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Numerical Study of Piled Raft Foundation in Non-Homogeneous Soil Using Finite Element Method

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ABSTRACT

This paper analyzes a piled-raft foundation on non-homogeneous soils with variable layer depth percentages. The present work aims to perform a three-dimensional finite element analysis of a piled-raft foundation subjected to vertical load using the PLAXIS 3D software. Parametric analysis was carried out to determine the effect of soil type and initial layer thickness. The parametric study showed that increasing the relative density from 30 % to 80 % of the upper sand layer and the thickness of the first layer has led to an increase in the ultimate load and a decrease in the settlement of piled raft foundations for the cases of sand over weak soil. In clay over weak soil, the ultimate load of the piled raft foundation was increased, and the settlement decreased by increasing the clay cohesion of the upper layer from 20 kPa to 70 kPa. It was observed that the load shared by the raft was very effective when using dense sand in the upper layer. In the case of dense sand over stiff clay, the percent of load carried by the raft is (30-40) %. Although, for the case of stiff clay over soft clay, the load percentage was almost constant (16-20) %. While for other issues, the sharing load of raft foundation was close and had the same behavior, the load carried by raft is between (8-12) %.

Keywords: Raft foundation, Piles, Layered soil, Finite element method, PLAXIS 3D

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دراسة عددية للاساس الحصيري المستند على ركائز في تربة غير متجانسة باستخدام طريقة العناصر المحددة

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الخلاصة

يصف هذا البحث عملية تحليل اسس حصيرية مستندة على ركائز في تربة غير متجانسة و بنسب اعماق متغيرة. يهدف العمل الحالي إلى إجراء تحليل ثلاثي الأبعاد للعناصر المحدودة للاساس الحصيري المستند على الركائز المعرض الى حمل رأسي باستخدام برنامج *PLAXIS 3D*. تم الاخذ بنظر الاعتبار في التحليل البارامترى تأثير نوع التربة وسمك الطبقة الأولية. أظهرت الدراسة البارامترية أن زيادة الكثافة النسبية من 30٪ إلى 80٪ لطبقة الرمل العلوية وسمك الطبقة الأولى أدى إلى زيادة قابلية التحمل الكلية و انخفاض في هطول الاساس الحصيري المستند على الركائز في حالات الرمل فوق التربة الضعيفة. في الطين فوق التربة الضعيفة ، تمت زيادة قابلية التحمل الكلية للاساس الحصيري المستند على الركائز ، وتناقص الهطول بزيادة تماسك الطين للطبقة العليا من 20 *kPa* إلى 70 *KPa*. لوحظ أن الحمل المنتقل الى الاساس الحصيري فعالة للغاية عند استخدام الرمل الكثيف في الطبقة العليا. في حالة الرمل الكثيف فوق الطين الصلب ، تكون نسبة الحمل المنتقل الى الاساس الحصيري (30–40)٪. بالرغم من ذلك ، بالنسبة للطين الصلب على الطين الطري ، كانت نسبة الحمل المنتقل الى الاساس الحصيري ثابتة (16–20)٪. بينما في حالات أخرى ، كان الحمل المنتقل الى الاساس الحصيري متقاربًا وله نفس السلوك ، فإن الحمل المنتقل الى الاساس الحصيري تتراوح بين (8–12)٪.

الكلمات المفتاحية: أساس حصيري ، ركائز ، التربة ذات الطبقات ، طريقة العناصر المحدودة ،PLAXIS 3D

1. INTRODUCTION

This work concerns the piled-raft foundation, which combines the advantages of raft and pile foundations. Piles accompany the raft to divide the total load acting, which is shared in part by the raft and in part by the piles **(Kaur et al., 2021; Ragheb et al., 2015)**. Piled raft foundations limit settlement by using pile support, with piles providing the majority of the stiffness at serviceability loads and the raft element giving additional capacity at the ultimate load **(Basile, 2015; Clancy and Randolph, 1993)**.

The numerical technique is a reliable and appropriate way to research the behavior of piled rafts because of how complex the interaction between the soil and the structure is. The finite element method is one of the numerical techniques that can represent the complex geometry of piled-raft foundations **(Comodromos et al., 2009; Ferchat and Houhou, 2021)**. This process is a reliable tool. It is a great option for doing foundation analysis due to its versatility in modeling and meshing and its power to integrate field conditions effectively **(Sri and Tjandra, 2015; Tank and Dave, 2011)**. A conclusion that can be drawn from earlier research is that the behavior of the foundation can be assessed using methods like the finite element method and a variety of software programs **(Ta and Small, 1996; Hussein et al., 2020)**. Some of the studies revealed that different pile sizes, both in terms of their diameters and lengths, have been considered to impact the effectiveness of the underlying structure.

