CIVED
Journal of Civil Engineering and Vocational Education

EISSN: 2622-6774
Vol 11 No.2 June 2024
http://cived.ppj.unp.ac.id/index.php/CIVED

The Influence of Raft Thickness on Settlement and Bending Moment of Pile Raft Foundation in Clay Soil

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Received 14th April 2024; Revision 21th May 2024; Accepted 29th June 2024

ABSTRACT

Geotechnical engineers often deal with shallow foundation designs to support relatively simple building structures. However, as the demand for construction grows over time, there is a need for larger and more complex building structures. This is closely related to the weight of the building that will be supported by the foundation as a substructure. Therefore, the development of knowledge about other types of foundations to support the structural loads above them is highly necessary. Pile foundations are a fairly good solution for supporting larger structural loads that cause significant settlement. In designing pile foundations as a structure, there will certainly be raft to combine each pile foundation into a unified group. Raft are often designed only for combining each pile, but in reality, It also provides additional influence on the foundation system besides just serving as pile heads and load distributors to the foundation system. The study will investigate the influence of raft thickness on settlement that occurs in piled raft foundations. The raft thickness varies, namely 0.25m; 0.40m; 0.80m; 1.50m; and 3.00m. The piled raft foundation will be modeled and analyzed using finite element program. This study shows that the raft thickness affects the differential settlement that occurs in the piled raft foundation system. The results indicate that the differential settlement can be addressed by designing the raft thickness.

Keywords: *Piled Raft Foundation; Raft Thickness; Differential Settlement; Finite Element Method.*

INTRODUCTION

Geotechnical engineers often deal with the design of shallow foundations to support simple building structures. As time progressed, the construction demand has increased and required more complex building structures. This is closely related to the weight of the buildings that will be supported by the foundation as the substructure. Therefore, it is essential to develop knowledge about other types of foundations to support the load of the structure. The determination of the type of foundation is a very important initial step in designing a high-rise building construction [1].

Pile foundations are a suitable solution for supporting larger structural loads that cause significant settlement [2]. In designing pile foundations, there will certainly be a pile cap or raft to integrate each pile foundation into a unified group. The conventional design concept of this pile foundation system assumes that loads are directly received by the piles, ignoring the stiffness of the raft.

Science continues to develop, and the use of pile foundation systems has been optimized by considering the stiffness of the raft in load transfer, now known as the piled raft foundation system. The piled raft foundation system was first introduced by Poulos and Davis in 1980. Poulos [3] in his writings explains the concept of the piled raft foundation system. The piled raft foundation system was consisted of three supporting elements: piles, a raft, and the soil. The most favorable condition for applying the piled raft foundation system is when a raft foundation can provide adequate bearing capacity, but the average settlement or differential settlement still exceeds the allowable limits. In such conditions, piles can be used to reduce the settlement, with the main objective of increasing the stiffness of the foundation system rather than increasing the bearing capacity. The suitable soil layers for the piled raft foundation system are stiff clay, dense sand layers, and soil layers where soft clay or loose sand is not beneath the supporting layer.

When analyzing the piled raft foundation system, the load distribution on the foundation system must be calculated. This interaction is quite complex and depends heavily on the stiffness of the superstructure, the stiffness of the raft, the stiffness of the piles, the stiffness of the soil, fill, excavation, and water pressure. Randolph [4] has defined three different design philosophies using the piled raft foundation system. The first is the conventional approach where piles are designed as a group of piles supporting the entire load. The second is creep piling under working loads, where piles are designed to start creeping, generally at 70% - 80% of the ultimate bearing capacity. In this condition, a number of piles are useful for reducing settlement. The third is differential settlement control, where piles are installed under the raft where the largest settlement occurs. This makes the settling area of the raft stiffer, significantly reducing differential settlement.

From the piled raft foundation system concept, it can be understood that using the piled raft foundation system concept is also very effective in reducing differential settlement. In many cases, using only a raft foundation often leaves the problem of excessive settlement, leading to building failure. Therefore, piles are needed under the raft to reduce the settlement. Systematic placement of piles under the raft can reduce the settlement caused by structural loads.

