Numerical analysis of piled raft foundation in sandy and clayey soils

Analyse numérique de la fondation dans pile rojet et sandy sols argileux

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ABSTRACT
This paper presents 2-D and 3-D numerical analysis of un-piled raft and piled raft foundation on two different soil conditions. The numerical analysis was carried out in two case studies with three typical load intensities of the serviceability load. The first case study investigates the raft-pile-soil interaction in sandy soil. The second case study examines the raft-pile-soil interaction in soft clay. Finally, the behaviours of piled raft foundation in two different case studies are assessed and conclusions are made.

RÉSUMÉ
Ce document présente en 2-D et 3-D de l'analyse numérique d'un radeau et empilés-raft empilés sur deux bases différentes conditions de sol. L'analyse numérique a été réalisée dans deux études de cas avec trois intensités de charge typique de la charge de service. La première étude de cas examine le radeau-pile-soil interaction dans les sols sableux. La deuxième étude de cas examine le radeau-pile-soil interaction en argile molle. Dans ce document, les résultats sont comparés avec les études. Enfin, les comportements de radier entassés dans deux études de cas sont évalués et les conclusions sont formulées.

Keywords : piled raft, raft thickness, PLAXIS, FLAC.

1 INTRODUCTION

Piled raft foundation is an economical alternative to the conventional piled foundation. This paper is on numerical analysis of piled raft foundations using PLAXIS (Brinkgreve and Broere, 2006.) and FLAC (1995). The numerical analysis was carried out in two case studies with typical load intensities of the serviceability load. Extensive parametric studies were carried out with the variables pile spacing, number of piles, pile diameter, raft dimension ratio, and raft thickness.

Historically, the pile raft analysis has its origin to the pile group analysis. Early work of Meyerhof (1959) were empirical in nature and relates to the settlements of pile groups. Later, the important work of Fraser and Wardle (1976), Poulos and Davis (1980), Randolph (2003) reviewed the relation to the pile group analysis, load transfer mechanism and other pertinent aspects related to the fundamentals of pile group analysis. The contributions from Tomlinson (1986), Coduto (2001), and Poulos (1993) also studied in relation to the equivalent raft analysis. The contributions from Poulos (1993), and Clancy and Randolph (1993) reviewed the equivalent pier methods of analysis in piled raft foundations. The more rigorous methods of piled raft analysis began with the contributions of Kuwabara (1989), and extended by Poulos (1993) with further contributions from Ta and Small (1996), and Zhang and Small (2000). Notably, Prakoso and Kulhawy (2001) used the PLAXIS software in the 2-D analysis of piled raft foundations.

In this paper, the first case study investigates the raft-pile-soil interaction in sandy soil (as shown in Figure 1). The stratigraphy of the soil layers for the first case study are: (a) Layer 1 - 5m of loose to medium dense sand; (b) Layer 2 – 8m of dense sand; (c) Layer 3 - Organic peat and silty clays with average thickness 3m; (d) Layer 4 - Very dense sand with thickness varying from depth of 16 to 22m; (e) Layer 5 - Stiff clay inter-bedded with sand strips; (f) Layer 6 - Argillite-weathered rock. The second case study examines the raft-pile-soil interaction in soft clay (see Figure 2). The subsoil is generalised into three layers: (a) 15m of soft clay; (b) 15m of stiff clay; (c) 12m of sand.

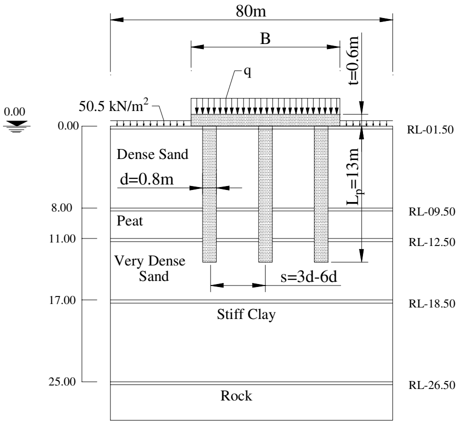

Figure 1. Geotechnical model for case study 1.