(Wulandari and Tjandra, 2015; Nguyen et al., 2013) did a study on an Unpiled and Piled raft foundation on sandy soil using the PLAXIS program; they have varying raft thicknesses, but this does not significantly impact the foundation's load-carrying performance.
The distance between piles, according to **(Patil et al., 2015; Kaavya et al., 2020)** has a significant impact on both the maximum and differential settlement. **(Poulos, 2001; De and Mandolini, 2006)** used PLAXIS to do a 3D investigation of the piled raft foundation of the Incheon skyscraper in South Korea. The foundation was tested horizontally and vertically, and the results were compared to those of the pile group foundation system. They reasoned that the piled raft would be secure in tall buildings. According to **(Vu et al., 2014; Mali and Singh, 2018),** in instances where the former cannot meet design requirements, piled rafts are a more cost-effective alternative to foundations than unpiled rafts. As a result, they suggested that a limited number of piles added to the foundation to increase its ultimate load capacity would enhance the foundation's performance in terms of settlement **(Poulos et al., 2011)**. They have determined from their research that the piled raft foundation is a viable option for any upcoming projects **(Prakoso and Kulhawy, 2001; Abdel-Azim et al., 2020)**. The present work aims to develop a numerical model capable of predicting the load carried by piles and the load carried by the raft using the three-dimensional models in the PLAXIS-3D V20 platform **(Huang et al., 2011; Ukritchon al., 2016)**. All these models have been studied for homogenous and non-homogeneous soil (layered soils) with different layers' depths **(Karim et al., 2013; Nguyen et al., 2021)**.

2. SOIL MODEL AND MATERIAL PROPERTIES

Soil is a complicated material that acts differently when it is first loaded, unloaded, and reloaded **(Banerjee et al., 2020; Hor al., 2016)**. It acts in a nonlinear way well before it breaks, and its stiffness changes with stress. Because they are the most commonly used models, the elastic-perfectly plastic models based on Mohr-coulomb (MC) are used. The piled raft foundation was analyzed on two soil layers, which comprised the soil body. The first layer is 4.5, 6.75, and 9 m below the ground's surface. At the same time, the second layer was dug down deeper than the required depth for stress distribution (5 d) **(Yamashita et al., 2011; Lee al., 2015)**, making the total depth 13.5 m. In this study, the groundwater surface was not taken into account. Two soil types were used: clay with different cohesions and sand with different densities. The various parameters of the four types of soil used in this analysis are given in **Table 1**. The pile and raft were modeled as linear elastic materials. The finite element parameters of the piled raft foundation used in the numerical analysis are given in **Table 2.**

3. GEOMETRY MODEL

This study employed two foundation analysis models (piled raft foundation and unpiled raft foundation). In the two models, the dimensions of the raft foundation were (2.1 x 2.1) meters, the thickness of the raft was 0.8 meters, and the length of the pile was 12 meters; in the case of an unpiled raft foundation, the Pile cap was raised 0.5 meters above the ground, and the diameter of the pile was fixed at 0.3 meters in all instances. The constant distance between heaps is 4 d (1.2 meters from center to center).

Table 1. Soil properties that are used in the numerical analysis.

Property	Loose Sand	Dense Sand	Soft Clay	Stiff Clay
Gs	2.65	2.65	2.71	2.71
relative density, Dr, %	30	80	-----	-----
Unit weight, kN/m^3	15.4	17.3	15.4	19.2
The angle of internal friction,	28	40	5	6
Undrained shear strength during test, c	0.2	0.2	20	70
Initial void ratio, eo	0.720	0.532	0.760	0.411
Compression index, cc	----	----	0.400	0.128
Swelling index, cr	----	----	0.004	0.017
Poisson's ratio, v	0.30	0.30	0.40	0.35
Young's modulus, E, kPa	14880	60000	4000	10000
Material behavior	Drained	Drained	Undrained (A)	Undrained (A)

Table 2. Material properties of the concrete foundation

Parameter	Value	Unit
Poisson's ratio, v	0.2	-
Young's modulus, E,	23500	MPa
Unit weight of concrete	24.0	kN/m^3

This analysis aims to determine how much the different layers affect the work and efficiency of the substrate. This analysis used two soil layers to find out how they affected the load-carrying capacity with settlement behavior. **Fig. 1** shows the pile raft geometry, and **Fig. 2** shows the unpiled raft geometry.