Balakumar et al. [5] in their research conducted a study by modeling a piled raft foundation system on sandy soil to obtain load-settlement and settlement reduction curves. This small-scale modeling was reviewed under two conditions: unpiled raft and piled raft. The results showed that the piled raft foundation system is quite effective in reducing the settlement.

El-Garhy et al. [6] also conducted experiments on the piled raft foundation system by applying loads to the foundation system. This foundation was on sandy soil. The results of this experiment provided the knowledge that the stiffness of the raft significantly affects differential settlement but does not have a significant impact on average settlement and load distribution between the raft and the piles.

Oh et al. [7] analyzed a case study of using the piled raft foundation system on sandy soil in Surfers Paradise of Australia. In this case study, the raft thickness was varied to observe its effect on raft stiffness. The study results showed that the settlement pattern of the piled raft foundation system was bowl-shaped except for foundation systems with raft thicknesses of 0.25m and 0.4m. Rafts with thicknesses of 0.25m and 0.4m showed a more obtrusive settlement pattern.

From the previous literature reviews studied, this study will model the piled raft foundation by applying loads on the foundation system to see how raft thickness affects average settlement, differential settlement, and bending moment in a piled raft foundation system on stiff clay soil. As in previous research, this piled raft foundation modeling system has been carried out on a piled raft foundation on sandy soil. The modeling will be done using finite element software. The piled raft foundation system will be modeled on stiff clay soil.

METHOD

Essentially, the research methodology to be carried out is a numerical study using finite element software. The foundation systems modeled in the finite element software are the raft foundation system and the piled raft foundation system. The steps of foundation system modeling and analysis, leading to the conclusion, can be seen in Figure 1 below.

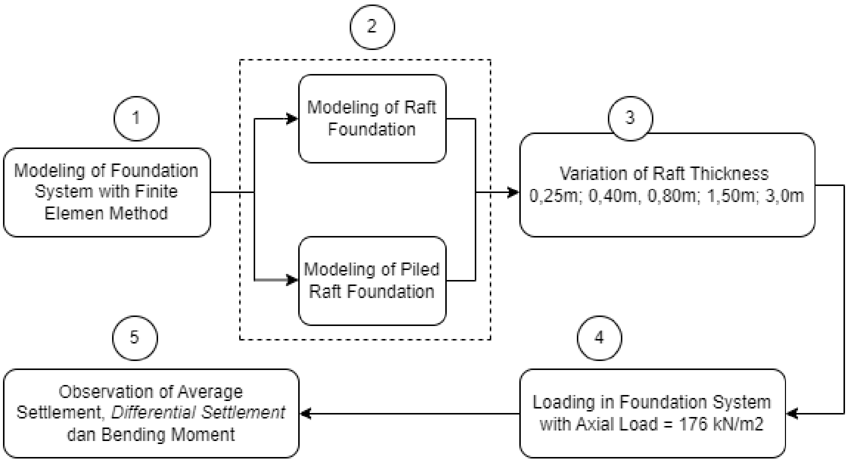


Figure 1. Methodology of Foundation System Modeling with Finite Element Method

For the raft foundation, the specified raft size is 16 x 16 m² with raft thicknesses of 0.25m, 0.4m, 0.8m, 1.5m, and 3.0m. The raft foundation system will be loaded axially with 176 kN/m². For the piled raft foundation system, the raft dimensions are the same, 16 x 16 m². The modeling of the piled raft foundation will vary the raft thickness. The raft thickness variations in the piled raft foundation are the same as those in the raft foundation system: 0.25m, 0.4m, 0.8m, 1.5m, and 3.0m. The difference from the raft foundation system is that the piled raft foundation will include piles with a diameter of 1.0m and a pile length of 25m. These variations in raft thickness are intended to observe the effect of raft thickness on load transfer mechanisms and settlement in the foundation system. The piled raft foundation system will be subjected to the same load as the raft foundation system, 176 kN/m², to determine the extent to which the piles function as settlement reducers. Detailed properties of the raft foundation system and the piled raft foundation system can be seen in Table 1 below.

