Investigation of the Behavior of Piled Raft Foundations in Sand by Numerical Modeling

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ABSTRACT

This paper is on 3-D analysis of piled raft foundations on sand. The numerical analysis was carried out with three typical load intensities of the serviceability load. Further, extensive parametric studies were carried out with the variables pile spacing, number of piles, pile diameter, raft dimension ratio, and raft thickness. The maximum settlement of the piled rafts depends on the pile spacing and the number of piles; while the raft thickness does not have a significant effect. In all cases, the normalized settlement recorded is mostly less than 2% of the raft width and the maximum value was noted for the 8x27m piled raft. The increase in raft thickness reduces the differential settlement in the foundations. The raft-soil stiffness (K_{rs}) is shown to influence the differential settlement and has the largest influence. The performance of piled raft in sandy soil condition is assessed and general conclusions are also made.

KEY WORDS: Numerical Analysis, Piled Raft Foundation, Sand

INTRODUCTION

This paper is on a detail 3-D analysis of piled raft foundations using the PLAXIS. A six-layer soil model is adopted which is commonly encountered in Surfers Paradise of Gold Coast. The numerical work is carried out on 3-D PLAXIS analysis. 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. The early work of Skempton (1953) and Meyerhof (1959) were empirical in nature and relates to the settlements of pile groups. The important work of Fraser and Wardle (1975), Poulos and Davis (1980), Randolph (2003), and Poulos (2006) are reviewed in 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 (1996), Poulos (1993) and Van Impe (1991) are also studied in relation to the equivalent raft methods of analysis. The contributions from Poulos (1993), and Clancy and Randolph (1993) are reviewed in relation to the equivalent pier methods of analysis in piled raft foundations. The rapid developments in the numerical analysis of pile behaviour and piled raft foundations saw numerous. 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), Zhang and Small (2000), and Mendoca and Paiva (2003). Notably, Prakoso and Kulhawy (2001) used the PLAXIS software in the 2-D analysis of piled raft foundations.

This paper will illustrate the practical applications of the piled raft foundation using PLAXIS 3-D software.

SOIL MODEL

General stratigraphy 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 favourable 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 Fig. 1. The stratigraphy of the soil layers are given below.

- 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.
- Layer 2: Dense sand 8m thick and SPT values over 50.
- Layer 3: Organic peat and silty clays with average thickness 3m.
- Layer 4: Very dense sand with thickness varying from depth of 16 to 22m and SPT values over 50.
- Layer 5: Mainly stiff clay inter-bedded with sand strips, but idealized as homogeneous stiff clay 8m thick with SPT values of about 30

- Layer 6: Argillite-weathered rock

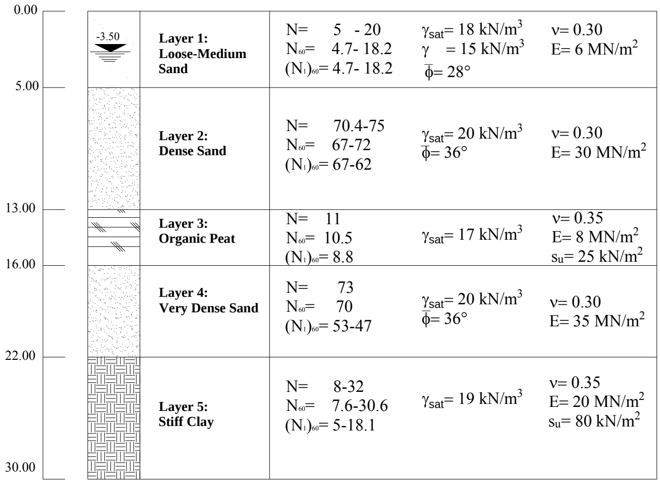

Fig. 1 Summary of soil properties used in PLAXIS Analysis.

Generally, the rock is assumed to be about 30m below the surface. It can be considered as the rigid boundary for the piled raft modelling because the stiffness of the rock is much higher than the upper soil layers. Table 1 summarizes the soil properties adopted in this research.

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 below and summarize in Table 2.