4. MESH PROPERTIES

A finer finite element mesh is used where high-stress concentrations are required, while medium mesh used for other geometry sections may not need a fine mesh. The local coarseness factor, defined for each geometric object, is linked to local refinement. For most geometry entities, the coarseness factor is set to 0.5 **(Park et al., 2016; Deb and Pal, 2019)**. To model the soil, a 10-node tetrahedral element is used. As shown in Fig. 3, Mesh-derived soil generated 11421 elements and 19756 nodes for four piles of soft clay over stiff clay.

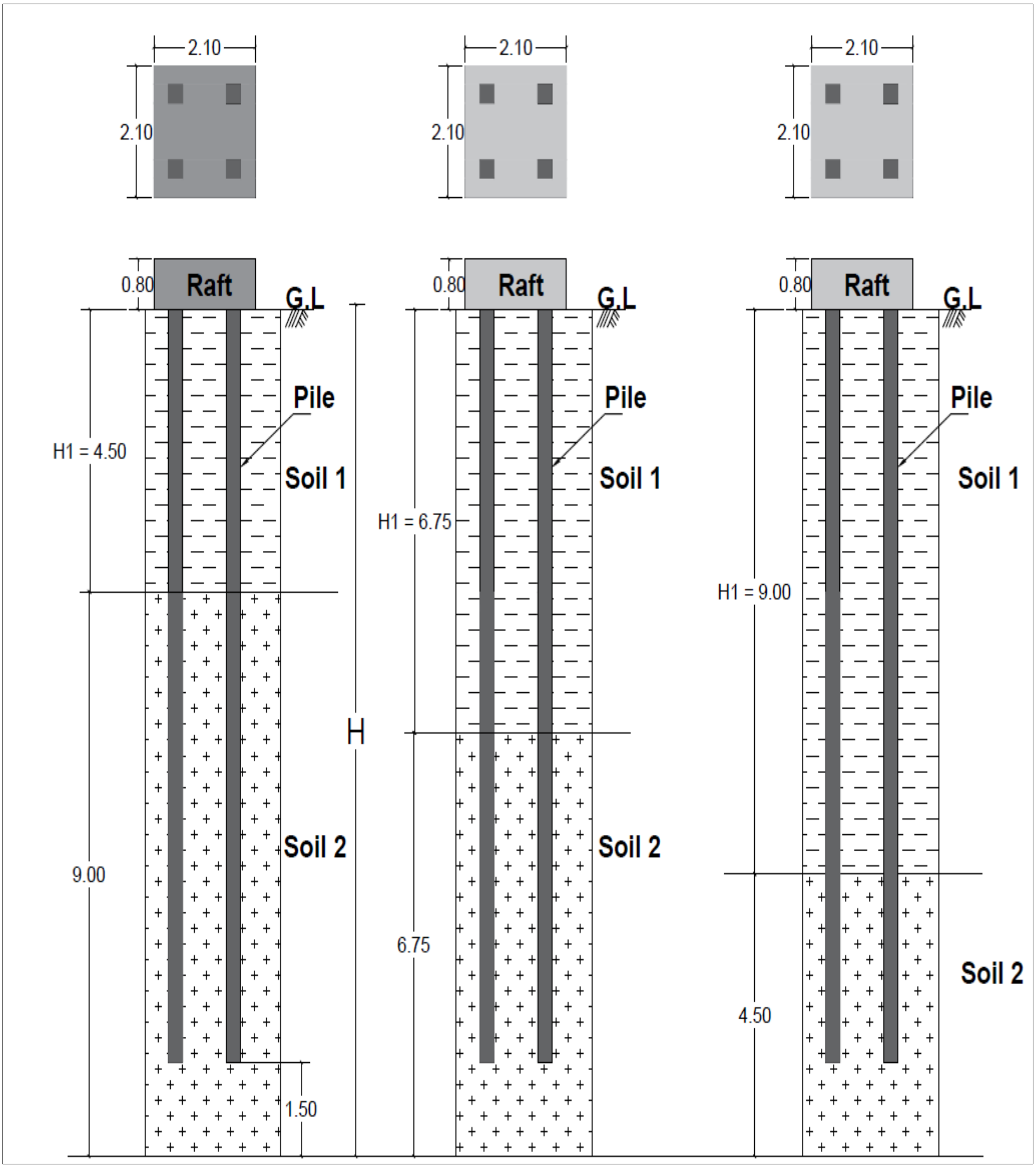

Figure 1. Piled-raft foundation model geometry.