Table 1. Properties of Raft Foundation and Piled Raft Foundation as The Input of Finite Element Method

Foundation System	**Properties of Foundation System**		
Raft Foundation System	Raft Dimension	16x16	m^2
	Area of Raft	256	m^2
	Raft Thickness	0,25	m
	Axial Load	176	kN/m^2
Piled Raft Foundation System	Raft Dimension	16x16	m^2

	Area of Raft	256	m^2
	Diameter of Pile	1,0	m
	Length of Pile	25	m
	Spacing between Piles	3,5d	-
	Axial Load	176	kN/m^2
	Variation of Raft Thickness	0,25	m
		0,40	m
		0,80	m
		1,50	m
		3,00	m

The raft foundation system and the piled raft foundation system are modeled on a homogeneous stiff clay layer. The soil material modeling in this study uses the hardening soil model. Modeling with hardening soil is used because it is an advanced model for simulating the behavior of both soft and hard soils. The Plaxis Manual [8] also explains that soil material modeling using hardening soil is superior to linear elastic and Mohr-Coulomb material modeling. For foundation system analysis cases, the use of hardening soil can adequately represent soil behavior. This is also evidenced by research conducted by Elsawwaf M et al.[9], which showed that the load-settlement curves from numerical modeling using hardening soil material modeling closely matched the load-settlement curves from experimental laboratory tests. The soil parameters for this study can be seen in Table 2 below.

Table 2. Artificial Soil Parameter (Medium Stiff Clay N-SPT = 6)

Soil Type	**Medium Stiff Clay N_{ave} = 6**	
OCR	*Normally Consolidated*	
Material Model	Hardening Soil	
Material Type	Undrained	
Soil Parameter	Value	Unit
γ_{dry}	16	kN/m^3
γ_{wet}	18	kN/m^3
$E_{50\ ref}$	7000	kN/m^2
$E_{oed\ ref}$	7000	kN/m^2
E_{ur}	21000	kN/m^2
Power, m	0,9	-
Poisson ratio, υ	0,33	-
Cohesion, c	40	kN/m^2
Friction Angle, φ	0	deg
Dilatation, ψ	0	deg
R_{inter}	1,0	-
Permeability, k	0,0008	m/days

It is known that the average N-SPT of the clay soil is 6 blows/30cm. In Look's book [10], it was explained that clay soil with an N-SPT value in the range of 5–10 blows/30cm falls into the category of clay with medium stiff consistency. Table 3 below shows the correlation between N-SPT values and the consistency of clay soil.

Table 3. Correlation between N-SPT and Soil Consistency

Soil Type	**N-SPT (blows/30cm)**	**Soil Consistency**
Clay	≤ 2	Very Soft
	2 – 5	Soft
	5 – 10	Medium Stiff
	10 – 20	Stiff
	20 – 40	Very Stiff
	> 40	Hard

Furthermore, Look [10] also provides the range of soil bulk density values based on the type and consistency of the soil material. The detailed values for the dry bulk density (γ_{dry}) and the saturated bulk density (γ_{sat}) can be seen in Table 4 below. For stiff clay soil, the dry bulk density (γ_{dry}) is 14 kN/m³ and the saturated bulk density (γ_{sat}) is 18 kN/m³.