- Case 1: Piled raft with unchanged thickness of 0.6m. the pile group has the same pile diameter of 0.8m, pile length of 18m (from actual soil surface, 13m in the model) while the pile spacing varies from 3 to 6 times of pile diameter. The change of the pile spacing results in the variation of the plan dimensions of the raft.
- Case 2: Piled raft 14m×14m with thickness of 0.8m. the pile group varies from 3x3 square pile group to 5x5 square pile group whereas the pile diameters and pile lengths keep unchanged to be 0.8m and 18m. Due to the constant of raft dimensions and variation of number of piles, the pile spacing will change from 4 times to 7 times of pile diameter.
- Case 3: Piled raft with thickness of 0.6m. The pile group size is 3x3 piles. The pile diameters are changed as 0.6, 0.8 and 1.0m. Although the pile spacing keeps the value of 4d but the pile group area and raft area increase due to the increase in pile diameter.
- Case 4: Piled Rafts have the same width 8m with unchanged raft thickness of 0.6m. The length of the raft is changed together with the length of the pile group which varied in numbers from 3x3, 3x6 and 3x9 piles. Other geometry dimensions of the pile group are constant such as 4 times the diameter in pile spacing, 0.8m in pile diameter, and 18m the pile length. For this case, the 2D models are also analysed correspondingly to each 3D model.
- Case 5: Piled raft 8.0 x 8.0 m with typical geometry such as pile spacing of 4d, 18m pile length, 3x3 piles in pile group and 0.8m in pile diameter. The raft thickness varied from 0.3m to 1.5m so that e the effects of raft stiffness on the piled raft performance can be investigated.

Table 1. Summary of soil properties adopted.

	Loose to Medium Sand	Dense Sand	Peat	Very Dense 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

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

Case	Varied Geometry	Raft Dimensions		Pile Group Geometry		
		Width x Length (m)	Thickness (m)	Pile Spacing	No. of Piles	Pile Diameter (m)
1	Pile Spacing	7×7	0.6	3d	3×3	0.8
		8×8		4d		
		10×10		5d		
		12×12		6d		
2	Number of Piles	14×14	0.8	7d	3×3	0.8
				5d	4×4	
				4d	5×5	
3	Pile Diameter	7×7	0.6		3×3	0.6
		8×8				0.8
		10×10				1
4	Raft Dimension Ratio	8×8	0.6	4d	3×3	0.8
		8×17			3×6	
		8×27			3×9	
5	Raft Thickness	8×8	0.3	4d	3×3	0.8
			0.4			
			0.6			
			0.8			
			1.5			

d is the pile diameter

RESULTS AND DISCUSSIONS

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. Fig. 2 provides the normalized settlement with different pile spacing. Table 3 contains details of the average settlement, maximum settlement, maximum differential settlement and the maximum bending moment. 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. The corresponding bending moments are 132, 303 and 463 kNm/m width. Table 4 gives ratio of the average settlement to maximum settlement. At 3d pile spacing this value is close to one and is 0.97. The corresponding values for twice and three times the service load intensity do not increase very much.

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 Fig. 3. 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. The same trend is exhibited in Fig. 4 for the normalized differential settlement.

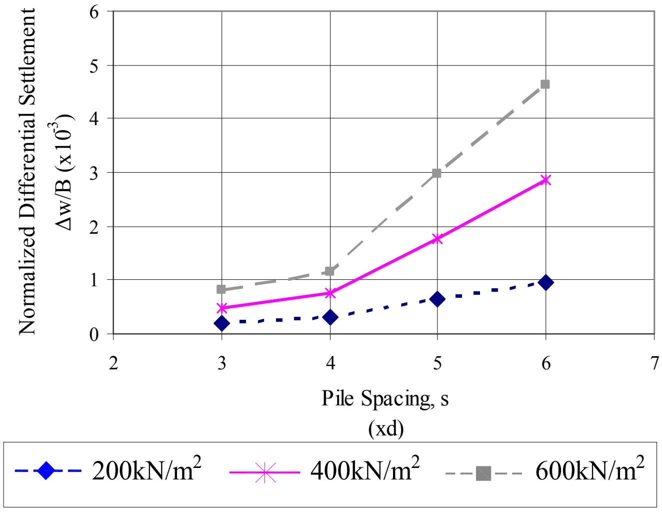

Fig. 2 Normalized settlement vs. pile spacing (Case 1).

