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Analysis of Decomposed Components of Raft and Piles of Piled-Raft Foundation in Sandy Soil

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Abstract. Piled-raft foundation is a concept, which has received increasing recognition in recent years. Due to the complexity of piled-raft system, an accurate design relies on numerical modeling. This study is directed to developing a numerical model to analyze and identify the influence of parameters governing its performance. The developed model was based on the finite element technique and accounts for the interactions of pile-to-pile, pile-to-raft, raft-to-soil and pile-to-soil. The results produced by the present model were validated with the available data in the literature. The analysis in the present study of decomposed components of raft and piles of piled-raft foundation embedded in sands includes the interaction effects. For this purpose, finite element analysis was performed using PLAXIS 3D for various foundation and soil conditions. A square raft was used to model the piled-raft. The developed model has been used to conduct a sensitivity analysis of the governing parameters that include pile length, pile spacing and raft thickness. Furthermore, the effects of variations of soil modulus of elasticity, friction angle, dilatancy angle and unit weight have also been examined. From decomposed load–settlement curves obtained from the analysis, the load-carrying capacity of piles is mobilized earlier than that of the raft, showing higher load-carrying proportion. As settlement further increases, raft tends to carry greater load than the piles. Due to the interactions between raft and piles, the load-carrying capacities of the decomposed components are smaller than those of the un-piled raft and pile group of the same configuration. As pile spacing increases, the load proportion of piles becomes higher.

Keywords: Piled-raft; Decomposed components; Interaction factors; Finite Element Model; PLAXIS 3D.

1 Introduction

Pile raft foundation is a combination of shallow foundation (raft or roof) and deep foundation (pile group). In this type of foundation, the role of the raft is to provide the required bearing capacity, and the pile is mainly used as a settlement reducing agent, but it can also increase the bearing capacity. Over the past three decades, the use of piled raft foundations to support different types of structures has greatly increased. Compared with other alternatives, this trend of using piled raft foundations can be attributed to the potential economic advantages of such foundations. In addition, the piled raft foundation can meet the most important design requirements at a lower cost, which makes the piled raft foundation more preferred than other types of foundations. Moyes et al. (2005) reported that piled-raft foundations satisfy the require serviceability performance while providing cost savings estimated to about 30% compared with conventional piled foundations systems. The pile with both skin friction and base resistance, offers a high resistance to settlement. Hence a group of piles underneath the raft can significantly reduce the settlements in piled raft foundation. In general, the raft alone can provide the required bearing capacity but it cannot control the settlement. Therefore, the piles are crucial to reduce the settlement of the raft. Due to combining raft and piles in one system, piled-raft foundations are regarded as very complex systems. The complexity of this type of foundations is caused by the presence of many interaction factors involved in the system such as pile-to-pile, pile-to-raft, raft-to raft and pile-to-soil interactions. Earlier, due to the lack of analytical solutions for determining the load distribution between the pile and the pile cap (connecting the pile as a group), the pile cap was not considered to bear any load. The pile is considered to be able to withstand all loads, thus providing additional safety design. But in fact, the raft/pile cap also bears some loads. This leads to an uneconomical design, resulting in the need for additional piles. This type of foundation considers both piles and rafts as load-bearing members. This method greatly reduces the need for piles and makes the design very economical.

2 Numerical Modeling

In this section, the main characteristics of the finite element model (FEM) used here are summarized. All numerical analyses were performed using the commercial code PLAXIS 3D (2012 version).

2.1 Geometric Configuration

The piled raft modeled in the finite element (FE) analysis consists of a square raft with a width (Br) of 15 m and piles of different structures. The diameter (Bp) and length (Lp) of all piles are 0.6 m and 20 m, respectively. For the configuration of the piles, three different pile spacing’s (Sp) were considered: 3Bp, 5Bp, and 7Bp. For un-pilled rafts, the size of single piles and piles is the same as the size used for piled-rafts. Assuming that the pile, un-piled raft and pile raft are all linear elastic materials, their elastic modulus and Poisson's ratio are equal to 30 GPa and 0.15, respectively. Please note that the stiffness conditions of rafts and piles are very close to the stiffness conditions compared to soil. The grid model is shown in Figure 2. The areas selected for the geometry are all 120 x 120 meters in the horizontal direction, and consider the soil depth of 80 m (vertical) underground.