Table 4. The Value of Bulk Density

Soil Type	**Soil Consistency**	**Bulk Density**	
		Dry	**Saturated**
Sand	Very Loose	14	17
	Loose	15	18
	Medium Dense	17	20
	Dense	19	21
	Very Dense	21	22
Clay	Soft – Organic	8	14
	Soft – Non Organic	12	16
	Stiff	16	18
	Hard	18	20

Another soil parameter in the hardening soil model is the soil shear strength. The shear strength parameters in hardening soil are cohesion and the internal friction angle. These two shear strength parameters are obtained from the results of triaxial tests: UU (Unconsolidated Undrained), CU (Consolidated Undrained), or CD (Consolidated Drained). However, if triaxial testing is not conducted, soil parameters can be obtained by correlating field test results, such as N-SPT values. Terzaghi & Peck (1967) conducted numerous experiments and established a relationship between N-SPT values and soil shear strength.

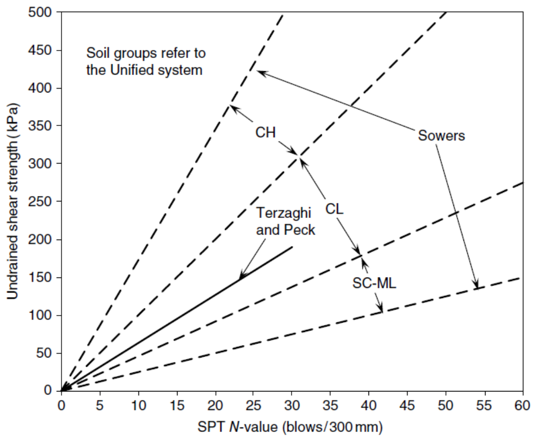


Figure 2. Correlation between SPT Value and Undrained Shear Strength, C_u [11]

From Figure 2, the undrained shear strength, c_u can be determined. With the N-SPT value of the clay soil being 6 blows/30cm, the undrained soil cohesion value is approximately 40 kPa. For normally consolidated clay, the internal friction angle is 0°.

Next, the stiffness parameters of the soil in the hardening soil model need to be determined. Modeling soil using the hardening soil model accounts for the effect of soil stiffness changes (hardening) along with changes in stress and deformation. Essentially, this model considers that the soil will experience increased stiffness or hardness as the stress applied to it increases. In the modeling, the soil stiffness input parameters in the hardening soil model are divided into three stiffness values: $E_{50\ ref}$, $E_{oed\ ref}$, and E_{ur}. $E_{50\ ref}$ in the hardening soil parameter is the elastic modulus at an effective stress value of 50% of its reference stress, which is 50 kPa if $p_{ref} = 100$ kPa. $E_{oed\ ref}$ is the soil's elastic modulus at effective stress related to its loading history (overconsolidation ratio value). E_{ur} is the soil's elastic modulus for unloading and reloading conditions. Practically, E_{50ref} has the same value as $E_{oed\ ref}$ if m = 1 (clay soil). For E_{ur}, the value is 3 x $E_{50\ ref}$.

Once all the necessary soil parameters for the modeling have been determined, the next step is to perform the modeling using finite element software. Figure 3 below shows the geometry model for analyzing the raft foundation system and the piled raft foundation system. The pile geometry in Figure 3 must be deactivated when analyzing the raft foundation system.

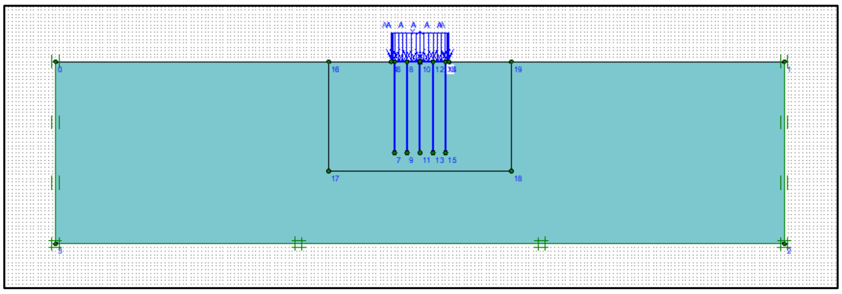


Figure 3. Geometry Model of Foundation System

The next step in modeling the raft foundation system and the piled raft foundation system is to mesh the geometry model. Figure 4 shows the mesh result for the raft foundation system model. Figure 5 shows the mesh result for the piled raft foundation system model. The mesh around the foundation system area is made more dense to improve the accuracy and precision of the analysis, allowing for a better representation of the more complex geometry and resulting in more accurate analysis outcomes.