2 CASE STUDY 1

2.1 *Soil Profile and Properties*

The simplified soil profile for case study 1 and the summary of the soil properties used in the numerical analysis are shown in Figure 1 and Table 1. The stratigraphy of the soil layers are given below.

i. Layer 1: Loose to medium dense sand 5m thick with SPT in the range of 5 to 20, with static water table 3.5m below ground surface.
ii. Layer 2: Dense sand 8m thick and SPT val-ues over 50.
iii. Layer 3: Organic peat and silty clays with av-erage thickness 3m.
iv. Layer 4: Very dense sand with thickness varying from depth of 16 to 22m and SPT values over 50.
v. Layer 5: Mainly stiff clay inter-bedded with sand strips, but idealized as homogeneous stiff clay 8m thick with SPT values of about 30
vi. Layer 6: Argillite-weathered rock

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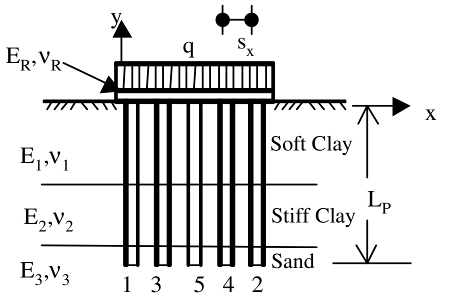


Figure 2. Geotechnical model for case study 2.

Table 1. Summary of soil properties adopted fro case study 1.

	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

2.2 *Parametric Study*

The main purpose of a parametric study is to investigate the piled raft performance under the changes of the geometry of the dimensions. Therefore, the numbers of cases for parametric study are as many as piled raft geometry dimensions. Specifically, the piled raft dimensions include pile spacing, number of piles, pile diameters, pile lengths for pile groups and raft thickness, raft dimension ratio (L/B) (B, L: the width and length of raft). The plane strain models are also simulated for the case of the variation in raft dimension ratio (L/B). Details of piled rafts and pile groups in this parametric study are described and summarized in Table 2.

2.3 *Settlement of Piled Raft Foundation*

Figure 3 illustrates a plan view of the piled raft in the 3D case. The piles are indicated by circles w_1 to w_4 represents the settlements at the corner points of the raft. w_5 to w_8 correspond to the settlement of the centre of the sides of the raft. w_9 to w_{12} are the settlements at the mid points of the lines bisecting the sides of the raft. w_{13} is the settlement at the centre of the raft. Thus the settlements are computed at 13 locations in the raft. The average settlement w_{3D} for the 3D case at the centre is given by

$$w_{3D} = \sum_{i=1}^{13} w_i / 13 \tag{1}$$

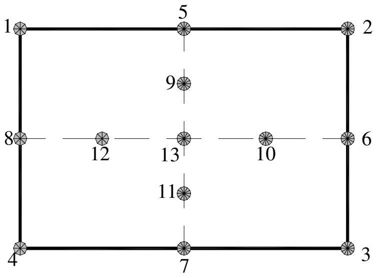
Figure 4 illustrates a diagram similar to Figure 3 for the 2D case. Only a half of the cross section of the raft is shown with the centre (C), the edge (E) and the mid point of the centre and the edge (F). The settlement values at the centre(C), the edge (E) and the point at midway between the centre and the edge (F) are denoted as w_C, w_E and w_F respectively. The positive values of the settlements are indicated in the downward direction. In the 2D case, the average settlement under plane strain is given by

$$w_{2D} = \left(w_C + 2w_F + 2w_E\right) / 5 \tag{2}$$

where, w_C is the settlement at the center of the raft (Point C); w_F is the settlement at the a quarter of raft width (Point F); w_E is the settlement at the edge point (Point E).