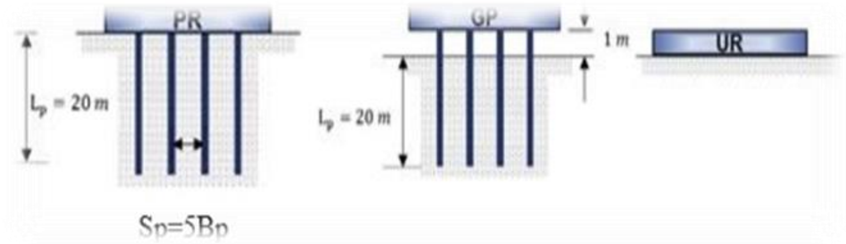

Fig.1. Types and configurations of foundations considered in FE analyses: piled raft, group pile and un-piled raft.

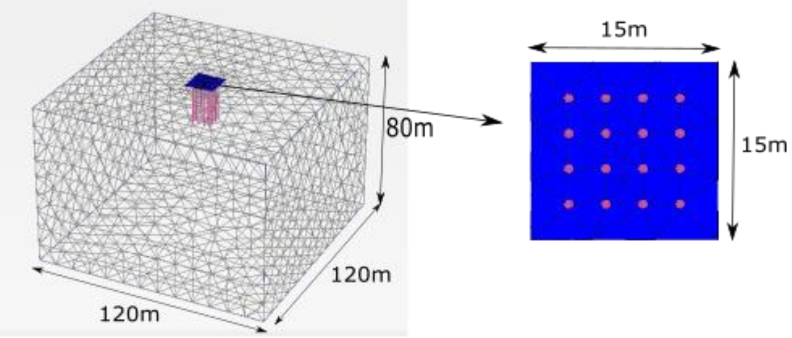

Fig.2. Finite element model for a piled-raft

3 Model Validation

The current numerical model was tested using a 2 m thick raft problem (size 15 m 15 m) with 16 piles with a diameter of 0.6 m and a pile length of 20 m (Lee et al. 2015). The purpose of this validation is to ensure accurate finite element modeling for this study. The material properties of soil, raft and piles are shown in Table 1. The results of this study are consistent with the results presented (Fig. 3).

Table 1. Material properties used in the validation

Material	Properties	Unit	Value
Soil	Young's modulus, E_s	kPa	37108
	Poisson's ratio, ν_s	-	0.25
	Unit weight, γ	kN/m	15.5
	Friction angle, ϕ	°	35
Raft	Young's modulus, E_r	GPa	30
	Poisson's ratio, ν_p	-	0.15
Pile	Young's modulus, E_p	GPa	30
	Poisson's ratio, ν_p	-	0.15

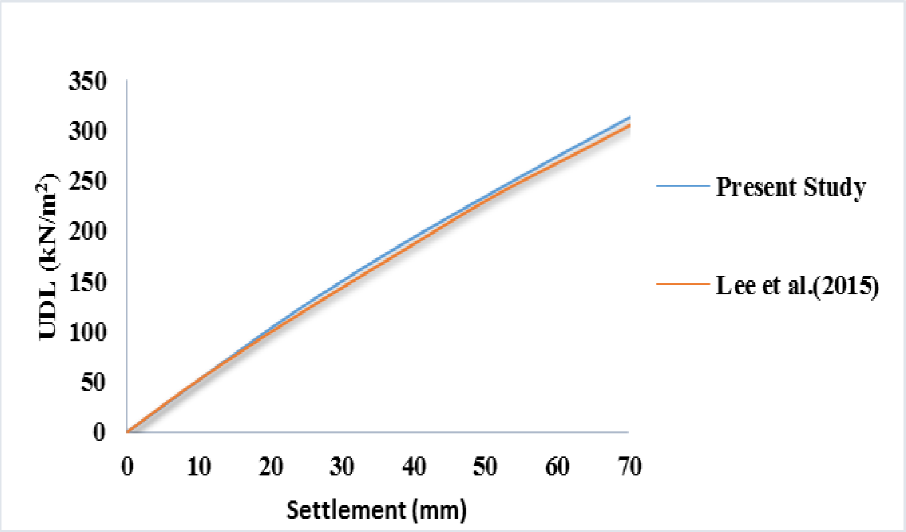

Fig.3. Comparison of load settlement curves of piled raft

4 Parametric Study

The settlement and load-sharing behavior of the piled-raft foundation have been studied by varying the raft thickness (t), raft embedment depth (m) and pile spacing (Sp). The different piled-raft configurations used in the study are listed in Table 2. The properties of the soil for different relative densities, study are summarized in Table 3.