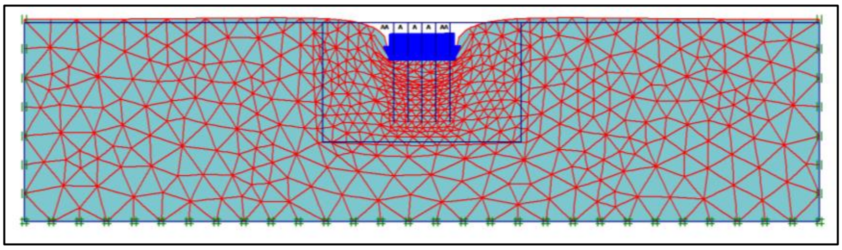


Figure 4. Generate Mesh of Raft Foundation Modeling

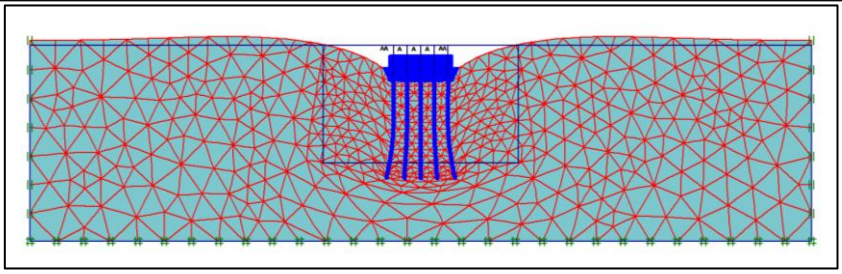


Figure 5. Generate Mesh of Piled Raft Foundation Modeling

Each foundation system is subjected to the same vertical load of 176 kN/m². The loaded foundation system will undergo deformation. Figures 6 and 7 below show the distribution of vertical deformation that occurs in the raft foundation system and the piled raft foundation system.

