available for the study of piles and piled raft foundations and have been reported by many researchers. For example, PILEGRP [8], UNIPILE [9], CAPWAP [10], GASP [11], GROUP [12], FLAC [13], NAPRA [14], FLAC [15], PLAXIS [16], ANSYS [17], PRAB [18], ABAQUS [19] and among others.

In this study, a finite element (PLAXIS) software is used and a two dimensional plane strain analysis is carried out. Ideally speaking, a 3-D analysis is the best for rafts and piled raft foundations, but as iterated before, this is the first attempt to study the foundation conditions in sand at Surfers Paradise, and it is important that a step by step cautious approach is followed. Additionally, the work of Prakoso

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and Kulhawy [16] has demonstrated that a 2-D plane strain analysis can yield good results for piled raft analysis without excessive computing and modeling time.

In this paper, the subsoils profiles at Surfers Paradise are analyzed using the data gathered from the 26 boreholes extending to 40-50m and to establish the sub-soil profile models. Further, analyses of un-piled raft foundation for typical cases are being conducted. These include three un-piled rafts varying in size (from 8m×8m, 15m×15m and 30m×30m) and also in each case the raft thickness is varied (as 0.25m, 0.4m, 0.8m 1.5m and 3m), and the applied vertical loading was 215 kN/m^2. Then, 8m×8m piled rafts are considered with different raft thicknesses (0.25m, 0.4m, 0.8m 1.5m and 3m) and vertical loading of 645 kN/m^2. A parametric study was made with piled raft 0.8m thick and piles (16 in numbers) spaced at 3d, 4d, 5d, 6d and 7d. For each case three vertical loadings of 215, 430 and 645 kN/m^2 were considered. All piles were 16m long. This paper provides information on the performance of piled raft foundation in sand.

2. METHOD OF ANALYSIS

This section summarizes the methodology adopted in this study and general condition of Surfers Paradise subsoil is described in this section. On the surface, there is a thin layer of fill material. The next layer of medium dense sand varied in thickness from 5 to 9.5m. The medium dense sand is underlain by a layer of very dense sand with thickness varying from 14 to 22m. Within the very dense sand layer, an organic peat strip is found. Although, the thickness of this peat layer is not much (about 1 to 3m), it has adverse effects on the settlement of foundations especially for raft foundations. Under the very dense sand layer, stiff clays are encountered with the thickness of about 8 to 10m. The last layer above the high stiffness weathered rock is clayey sand or a mixture of sand, gravels and clays. The clayey sand layer is about 3m thick. The weathered rock is found at the level of 30m. The static water level is about 3.5m to 4m below the surface. Generally, the soil has high bearing capacity at the surface so it is quite favorable for raft foundations. However, the highly compressive peat can cause excessive settlements for buildings founded above it. Thus, deep foundations such as piled foundation and piled raft foundation should be used. The simplified soil profile at the Surfers Paradise and the summary of the soil properties used in the numerical analysis are shown in Figure 1 and Table 1. Generally, the rock is assumed to be about 30m below the surface. It can be considered as the rigid boundary for the piled raft modeling because the stiffness of the rock is much higher than the upper soil layers.