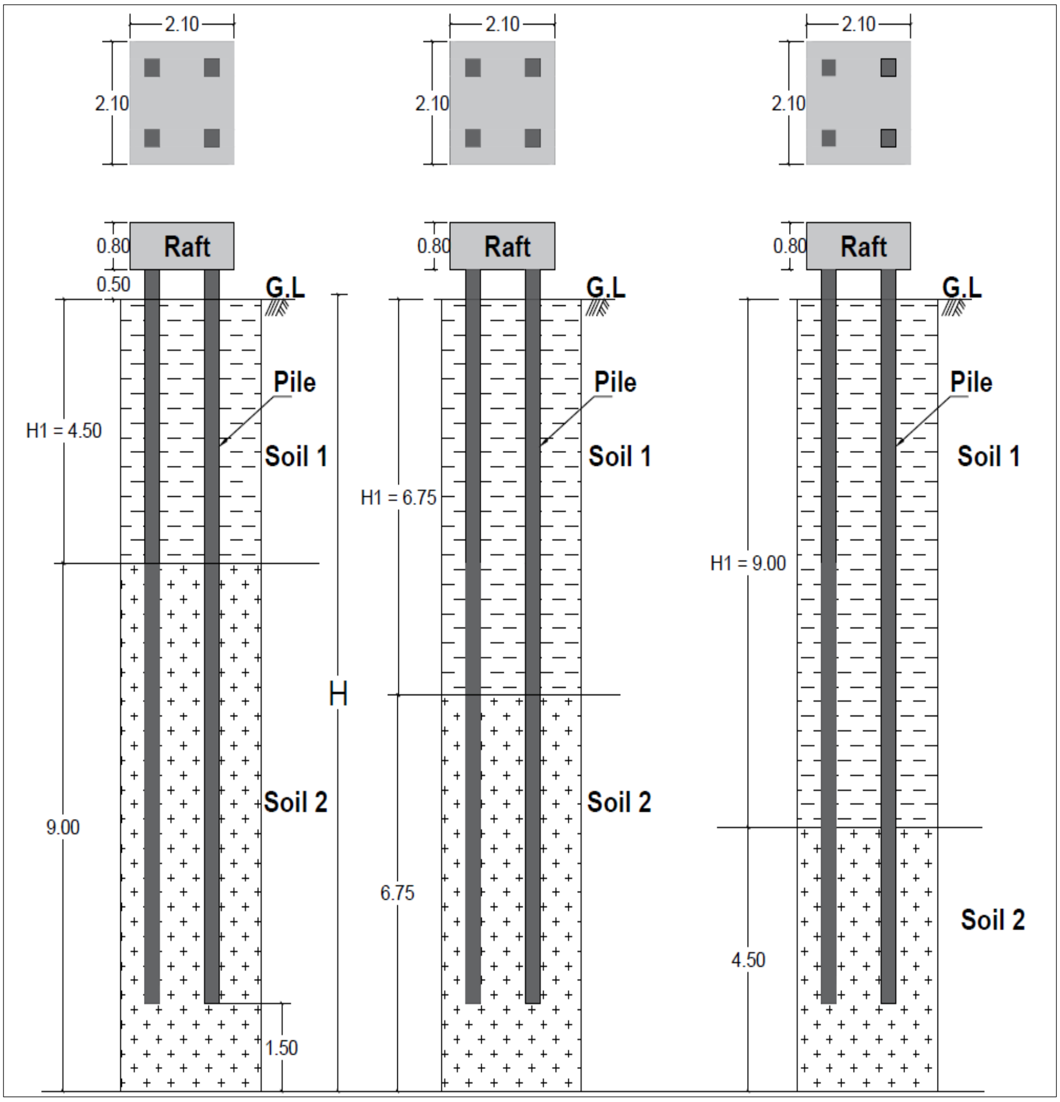

Figure 2. Unpiled-raft foundation model geometry.

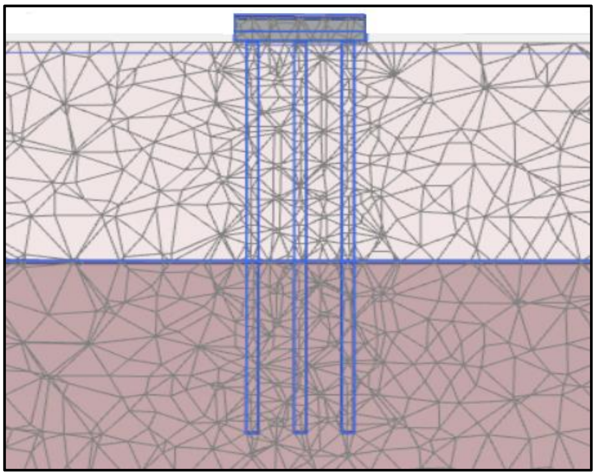

Figure 3. Cross-section of a typical mesh of pile and raft in Plaxis-3D model.