Effect of Pile Diameter

The normalized settlement presented in Fig. 5 is more or less the same for the three pile diameters studied. In Fig. 6, the normalized differential settlement is found to increase more sharply at the higher values of q and when the pile diameters are 0.8 and 1.0 m. The normalized pile group loads in Fig. 6 shows a peak, when the pile diameter is 0.8m. Further, Fig. 6 shows that the total pile load (R_g, in dimensionless unit) reaches the maximum value at the pile diameter of 0.8m and it varies from 48% to 60% of the total applied load. In Fig. 7, the pile butt loads ratio decrease steadily with increase in pile diameter and increase in q. Further, the pile butt ratio recorded has the highest value of 2 at $200kN/m^2$, and value of 2.6 at $600kN/m^2$, as the pile diameter is 0.6m. Then, this ratio significantly decreases at the pile diameters of 0.8m and 1.0m. 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.

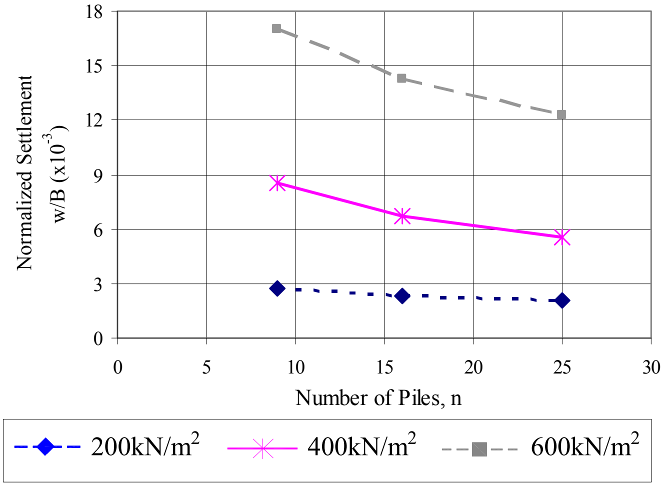

Fig. 3 Normalized settlement vs. no. of piles (Case 2)

Table 3. Variation of pile spacing with settlement (Case 1).

Pile Spacing	Average Settlement w_{3D} (mm)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	13	32	61
4d	15	39	80
5d	21	58	121
6d	27	83	174
Pile Spacing	Maximum Settlement w_{max} (mm)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	13	33	62
4d	16	41	83
5d	23	64	130
6d	31	94	192
Pile Spacing	Differential Settlement Δw (mm)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	1	3	6
4d	3	6	9
5d	7	18	30
6d	11	34	56
Pile Spacing	Maximum Moment (kNm/m)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	132.2	303.4	463.7
4d	172.0	402.9	588.1
5d	285.1	721.7	1106.9
6d	356.5	956.1	1543.9

Table 4. Results of settlement ratios (Case 1)

Pile Spacing	w_{3D}/w_{max} (%)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	97	97	98
4d	95	95	97
5d	90	90	93
6d	88	88	91
Pile Spacing	$\Delta w/w_{3D}$ (%)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	11	10	9
4d	16	15	11
5d	31	30	25
6d	41	41	32
Pile Spacing	$\Delta w/w_{max}$ (%)		
	q=200 (kN/m^2)	q=400 (kN/m^2)	q=600 (kN/m^2)
3d	10	10	9
4d	15	15	11
5d	28	28	23
6d	36	36	29

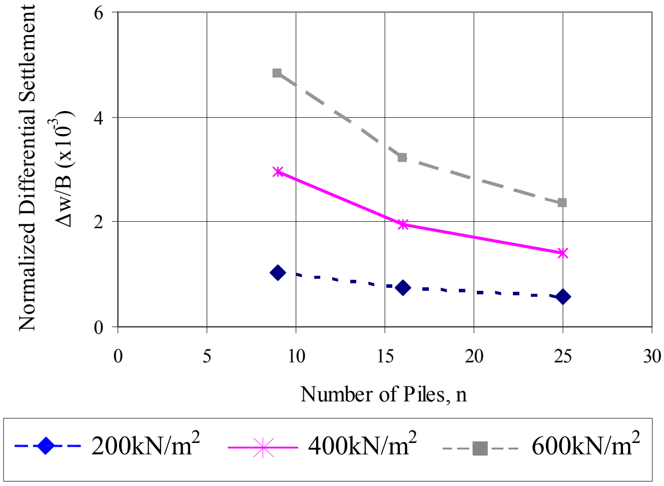

Fig. 4 Normalized differential settlement vs. no. of piles (Case 2)

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 Fig. 8. The normalized settlement increased sharply with the (L/B) ratio when the q value is 600 kN/m^2. The normalized bending moment (M/qBL) is found to decrease more or less linearly (for a first degree of approximation) with the L/B ratio (see Fig. 9). The total normalized pile group load in percentage (R_g/qBL) appear to be not affected by the L/B ratio; however as the q value increase this ratio (R_g/qBL) is found to increase (see Fig. 10).