Table 2. Foundation parameters considered in the study

Type	Size (m)	Pile configuration	Pile spacing(Sp)
Un-piled Raft (UR)	Br=15,t=0.5,1,2	-	-
	Bp=0.6	2X2 (4 piles)	3Bp,5Bp,7Bp
Group pile (GP)	Lp=20,15,10	3X3 (9 piles)	3Bp,5Bp,7Bp
	Br=15, t=0.5,1,2	4X4 (16 piles)	3Bp,5Bp,7Bp
	Bp=0.6	2X2 (4 piles)	3Bp,5Bp,7Bp
Piled raft (PR)	Lp=20,15,10	3X3 (9 piles)	3Bp,5Bp,7Bp
	Br=15, t=0.5,1,2	4X4 (16 piles)	3Bp,5Bp,7Bp

Table 3. Soil properties for different relative densities

Dr (%)	e	γ (kN/m^3)	E (kPa)	Φ^0
30	0.69	15.5	32,508	32
50	0.63	16.1	37,108	35
70	0.57	16.7	42,261	38

5 Results and Discussion

In this chapter, various interactions and pile behavior will be discussed. The vertical load pile raft with various pile configurations and spacing's is analyzed, and the results are discussed here. The load is converted into a uniformly distributed strip load, and the load is gradually applied to determine the level of settlement.

5.1 Load settlements curve

The pile-raft load-settlement curves of all pile configurations are studied. In the load-deformation curve, the raft and pile are decomposed to closely analyze their behavior, and how much each member increases as the load increases. According to finite element analysis, the load settlement curves of un-piled raft (UR), group pile (GP) and piling raft (PR). Figure 4 shows that the bearing capacity of piled rafts is higher than that of un-piled rafts and group piles, which is reasonable and can be expected to a certain extent. In addition, under a certain settlement level, the carrying capacity of GP is higher than that of UR. Above this upper limit, the carrying capacity of UR will be higher than that of GP. This results is also reasonable, considering that the load carrying capacity of the piles is mobilized earlier than that of the raft due to smaller settlement level. The load–settlement curve of piled rafts represents a combination of the load responses of both raft and piles and thus can be decomposed into raft (Rpr) and pile (Ppr) components, as plotted in Fig.5. The load-settlement curve of piled raft represents the load response combination of piled raft and pile body, so it can be decomposed into raft (Rpr) and pile (Ppr) components, as shown in Figure 5. As shown in Figure 5, the bearing capacity of the pile is earlier than that of the raft, showing a higher bearing rate. With the further increase of the settlement, the load carried by the raft continues to increase, and the ratio of the bearing capacity is higher than that of the pile. For other cases with different DR and Sp values, similar results and trends were observed. Due to the interaction between rafts and piles, the bearing capacity of piles and piles in piled rafts is different from un-piled rafts and group piles. Figure 6 compares the decomposed load-settlement curve of the raft (Rpr) and pile components (Ppr) with the load-settlement curve of the un-rafted raft (UR) and group pile (GP). For different DR and Sp. Figure 7 shows that under all soil and foundation conditions, Rpr's carrying capacity is less than UR. As the pile spacing increases, the load-bearing capacity of Rpr decreases, which indicates that the pile bears a higher proportion of the load.