Table 2. Details of piled rafts and pile groups in parametric study

Varied Geometry	Raft Dimensions		Pile Group Geometry		
	Width x Length (m)	Thickness (m)	Pile Spacing	No. of Piles	Pile Diameter (m)
Pile Spacing	7×7	0.6	3d	3×3	0.8
	8×8		4d		
	10×10		5d		
	12×12		6d		
Number of Piles	14×14	0.8	7d	3×3	0.8
			5d	4×4	
			4d	5×5	
Pile Diameter	7×7	0.6		3×3	0.6
	8×8				0.8
	10×10				1
Raft Dimension Ratio	8×8	0.6	4d	3×3	0.8
	8×17			3×6	
	8×27			3×9	



$\Delta w = \max (w_1, w_{13}) - \min (w_1, w_{13})$

$w_{3D} = \sum_{i=1}^{13} w_i / 13$

Figure 3. Plane view of 3-D piled raft and raft settlement.

For the 3D as well as for the 2D case, the maximum settlement of the raft (w or w_{max}) is always found to be at the centre. The maximum settlement will simply be referred to as the raft settlement. In presenting the results of the settlement, often the raft settlement is normalized with the raft width. In this paper the term normalized settlement thus refers to w/B, where w is the maximum settlement (at the centre) and B is the width (smaller dimension in plan) of the raft. For 3D analysis, the differential settlement of the raft is taken to be the difference between the maximum and minimum value of the 13 points mentioned above (as in Figure 3). Normally, the value of the differential settlement is the difference in settlement values of the center point and the 4 corner points. For 2D models, the differential settlement is the difference in settlement between the center and the edge. Similar to the maximum settlement, the differential settlement is also normalized with the width of the raft. Thus the normalized differential settlement refers to is taken as ($\Delta w/B$).

3 RESULTS AND DISCUSSIONS FOR CASE STUDY 1

3.1 *Effect of Pile Spacing*

A 3x3 pile group is analysed with pile spacings of 3d, 4d, 5d and 6d. The pile length is kept constant as 18m. The diameter of the piles is 0.8m. The intensity of loading q is 200, 400 and 600 kN/m^2. Figure 5 provides the normalized settlement with different pile spacing. The average settlement increased from 13mm to 27mm when the intensity of loading is 200kN/m^2 and the pile spacing increased from 3d to 6d. Generally, a pile spacing of 2d to 3d is adopted and as such for this spacing a settlement of 13mm is noted when the intensity of loading is 200 kN/m^2. The maximum settlements are very close to the average values. The differential settlements for the above cases are 1, 3 and 6 mm and are rather small.

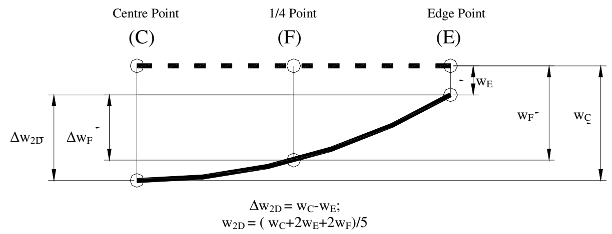


Figure 4. Definition of raft settlement for the 2-D Case

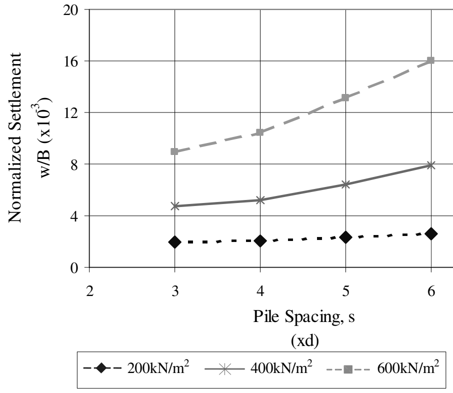


Figure 5. Normalized settlement vs. pile spacing.

3.2 *Effect of Number of Piles*

A 14x14m raft is analysed with 3x3, 4x4 and 5x5 piles. The pile spacing varied from 4 to 7d. The results are presented in Figure 6. The increase in the number of piles had little effect on the normalized settlements. The effects are more pronounced at higher values of q and when the number of piles increased from 9 to 16.