5. RESULTS AND DISCUSSION

5.1 Effect of Soil Layer Type

The displacement control method was used to examine the load-settlement curve. This method specifies the load needed to achieve the desired displacement **(Azizkandi and Baziar, 2018; Halder and Manna, 2020)**. The ultimate load capacity in foundation design is often calculated using a settlement equal to 10% of the pile diameter or raft width (**Sinha and Hanna, 2017; Hussien et al., 2016**). Loading continued throughout the model testing until the raft settlement reached 50 mm. The load-settlement curve of the PLAXIS 3D-analyzed piled raft foundation is shown in **Figs. 4 to 9**. **Table 3** displays the value of the ultimate load of piled-raft and unpiled-raft foundations with different soil types and layer depths as determined by the load-settlement curve from **Figs. 4 to 9** using the (0.1D) technique.

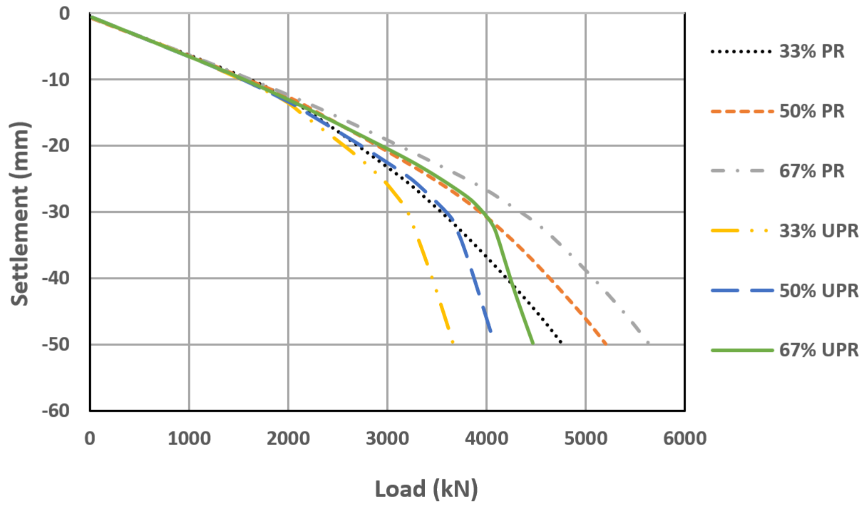

Figure 4. Load settlement variation of piled and unpiled raft foundation for stiff clay over loose sand.

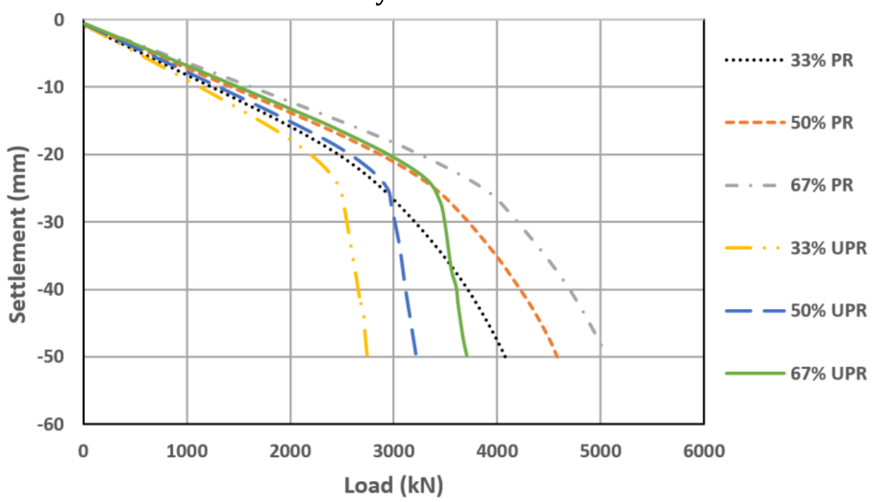

Figure 5. Load settlement variation of piled and unpiled raft foundation for stiff clay over soft clay.

Table 3. Value of ultimate load with different soil type and depth.