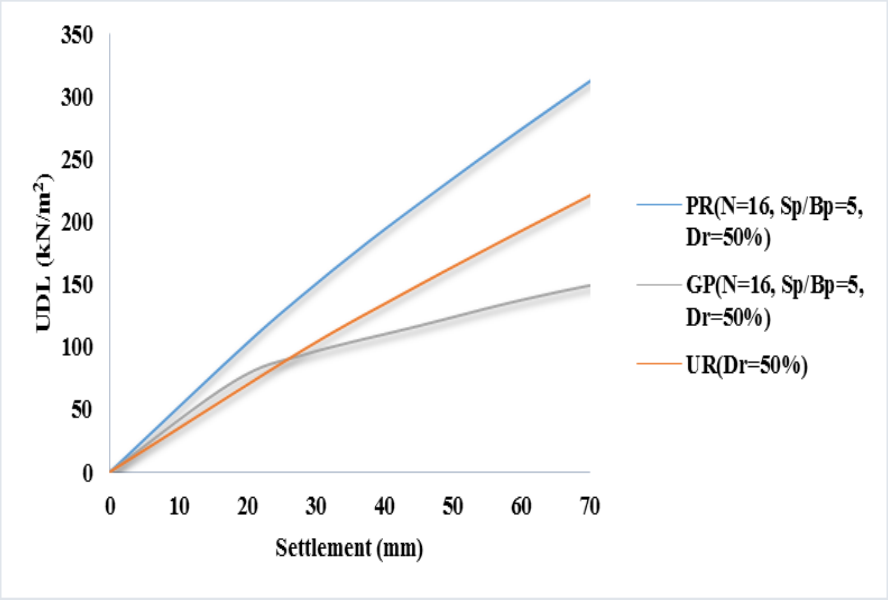

Fig.4. Comparison of load settlement curves of piled-raft, un-piled raft and group piles

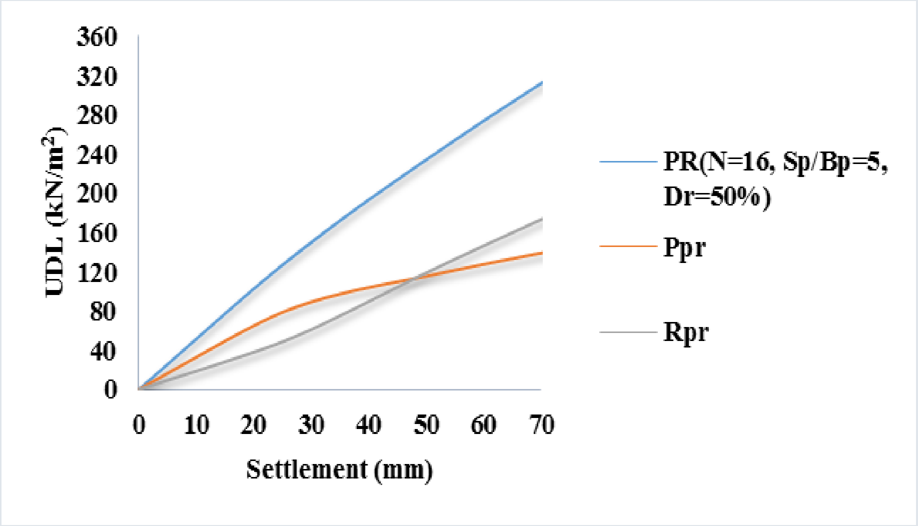

Fig.5. Comparison of load-settlement curves of decomposed foundation components of raft and pile