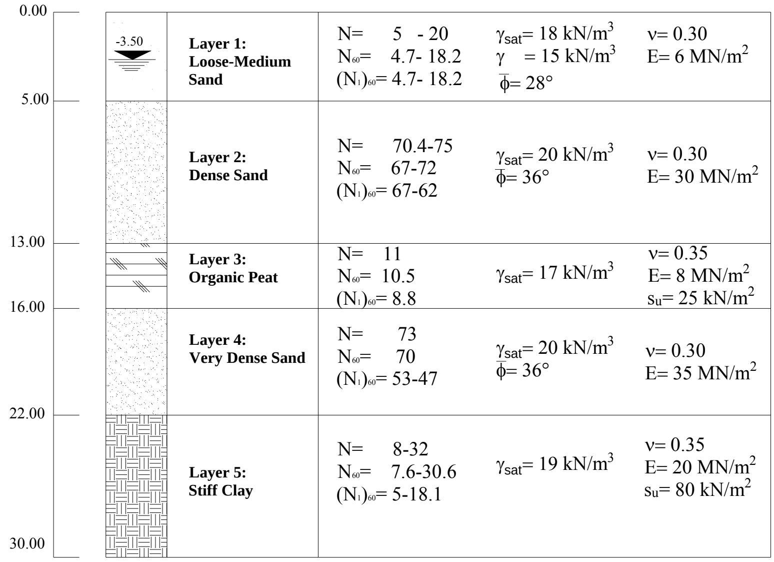


Figure 1: Summary of soil properties adopted in analysis

Numerical analyses using finite element techniques are popular in recent years in the field of foundation engineering. To date, a variety of finite element computer programs have been developed with a number of useful facilities and to suit different needs. The behavior of soil is also incorporated with appropriate stress-strain laws as applied to discrete elements. The finite element method provides a valuable analytical tool for the analysis and design of foundations. The analyses of piles and piled raft using finite element method are done in an excellent manner by many authors [19, 20].

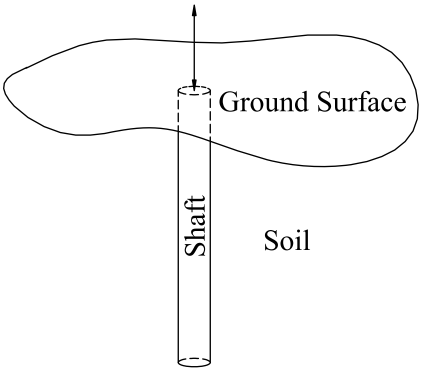
Table 1. Summary of soil properties adopted.

	Loose to Medium Sand	Dense Sand	Peat	Medium Sand	Stiff Clay
Thickness (m)	5	8	3	6	8
Unit Weight, γ (kN/m^3)	15	17	-	17	16
Saturated Unit Weight γ_{sat}, (kN/m^3)	18	20	17	20	19
Undrained Cohesion s_u (kN/m^2)	0	0	25	0	80
Frcition Angle, ϕ (deg)	28	36	-	36	-
Dilatant Angle, ψ (deg)	-	6	-	6	-
Young's Modulus, E_s (MN/m^2)	6	30	8	35	20
Poisson's Ratio, ν	0.3	0.3	0.35	0.30	0.35

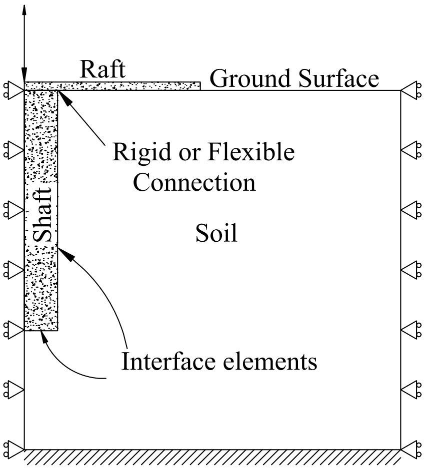
In reality the analysis of axially loaded piled raft represents a three dimensional problem. Since the loading and geometry are symmetrical, symmetric approaches permit to reduce it to two dimensions. Figure 2 illustrates the symmetric idealization of the piled raft problem. Since the piled raft is a typical example of soil-structure interaction, a special type of element at pile-soil interface, simulating the displacement discontinuity between the pile and the soil mass is needed. This element should be capable of simulating different models of interface behavior. For the piles under static vertical loading conditions, the relative slip between the pile and the soil mass becomes very important.

Based on the materials and for mainly sand soil, it is preferable to use the Mohr-Coulomb model for relatively quick and simple and first analysis of any problem considered. In many cases, if good data can be collected on dominant soil layers, it is perhaps appropriate to use the hardening-soil model as a refinement in the analysis. It should be known that Mohr-Coulomb analysis is relatively quick and a simple way to model the soil behavior in sand.