Type Soil	System	Depth Ratio of First Layer, H1/H (%)	Ultimate Load (kN)
Soil Case No-1 Stiff Clay over Loose Sand	Piled Raft	33	3550
		50	3950
		67	4340
	Unpiled Raft	33	3200
		50	3600
		67	3960
Soil Case No-2 Stiff Clay over Soft Clay	Piled Raft	33	3200
		50	3720
		67	4190
	Unpiled Raft	33	2550
		50	3010
		67	3490
Soil Case No-3 Loose Sand over Stiff Clay	Piled Raft	33	4064
		50	3710
		67	3300
	Unpiled Raft	33	3560
		50	3120
		67	2765
Soil Case No-4 Soft Clay over Stiff Clay	Piled Raft	33	4034
		50	3600
		67	3015
	Unpiled Raft	33	3643
		50	3205
		67	2790
Soil Case No-5 Dense Sand over Stiff Clay	Piled Raft	33	5670
		50	5850
		67	5705
	Unpiled Raft	33	3895
		50	3435
		67	3180
Soil Case No-6 Stiff Clay over Dense Sand	Piled Raft	33	6175
		50	6440
		67	6850
	Unpiled Raft	33	5350
		50	5630
		67	6035

The layer distribution in the models causes this impact to show up. The rate of improvement increases as the upper layer, which is located further away from the surface than the lower layer, has a larger bearing capacity than the lower layer. When the layer close to the surface is weak and has a limited bearing capacity, the improvement rate is lowered and almost tangible.

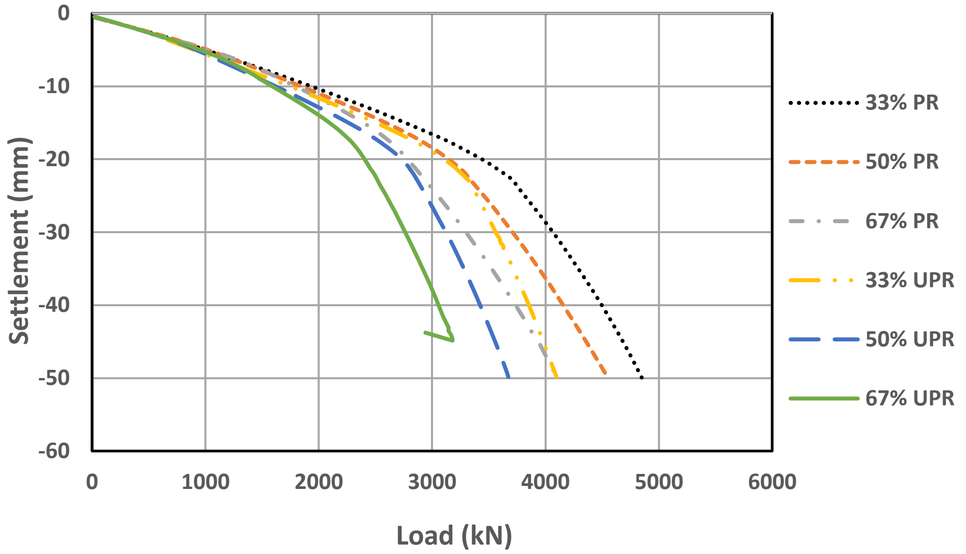

Figure 6. Load settlement curve of the piled and unpiled raft foundation for loose sand over stiff clay.

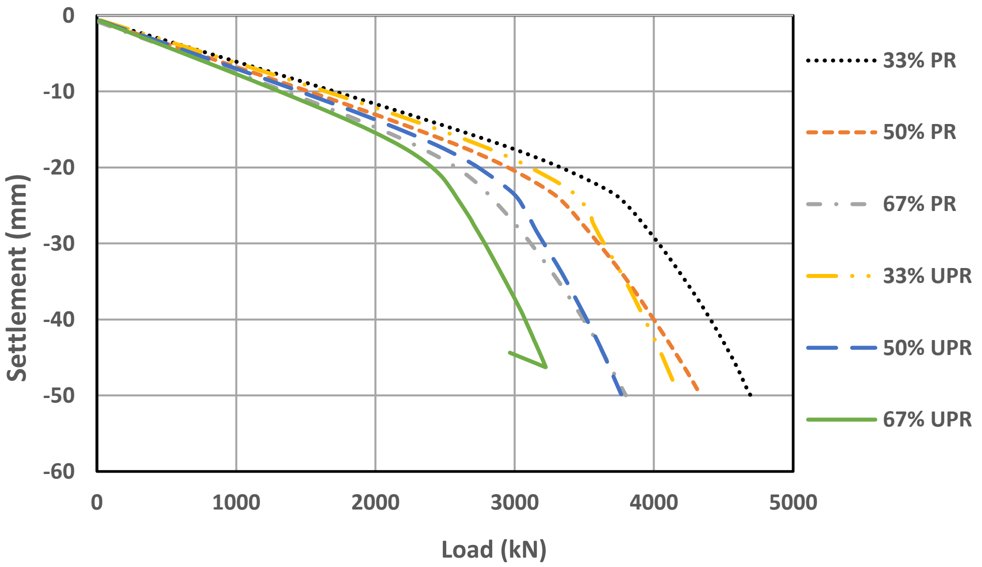

Figure 7. Load settlement curve of the piled and unpiled raft foundation for Soft Clay over Stiff Clay.