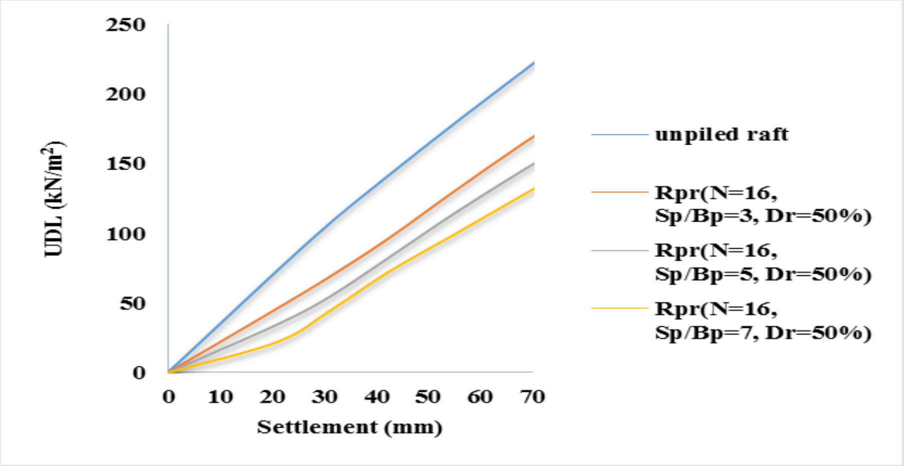

Fig.6. Decomposed load-settlement curves of Rpr compared with UR

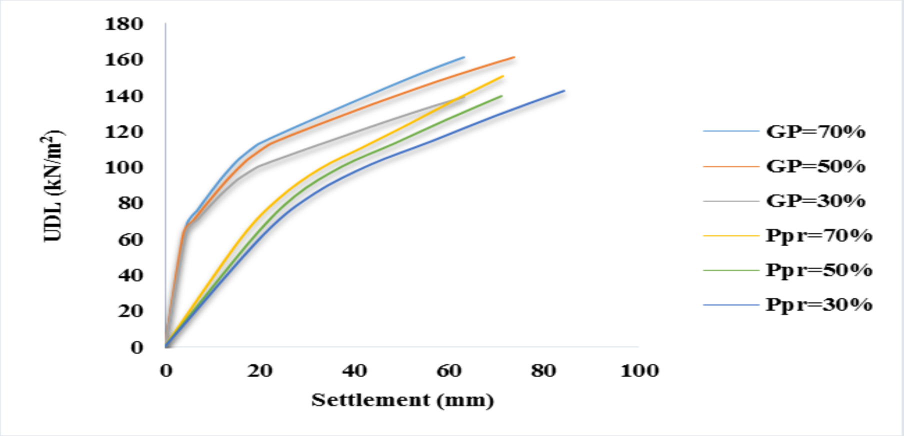

Fig.7. Decomposed load-settlement curves of Ppr compared with GP

5.2 Load Sharing ratio

The load-sharing ratio is determined by the load-settlement curve of the raft and pile decomposed by the finite element analysis method, and the load-sharing rate αp and its variation with settlement under different soil and foundation conditions are obtained. For different DR and Sp conditions, these results are shown in Figures 8 and 9, respectively, and plotted as a function of normalized sedimentation s/Br. Since the bearing capacity of small-diameter piles is earlier than that of large rafts, the αp value is initially high, and then decreases nonlinearly with the increase in settlement. In particular, a significant decrease in αp was observed in the initial settlement range until s / Br = 0.001. After this initial settlement range, the value of αp decreases continuously, while the observed decrease in αp is small and converges to certain values.

As shown in Figure 8, under different DR conditions, no significant changes in αp were observed, because changing the DR will affect the load response of the raft and pile, thereby compensating for the change in the load-bearing capacity of the raft and pile. However, the influence of the pile spacing (Sp) shown in Figure 9 is somewhat obvious.
As Pile spacing increases, the values of α_p increase, meaning that the pile load capacity tends to decrease as pile spacing decreases, due to higher pile group interactions between neighboring piles.