The boundary condition should be considered as a proper restrain on the mesh. The nodes belonging to the periphery of the symmetrical mesh are fixed against displacement in both horizontal directions, yet remain free to have the displacement vertically, and the nodes constituting the bottom of the mesh are fixed against displacement in both horizontal and vertical directions. In addition, the boundary should be placed far enough from the region of interest in order not to affect the deformations within the region. The mesh is designed to be denser in the vicinity of the pile shaft and area under the raft, where the deformations and stresses are expected to have major variations. The boundary conditions used in this study are: (1) The horizontal boundary was placed at least 5 times the piled raft cluster radius measured from piled raft symmetrical axis (see Figure 3). (2) The vertical



a. Basic Problem



b. Symmetric Generalization

Figure 2: Finite element idealization of the pile raft element

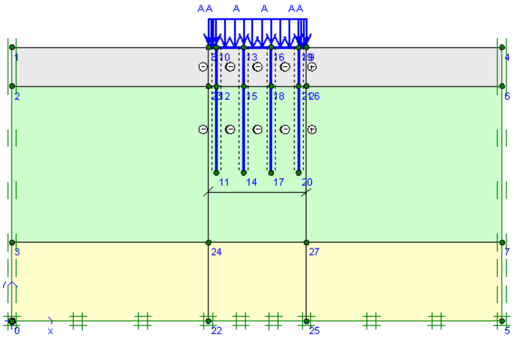


Figure 3: Diagrammatic view of boundary condition using for modeling

boundary was placed until the bottom of the stiff clay, where the weathered rock starts. It is 35m under the ground surface.

3. PARAMETRIC STUDY

In the plane strain analysis using PLAXIS, the raft was modelled as a plate element, while the piles are modelled as series of beam elements with the appropriate geometrical parameters and geometrical boundaries as suggested by Prakoso and Kulhawy [16]. Different types of case studies were carried out. The details are listed below:

- Case - 1: Unpiled raft 8m×8m with thicknesses of 0.25m, 0.4m, 0.8m, 1.5m and 3m. Vertical loading intensity 215 kN/m^2.
- Case - 2: Unpiled raft 15m×15m with thicknesses of 0.25m, 0.4m, 0.8m, 1.5m and 3m. Vertical loading intensity of 215 kN/m^2.
- Case - 3: Piled Raft, 8m×8m with raft thicknesses of 0.25m, 0.4m, 0.8m, 1.5m and 3m. The pile spacing is 3d. The length of piles is 16m.
- Case - 4: Piled raft with raft thickness of 0.8m. Pile spacing varied as 3d, 4d, 5d, 6d and 7d and for each pile spacing with vertical loading intensity of 215 kN/m^2, 430 kN/m^2, 645 kN/m^2 . The pile length is 16m.
- Case - 5: Piled raft 8mx 8m and thickness 0.8m with 4, 8, 12 and 16 piles. The pile length is 16m. The vertical loading intensity is 645 kN/m^2.

The serviceability load is 215kN/m^2, twice of serviceability load is 430kN/m^2 and three times of the serviceability load is 645kN/m^2. The thickness of the raft was varied to investigate the effect of the relative stiffness of raft on settlements differential settlements, bending moments and the proportion of the loads shared by the piles. Similarly, the effects of pile spacing, pile length and number of piles were also investigated.

4. RESULTS AND DISCUSSIONS

4.1 SETTLEMENT OF UNPILED RAFT

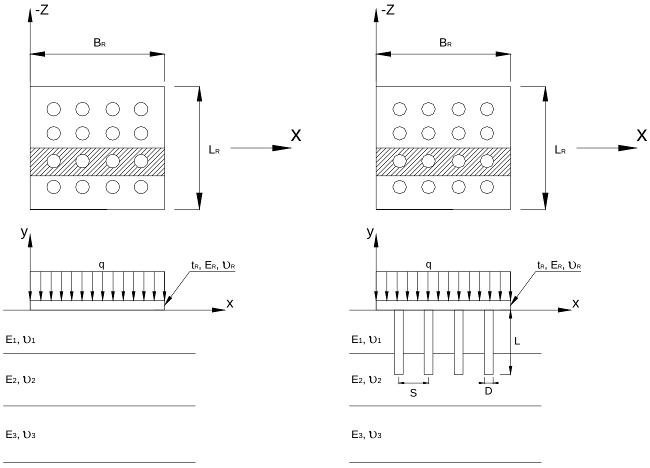
The Settlement of the un-piled raft (see Figure 4) was investigated for different sizes (8m and 15m) of raft and for different raft thickness (0.25m, 0.4m, 0.8m, 1.5m and 3m), under a uniform intensity of vertical loading. The settlement was normalized and can be described by the influence factor I_R:

$$I_R = \frac{w_i E_s}{q B_R (1-\upsilon_s^2)} \tag{1}$$

Where q is the uniform distribution loads acting on the raft, and w_i is the settlement of raft, B_R is the width of raft. E_s and υ_s represent the young's modulus and Poisson's ratio of the soil below the raft.