In the case of a strong layer over a weak layer, such as stiff clay over loose sand or stiff clay over soft clay, the improvement results for piled raft foundation load carrying capacity rose by (9.5-11) % and (20-25.5) %, respectively, as illustrated in **Figs. 4 and 5** for load settlement curves. For the weak layer on top of the strong layer, the load carrying capacity of piled raft foundation will decrease, the same as it did for soft clay on top of stiff clay and loose sand on top of stiff clay, as illustrated in **Fig. 6 and 7** for the load settlement curve.

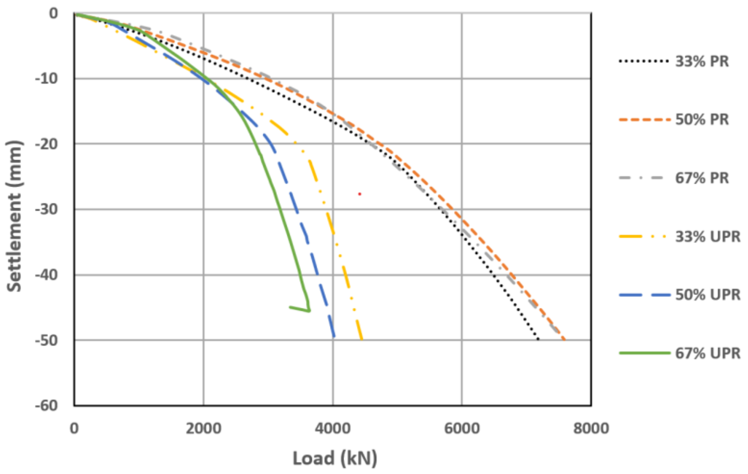

Figure 8. Load settlement curve of the piled and unpiled raft foundation for dense sand over stiff clay.

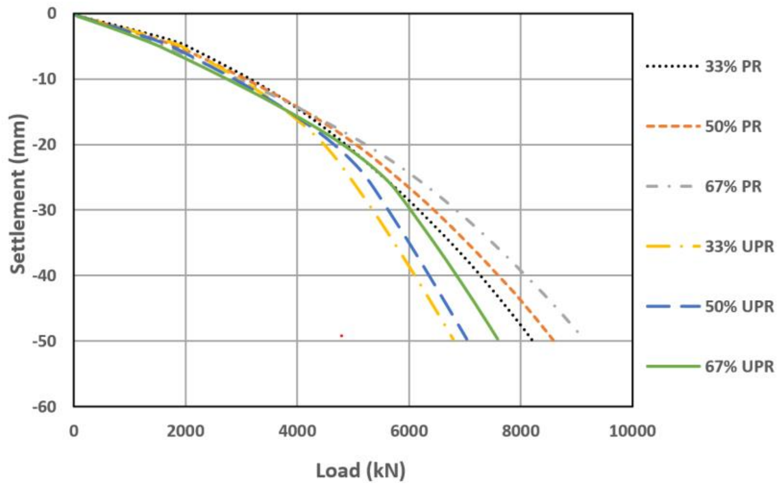

Figure 9. Load settlement curve of the piled and unpiled raft foundation for Stiff clay over dense sand.

As shown in **Fig.s 8 and 9**, the improved results are clear if the two layers on which the model is based have a high bearing capacity, like when stiff clay is on top of dense sand or when dense sand is on top of stiff clay. This improvement is due to the closer proximity of the bearing layer to the surface. As a result, the shallow foundations will function more effectively, as they will bear most of the applied loads.

5.2 Effect Of Layering Depth

The models used to study the six cases show that when the layers have a high load-bearing capacity and are deep, the value of the piled-raft foundation's load-carrying capacity has improved and grown. In the case of stiff clay on top of loose sand, the upper layer can hold more weight than the lower layer. As shown in **Fig.10**, the ultimate load increased with depth by 11.2 % when the thickness of the first layer was raised to 50% of the total depth and by 22.5 % when the thickness of the first layer was raised from 33% to 67% of the total depth.