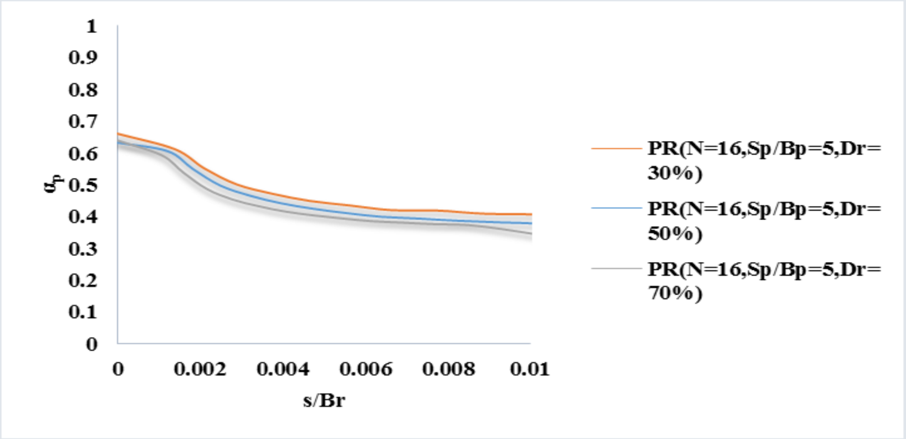

Fig.8. Variation of α_P with changes in relative density

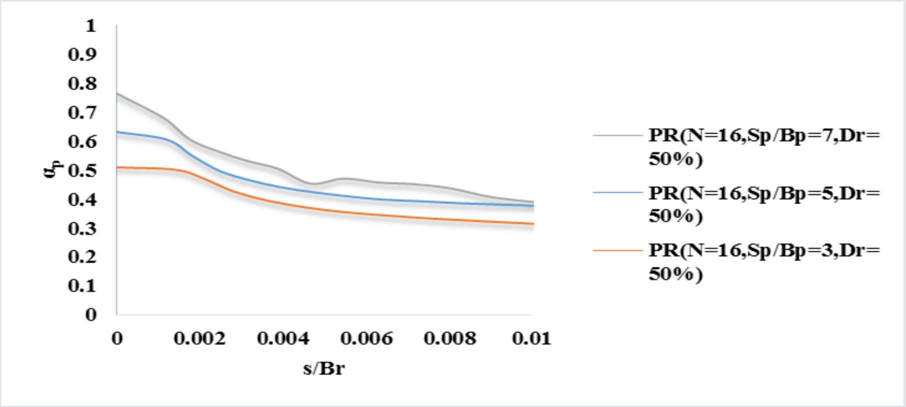

Fig.9. Variation of α_P with changes in pile spacing

5.3 Effect of Pile Length

The effect of pile length on the load settlement relationship of piled raft foundations supported by 2×2, 3×3 and 4×4 pile groups is shown in Fig. 10. It can be seen that before the yield point of the system, the stiffness of the pile-raft system increases as the pile length increases, and becomes larger as the number of piles supporting the raft increases. After the yield point, the stiffness of the pile-raft foundation is not affected by the change in pile length because it is equal to the stiffness of the individual raft. On the other hand, as the pile length increases before and after the yield point, the bearing capacity of the piled raft foundation increases significantly.

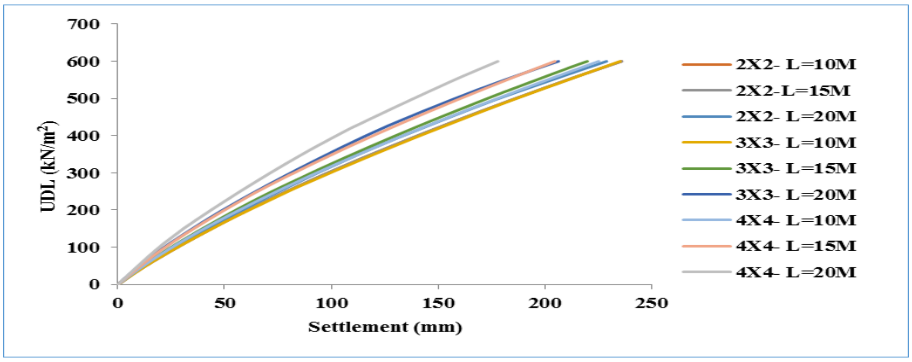

Fig.10. Effect of pile length on the load-settlement relationship of piled-raft supported by 2X2, 3X3 and 4X4 pile group

5.4 Effect of Pile Spacing

Pile spacing has no effect on the load-settlement relationship of a pile raft supported by a small number of piles. Figure 12. The results show that the pile spacing within the range of S = 3Bp, 5Bp and S = 7Bp has no effect on the load-settlement relationship of the piled raft supported by the 2×2 pile group. On the other hand, as can be seen from Figure 11, the spacing between the piles affects the load settlement curve of the piled raft foundation supported by the 3×3 and 4×4 pile groups, as the number of piles supporting the raft increases. When the number of piles supporting the raft increases and the pile spacing increases, better distribution of the piles under the raft will provide important enhancements to the performance of the pile-raft foundation.