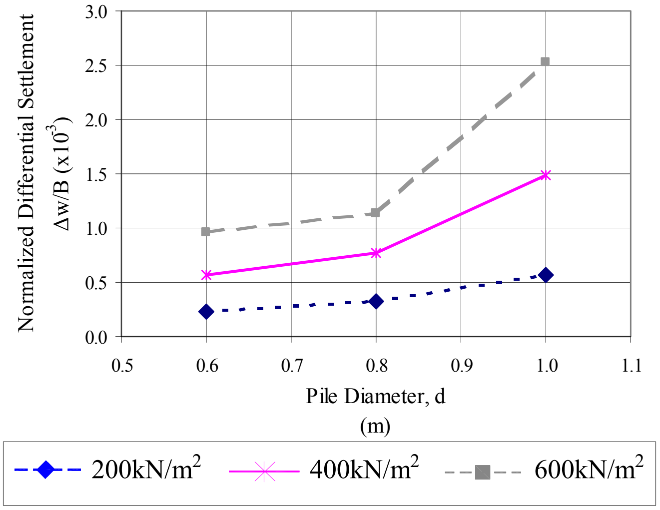

Fig. 5 Normalized Differential Settlement vs. Pile Diameter (Case 3)

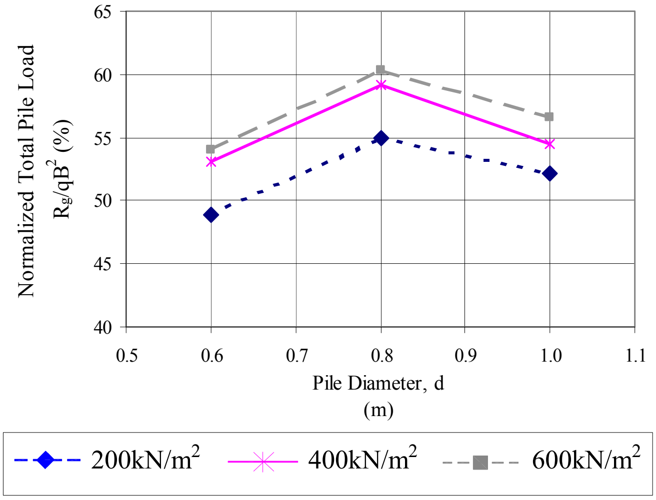

Fig. 6 Normalized total pile vs. load pile diameter (Case 3)

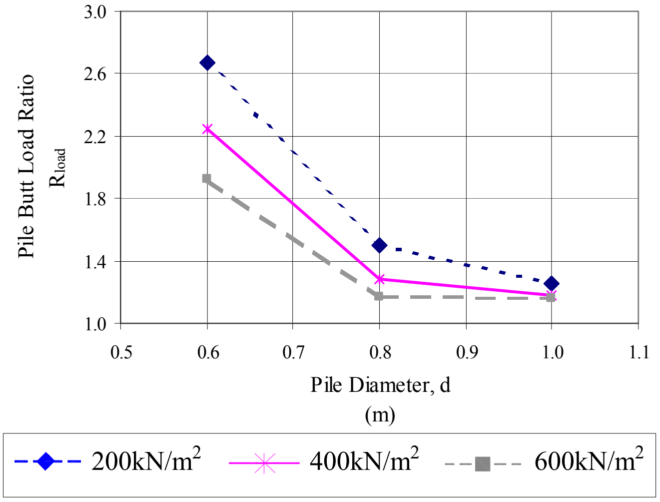

Fig. 7 Pile butt load ratio vs. pile diameter (Case 3)