As a result, it was seen that a direct proportion appears with the increase in the depth of the layer near the surface.
When a weak layer was put on top of a strong layer, the final load dropped by 8.7% and 18.8 % when the depth went from 33% to 50% and from 33% to 67%, respectively. This is the opposite of what happens when loose sand is put on top of stiff clay. When the top layer is strong, and the bottom layer is weak, the effect is that the final level will rise as the depth increases. This is clear in the case of hard clay over soft clay. However, when the weak layer is on top of the strong layer, the effect of depth is the opposite. We can see that the improvement is less the deeper the weak layer is. This is because depth has a negative effect on the model as a whole, and we can see this when loose sand is on top of stiff clay.

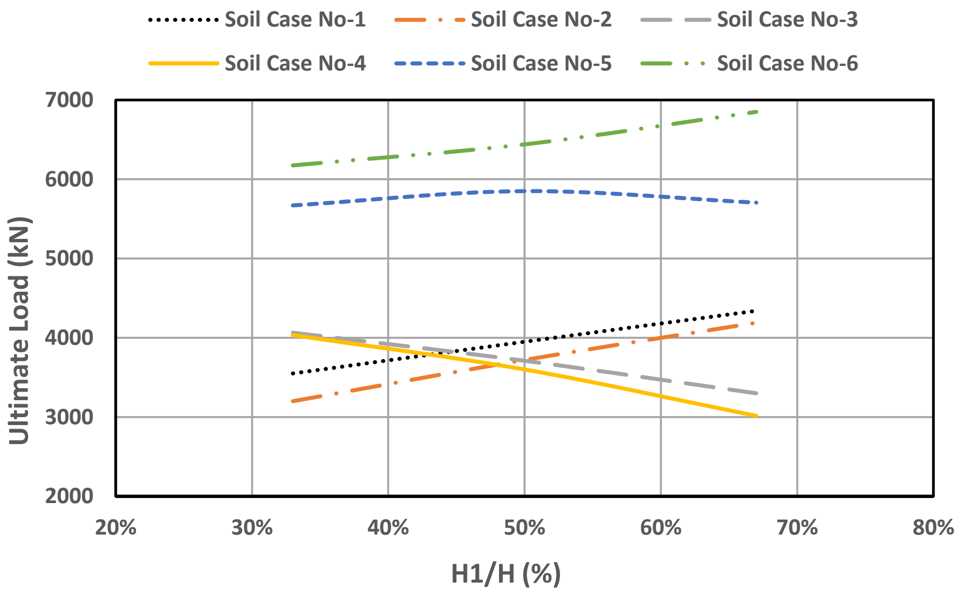

Figure 10. Depth ratio (H_1/H), ultimate load curve for different soils.

6. CONCLUSIONS

In this study, a parametric analysis of piled raft foundations on two layers of soil has been conducted. The analysis of this parametric study has focused on two main topics. The first was to study the influence of non-homogeneous soil on the load settlement relation of a piled raft foundation. The second one has focused on investigating the effect of (the height of the first layer and type of soil, including clay with different cohesions and sand with different relative densities) on the sharing load of piled raft foundation. The parametric study showed that increasing the relative density from 30 % to 80 % of the upper sand layer, the thickness of the first layer, and the number of piles has led to an increase in the ultimate load and a decrease in the settlement of piled raft foundations for the cases of sand over weak soil. In clay over weak soil, the ultimate load of the piled raft foundation was increased, and the settlement decreased by increasing the clay cohesion of the upper layer from 20 kPa to 70 kPa. From the obtained results, the following points can be concluded as follows.

- The ultimate load of (piled-raft or unpiled-raft) foundations increases by increasing the depth ratio (the thickness of the upper soil layer / the total thickness of the soil layers) if the upper layer has a high bearing capacity.

- The ultimate load of (piled-raft or unpiled-raft) foundations decreases by increasing the depth ratio if the upper layer has a weak bearing capacity.
- If the upper layer is stiff clay, the ultimate load of the piled raft foundation was increased as the thickness of the first layer increased (D1/H) by 10% when the lower layer was weak and by 5% when the lower layer was strong.
- If the lower layer is stiff clay, the ultimate load of the piled raft foundation was decreased as the thickness of the first layer increased (D1/H) by 12% when the upper layer was weak.
- For stiff clay or soft clay of one layer, the sharing mechanism is the same, and the sharing `load of the raft foundation is between (10% - 20%).

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