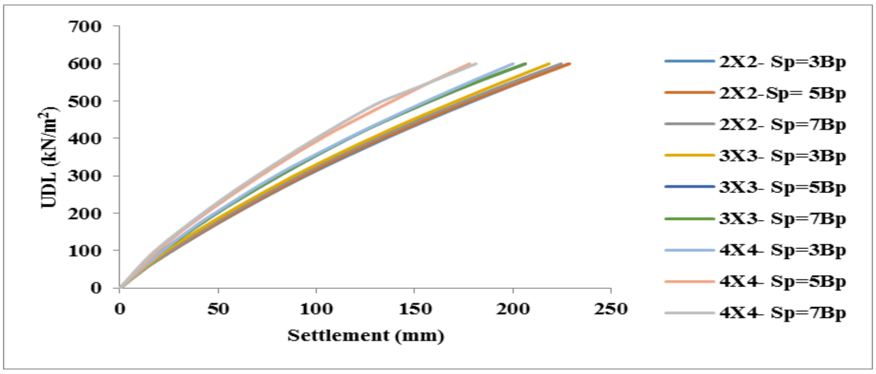

Fig.11. Effect of pile spacing on the load-settlement relationship of piled-raft supported by 2X2, 3X3 and 4X4 pile group

5.5 Effect of Raft Thickness

Within the range of raft thicknesses (0.5m, 1m and 2 m) considered in this study it was found that the raft thickness has no effect on the load settlement relationship of piled-raft foundations either at small settlement or at large settlement levels as shown in Fig.12.

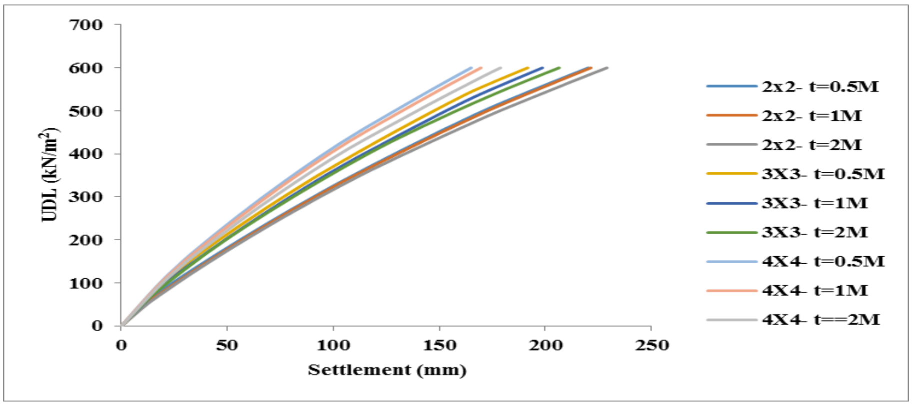

Fig.12. Effect of raft thickness on the load-settlement relationship of piled-raft supported by 2X2, 3X3 and 4X4 pile group

6 Settlement Contours for Different Pile Configuration

In Figure 13, 14 and 15, we can see how the soil settled under three different conditions. We can see that the soil underneath and the soil around the pile settled more than the rest of the soil in the area. Also, the part settled almost evenly, which indicates that the pile dominates the soil settlement in the pile raft box because the pile is harder than the pile raft and the soil.