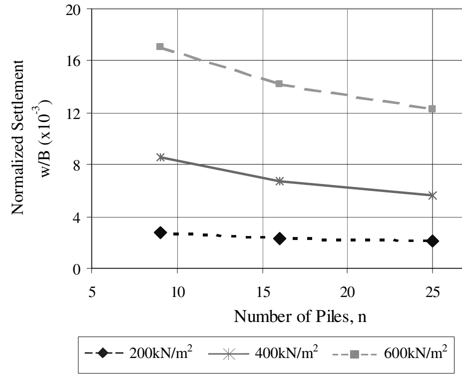


Figure 6. Normalized settlement vs. no. of piles.

3.3 *Effect of Pile Diameter*

The normalized settlement presented in Figure 7 is more or less the same for the three pile diameters studied. It is likely because the value of pile spacing increases when the pile diameters rises. Consequently, the effect of pile-pile interaction becomes less and piles in piled raft work likely as single piles.

3.4 *Effect of Raft Dimension Ratio*

In this section, the results of the analysis where the (L/B) ratio of the raft is changed while B is kept constant will be presented and discussed. The (L/B) ratio was changed from 1 to 3, while the number of piles changed from 3x3 to 3x9. The normalized settlement is presented in Figure 8. The normalized settlement increased sharply with the (L/B) ratio when the q value is 600 kN/m^2.

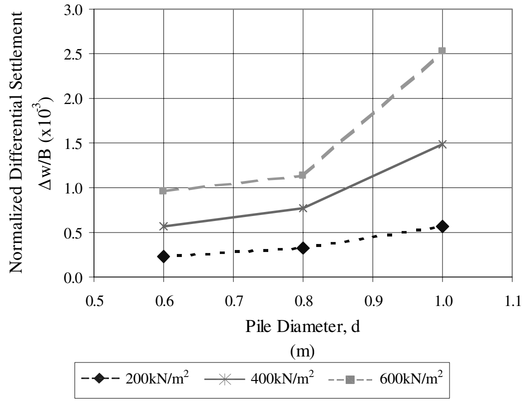


Figure 7. Normalized differential settlement vs. pile diameter

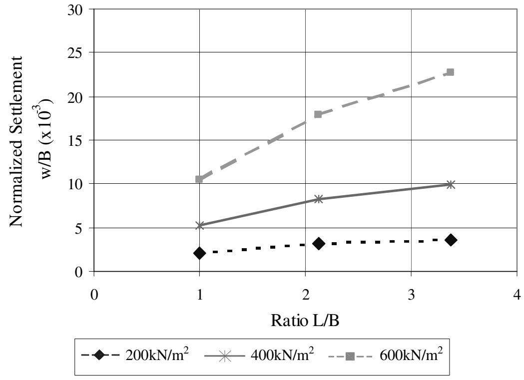


Figure 8. Normalized settlement vs. raft dimension ratio (Case 4)

4 CASE STUDY 2

In the second case study, the load capacity of raft as well as pile group is considered for the analysis. The piled raft foundation system is approximated to a plane strain case and analysed using two-dimensional finite difference method. The soil is discretized into a rectangular finite difference mesh and is modelled as a linear elastic material. The raft is modelled as a beam structure under plane strain condition. The piles are modelled using pile elements, which allow the shear and normal interaction at the pile-soil interface with appropriate scaled stiffness and strength values. The effect of structural connections between raft and piles is also considered. The suitability of piled raft foundation in soft clay is assessed. FLAC program was adapted to analyse of the piled raft system. The conversion of problem from 3-D to 2-D plane strain condition was carried out through scaling the pile parameters with spacing in the out-of plane direction.

The loading was chosen in the working range as encountered in practice. The thickness of the raft was varied to investigate the effect of the relative stiffness of the raft on load transfer, load proportion and settlement. The numerical experimental variables are summarized in Table 3. The subsoil for case study 2 is generalized into three layers (see Figure 2) for the simplicity of analysis. The soil parameters obtained from the back analysis are given in Table 4.

5 RESULTS AND DISCUSSIONS FOR CASE STUDY 2

The settlement from the analysis of the piled raft system were presented with normalized distance (x / B_R), as an abscissa and normalized settlement ($I = w_i E_s / q B_R (1-\upsilon_s^2)$) as an ordinate. w_i is settlement at point i, E_s is the Young's modulus of soft clay,

υ_s is the Poisson's ratio, q is the vertical load intensity at the raft surface and B_R is the raft width.