The distance from edge of the raft was normalized as x/B_R to plot the results. The results of the settlement analysis of the un-piled rafts of widths 8m and 15m are shown in Figures 5 and 6 respectively. The I_R values were found to decrease as the raft width is increased. Also, the I_R values reduced with increase in thickness of the raft. The influence factor I_R is found to vary in a parabolic type of manner with the maximum value at the centre of the raft. The values for I_R were in the range 1.02 to 1.15 when the raft size is 8m×8m. This value reduced to the range 0.64 to 0.81 when the raft size is increased to 15m×15m.

It can be concluded that the general settlement profile of the raft foundation, which the base was in full contact with the underlying soil under uniform distribution showed in bowl shaped, with the maximum settlement (Table 5.3) at the centre of the raft. For the 8m×8m raft, the variation in the settlement is in a narrow range from 31.5 mm to 32.8 mm. This range increased to 40.1 to 43 mm when the raft size increased to 15m×15m. The raft thickness did not have substantial effect on the maximum settlement.



(a) Unpiled Raft

(b) Piled Raft

Figure 4: Typical raft and piled raft configurations for analysis

4.2 EFFECTS OF RAFT THICKNESS ON PILED RAFT FOUNDATION

Except for the thinner rafts (0.25m, 0.4m), the piled raft show bowl shaped settlement pattern within the pile area and the edge strips indicated downward curvature (see Figure 7). Thin rafts (0.25m, 0.4m) show more prominent settlement pattern. Maximum settlements for different thickness are tabulated in Table 5.7. These values ranged from 62mm to 64 mm in a narrow range. Increasing the raft thickness, had a greater effect on the maximum bending moment (see Figure 8) and these values increased from 107 kNm to 485 kNm. The bending moment within the pile group area was affected significantly by increasing the raft stiffness (thickness). For the case considered here, there is little effect on the maximum bending moment when the raft thickness is increased beyond 1.5m.

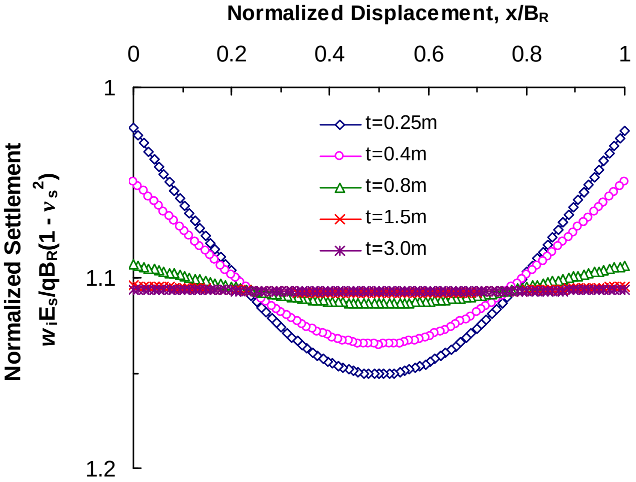


Figure 5: Normalized vertical displacement of 8m×8m square un-piled raft

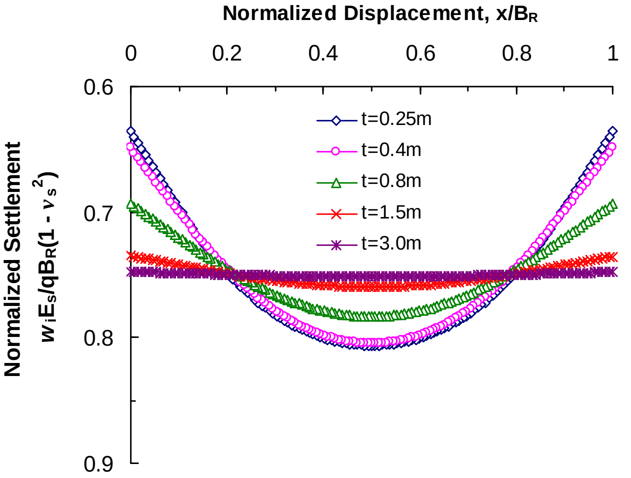


Figure 6: Normalized vertical displacement of 15m×15m square un-piled raft

It can be concluded that increasing the raft thickness of 0.25m do not influence the bending moment in the pile (as shown in Figure 9). However it may be beneficial in resisting the punching shear resulting from the piles and the column loadings.