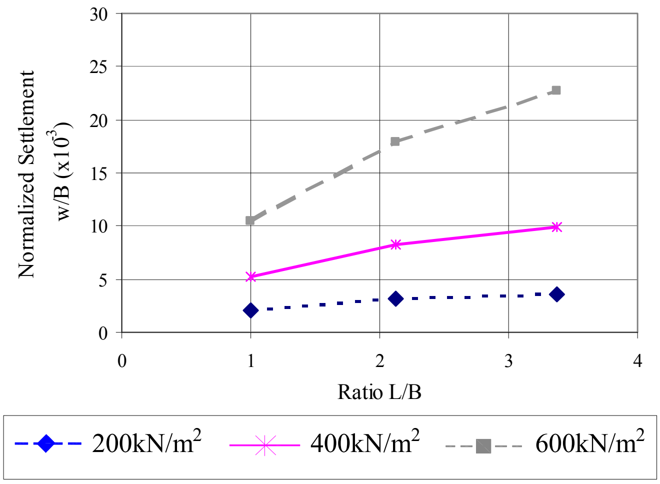

Fig. 8 Normalized settlement vs. raft dimension ratio (Case 4)

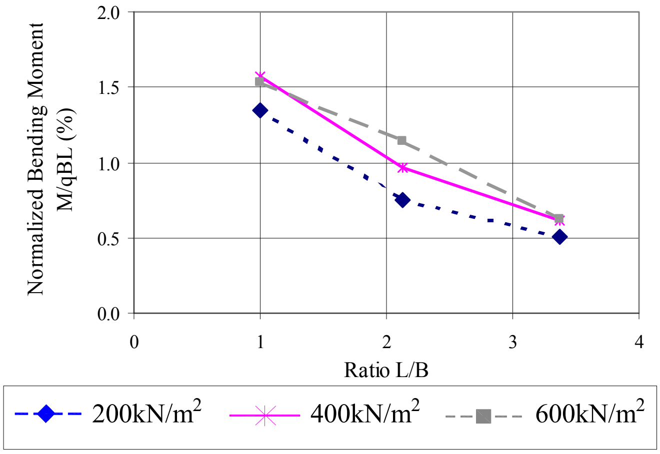

Fig. 9 Normalized bending moment vs. raft dimension ratio (Case 4)

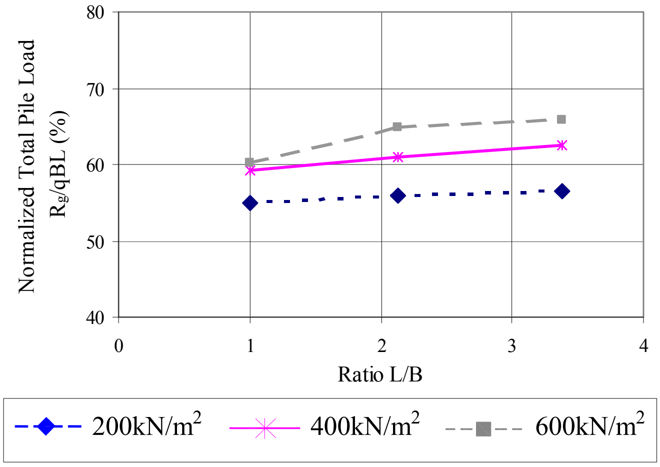

Fig. 10 Normalized total pile load vs. raft dimension ratio (Case 4)

Effect of Raft Thickness

In Fig. 11, the normalized settlement is found to decrease very slightly in the early stage and thereafter remain un-affected by the values of the raft thickness. However, the normalized differential settlement is found to reduce rather sharply as the raft thickness is increased. At 1.5m raft thickness these values are found to be approximately the same (see Fig. 12).

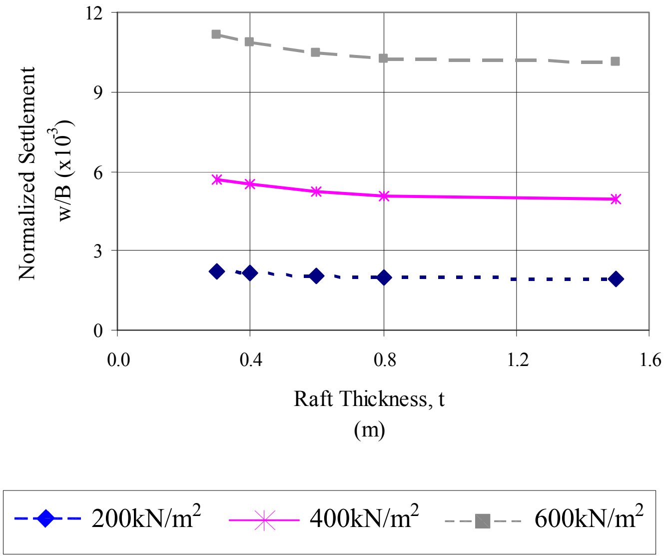

Fig. 11 Normalized settlement vs. raft thickness (Case 5)