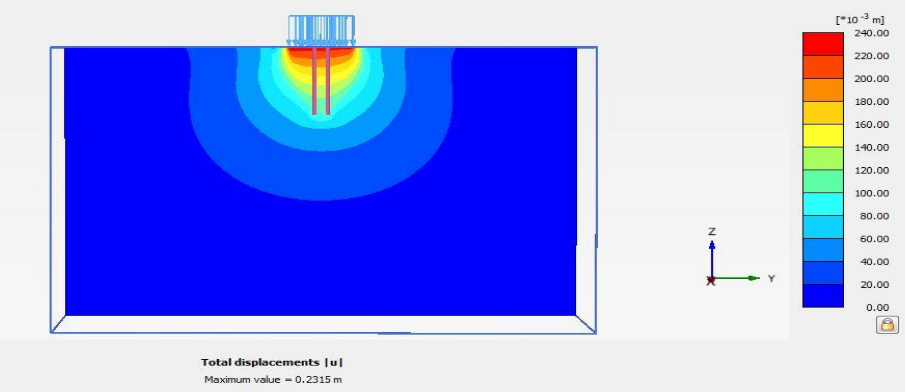

Fig.13. Settlement contours for 2X2 pile configuration

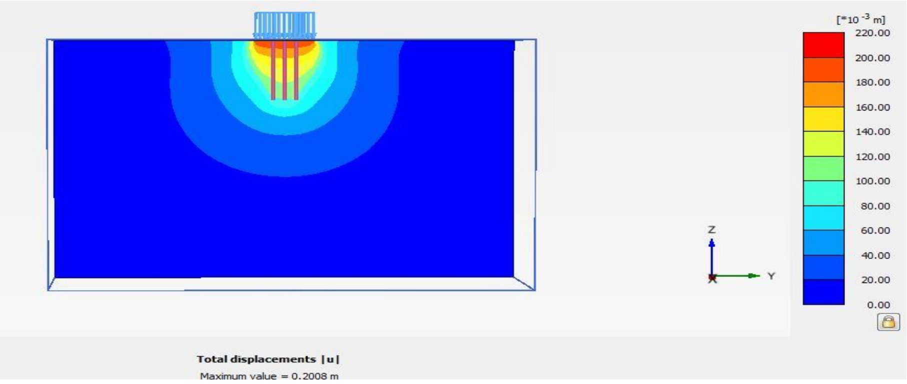

Fig.14. Settlement contours for 3X3 pile configuration

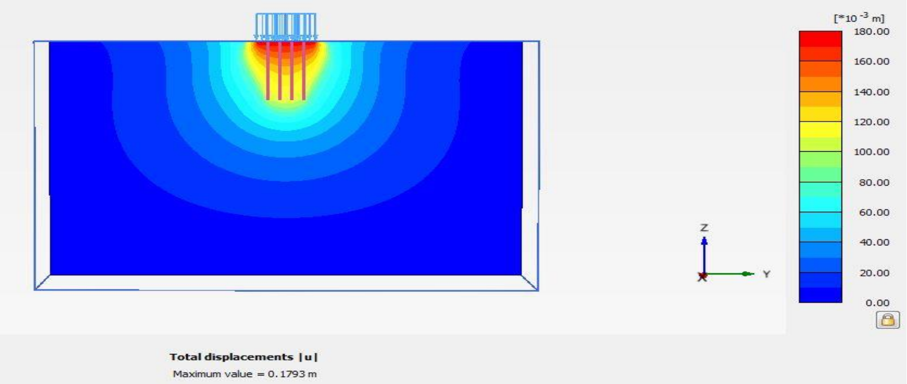

Fig.15. Settlement contours for 4X4 pile configuration

7 Conclusions

In this study, a finite element analysis was conducted to study the load sharing behavior of piled rafts buried in sand. The numerical model is used for parameter research to study the influence of some important parameters on the performance of piled raft foundations in small-scale and large-scale settlements. The effect of pile-raft interaction on load sharing behavior is the focus of research. Various foundation and soil conditions were considered in the analysis, including pile configuration, pile spacing and relative density. From the results reported in this article, the following conclusions are drawn:

1. From the decomposed load-settlement curve, the bearing capacity of the pile is earlier than the bearing capacity of the raft, which shows a higher bearing rate. As the settlement increases further, the raft tends to carry a greater load than a pile compared to a pile. Due to the interaction between rafts and piles, in piles of

rafts, the bearing capacity of each pile is smaller than that of un-piled rafts and group piles. As the pile spacing increases, the pile load ratio becomes higher.

2. The value of the load sharing ratio αp is initially high, and decreases nonlinearly as the settlement increases. A significant decrease in αp was observed in the initial settlement range until s/Br was equal to 0.001. The effect of pile spacing is very obvious, while the effect of DR is not obvious. As the pile spacing increases, the value of αp increases, which indicates that when the pile spacing decreases, the bearing capacity of the pile tends to decrease.

The results of this study showed that the influence of certain parameters on the load settlement relationship of the small settlement area is different from that of the large settlement area. The most important observations regarding the influence of the studied parameters on the load-settlement relationship of the piled raft foundation can be summarized as follows:

1. The raft thickness has no effect on the load-settlement relationship of the small-scale or large-scale settlement of the piled raft foundation.
2. The effect of pile spacing on the load-settlement relationship of the pile-raft foundation in small-scale settlements is negligible, and it has a significant effect on large settlements.
3. . Pile length has an important influence on the load-settlement relationship of pile-raft foundation in large and small pile foundations.

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