4.3 EFFECTS OF PILE SPACING

The effect of the pile spacing (3d to 7d) on the piled raft behavior is studied for the bending moment and the settlement of the raft for three values of intensity of loading as 215 and 430 kN/m^2. In this analysis, the raft thickness is 0.8m and the dimension of the raft will increase with increased pile spacing. The piles are 0.7m diameter and 16m length. When the intensity of loading is 215 kN/m^2, the reduction in pile spacing has the effect of reducing the raft settlement (Figure 10). However the differential settlement is not affected much as the loading is very light. Figure 11 indicates that the bending moment in the raft increased significantly especially at the pile location, as the pile spacing becomes large. When the intensity of loading is 430kN/m^2 there is no significant difference in the settlement below the raft and its bending moment (see Figures 12 and 13).

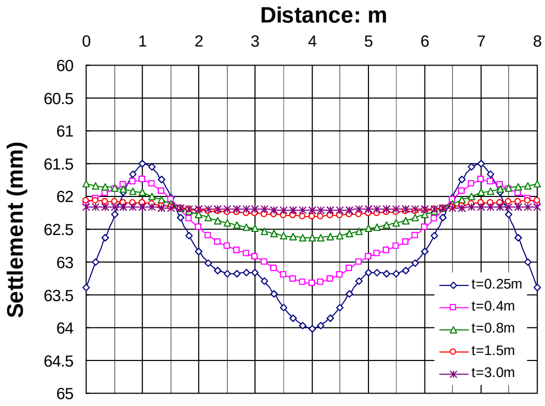


Figure 7: Effect of raft thickness on computed settlement of piled raft (q = 645 kN/m^2)

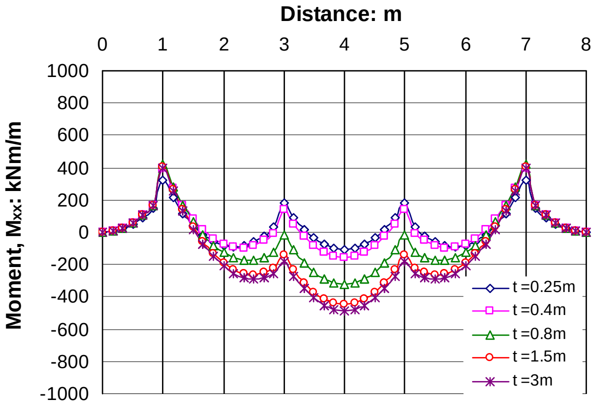


Figure 8: Effect of raft thickness on bending moment of piled raft (q = 645 kn/m^2)

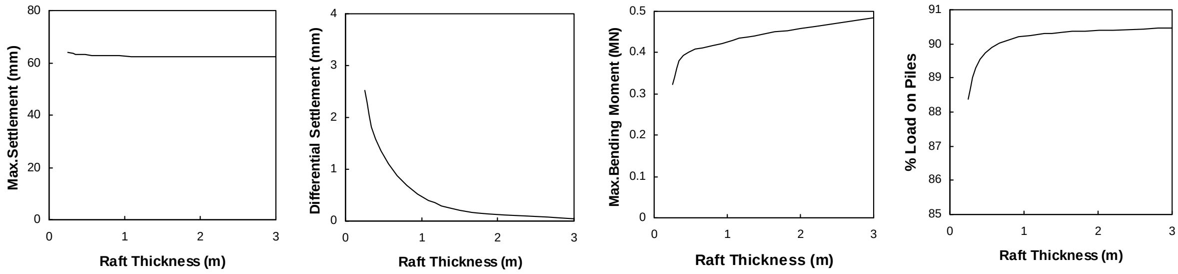


Figure 9: Summarized effect of raft thickness on piled raft performance (raft with 16 Piles, 16m long, q = 645 kN/m^2)