The Effect of Raft-Soil Stiffness (K_{rs}) on Differential Settlements

The raft-soil stiffness is found to have a pronounced effect on the normalized differential settlement ($\left[\Delta w/B\right]x10^{-3}$). In summary (see Fig. 13) when the raft –soil stiffness is less than 0.8m, the $\left[\Delta w/B\right]x10^{-3}$ values seem to lie in a very wide band and generally reduce with the raft-soil stiffness for all the parametric studies conducted to study the influence of the pile spacing, the pile diameter, the raft thickness, the number of piles and the (L/B) values of the raft. However, when the raft-soil stiffness exceed a value of 0.8, the $\left[\Delta w/B\right]x10^{-3}$ reach an asymptotically constant value of 0.2

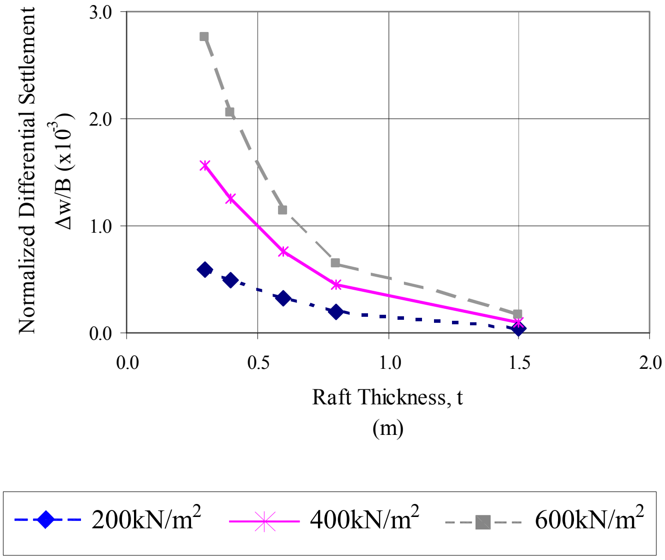

Fig. 12 Normalized differential settlement vs. raft thickness (Case 5)

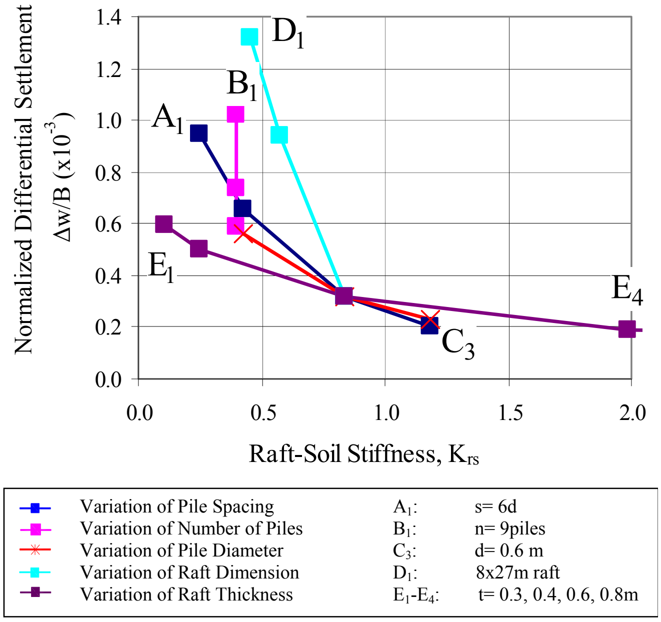

Fig. 13. Normalized differential settlement vs. raft-soil stiffness (q= 200 kN/m^2).

CONCLUDING REMARKS

In this paper, three dimensional finite element method under plane strain condition was applied to investigate the piled-raft performance under layered soil condition. The geotechnical parameters were obtained several in-situ tests. Based on the results in the parametric studies, the following concluding remarks can be given.

1. 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.
2. The raft thickness has a significant effect on the differential settlement. The increase of raft thickness reduces the differential settlement in the foundations. More generally, the raft-soil stiffness (K_{rs}) is shown to be the factors affecting the differential settlement.

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