As shown in Figure 9, the un-piled raft shows a bowl shaped settlement. The differential settlement of thin raft is larger than thick rafts. As shown in Figure 10, similarly, the piled raft shows a bowl shaped settlement. The settlement at the edge of raft strip deviates downwards from the general bowl shape. Thinner piled rafts shoed a slightly wave shape of settlement, and have larger differential settlement than the thick piled rafts. The values of settlement for various loading cases and raft thickness of un-piled and piled raft are presented in Table 5.

Table 3 Loading case and raft dimension

Load case	Vertical Load, kPa	Horizontal Load, kPa	Moment, kN-m/m^2	Raft thickness, m
1	333	0	0	1.0
2	293	20	133	1.0
3	333	0	0	5.0

Table 4. Summary of soil properties adopted for case study 2.

Soil layers	Soft clay	Stiff clay	Sand
Depth, m	0~15	15~30	30~90
Young's modulus, E, MPa	16.5	60	205
Poisson's ratio, ν	0.49	0.49	0.3
Mass density, ρ_i, kN/m^3	16.4	20	21

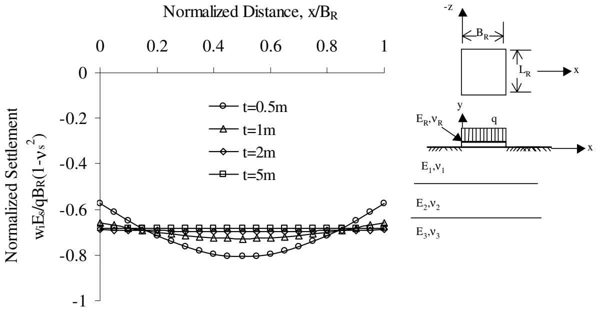


Figure 9. Normalized settlement of un-piled raft with 15m width.

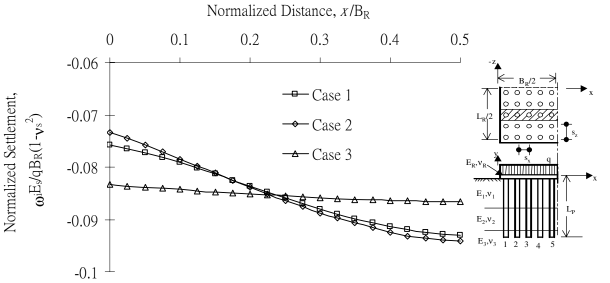


Figure 10. Normalized settlement of piled raft.

Table 5. Summary of raft and piled raft settlement.

Unpiled raft Wi (mm)		Piled raft Wi (mm)	
Edge	Centre	Edge	Centre
25.95	44.63	28.74	38.05
(t=0.5m)	(t=0.5m)	(case 2, t=1m)	(case 2, t=1m)
37.08	37.35	38.19	40.03
(t=5m)	(t=5m)	(case 3, t=5m)	(case 3, t=5m)

6 CONCLUSIONS

In this paper, numerical analysis of un-piled raft and piled raft foundation on two different soil conditions are presented. The numerical analysis was carried out in two case studies with three typical load intensities of the serviceability load. The subsoil was modelled as linear elastic materials the raft being modelled as beam element, and the piles were simulated by element with shear and normal coupling springs.

In case study 1, geotechnical parameters were obtained several in-situ tests. As for case study 2, the geotechnical and structural parameters were obtained from the back analysis of static pile load test data.

As presented in case study 1 with sandy soil condition, the maximum settlement of the piled rafts depends on the pile spacing and the number of piles. The raft thickness does not have a significant effect.

From the results given in case study 2 with clayey subsoil, the settlement of un-piled raft was similar for different raft thickness. Raft thickness was found to have obvious effect on differential settlement. The settlement of piled raft at the piled areas showed a bowl shape settlement pattern. Further, the edge of the raft strip showed a downward deviation from the settlement bowl.

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