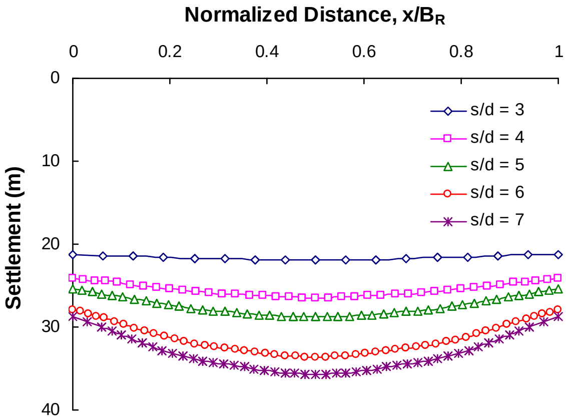


Figure 10: Comparison of piled raft settlement response for different spacing of piles (q = 215 kN/m^2).

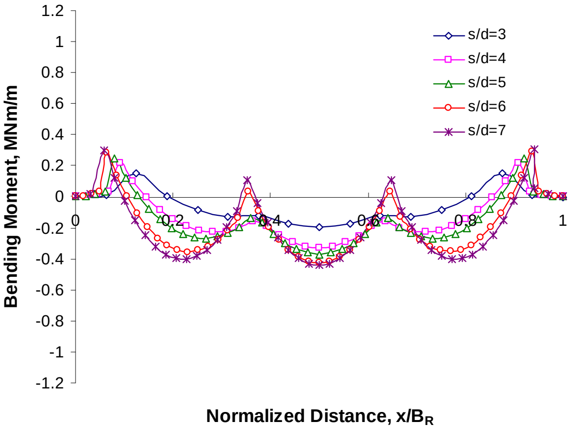


Figure 11: Comparison of piled raft bending moment response for different spacing of piles (q = 215 kN/m^2)

5. CONCLUDING REMARKS

A series of case studies were conducted on un-piled raft and piled raft foundation in sandy subsoil condition. Although the examined piled raft conditions are limited, the following conclusions can be drawn.

- Under the working load intensity of 215 kN/m^2, maximum settlements for 0.25m thickness raft are 33mm and 44mm for the 8m×8m and 15m×15m rafts respectively. Increasing the raft thickness to 3m reduced these maximum values to 31mm and 40mm respectively. The corresponding bending moments are 0.026 and 0.017 MNm respectively. Increasing the raft thickness to 3m increased these maximum values to 0.14 and 0.59 MNm respectively.
- When the raft thickness of the piled raft varied as 0.25, 0.4, 0.8, 1.5 and 3m, the corresponding maximum settlements were 64, 63.3, 62.6, 62.3 and 62.2mm. The corresponding hogging moments for the piled rafts with raft thicknesses of 0.25, 0.4, 0.8, 1.5 and 3m are 107, 160, 321, 446 and 485 kNm.
- Under an intensity of loading of 215 kN/m^2, when the pile spacing is varied as 3d, 4d, 5d, 6d and 7d, the corresponding maximum settlements were 22, 26, 29, 34 and 36mm. The hogging moment in the raft centre developed as 0.197, 0.329, 0.369MNm, 0.42 and 0.44MNm. Similarly, the pile loads increased from 0.265MN to 0.835MN in the edge pile, and 0.475MN to 0.639MN in the centre piles as the pile spacing increased. The pile head bending moment increased greatly in both the edge piles and the centre piles and these ranges are 91.37kNm to 246.17kNm, and 28.91kNm to 69.44kNm respectively.

Further, it can be concluded that the foregoing simple example demonstrates the following important points for practical design:

- The raft thickness affects differential settlement and bending moments, but has little effect on load sharing or maximum settlement.
- Piles spacing plays an important role on the performance of piled raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft, and the load shared by the piles.
- To reduce the maximum settlement of piled raft foundation, optimum performance is likely to be achieved by increasing the length of the piles involved. While the differential settlement, the maximum bending moment and the load sharing are not affected much by increasing the pile lengths.

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