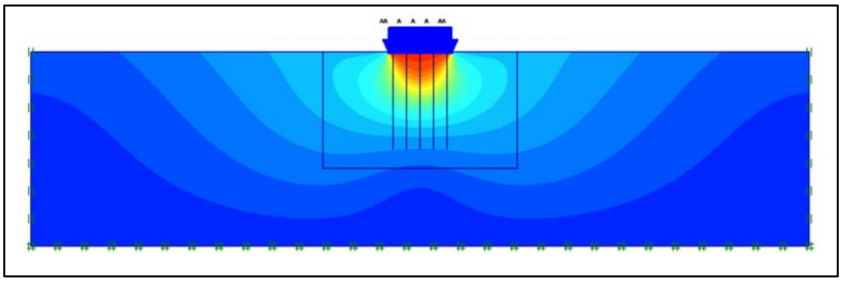


Figure 6. Distribution of Vertical Displacement in Raft Foundation

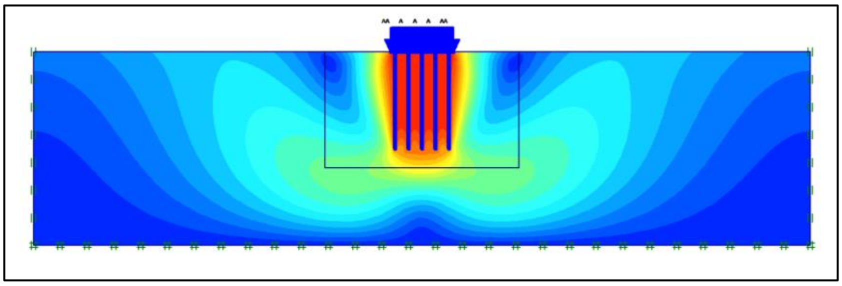


Figure 7. Distribution of Vertical Displacement in Piled Raft Foundation

RESULTS AND DISCUSSION

A load of 176 kN/m² was loaded on the raft foundation system with each raft thickness of 0.25m, 0.40m, 0.80m, 1.00m, and 3.00m. The results showed an average settlement of 0.55m for the raft foundation system with a thickness of 0.25m and an average settlement of 0.45m for the raft foundation system with a thickness of 3.00m. Then, the raft foundation system was enhanced by adding piles under the raft foundation. The result of modeling showed a reduction in the average settlement. The piled raft foundation system with a raft thickness of 0.25m showed a maximum settlement of approximately 0.10m. Similarly, the piled raft foundation system with a raft thickness of 3.00m showed a maximum settlement of approximately 0.09m. Detailed modeling results can be seen in Figure 8 below.

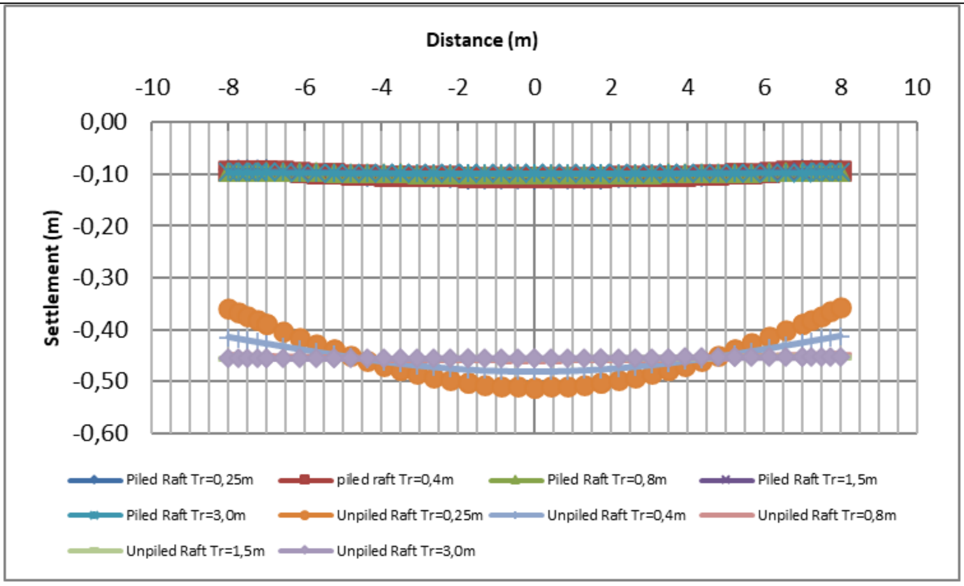


Figure 8. The Result of Foundation System (Average Settlement)

Figure 8 shows that the raft foundation system subjected to a load of 176 kN/m² with varying raft thicknesses does not demonstrate a reduction in the average settlement of the foundation system. However, the average settlement decreases when piles are added under the raft foundation. This indicates that piles can function as settlement reducers. Although the raft thickness does not significantly impact reducing the average settlement, it can minimize differential settlement in the foundation system. Figure 8 shows that the raft foundation system with a thickness of 0.25m has a substantial differential settlement, approximately 0.35m on the right and left sides of the foundation and around 0.55m in the center, resulting in a differential settlement of 0.20m. Figure 8 also shows that the thicker the raft, the smaller the differential settlement. The differential settlement in the raft foundation system with a thickness of 3.00m is only around 0.01m, with a settlement of 0.46m on the right and left sides of the foundation and 0.45m in the center of the foundation.

The effect of raft thickness on differential settlement is also examined in the piled raft foundation system. Figure 9 shows similar behavior between the raft foundation system and the piled raft foundation system. The piled raft foundation system with greater raft thickness will reduce the differential settlement in the piled raft foundation system. This result indicates that raft thickness can reduce differential settlement in a foundation system. The results of the raft thickness variation modeling in the piled raft foundation system can be seen in Figure 9 below.

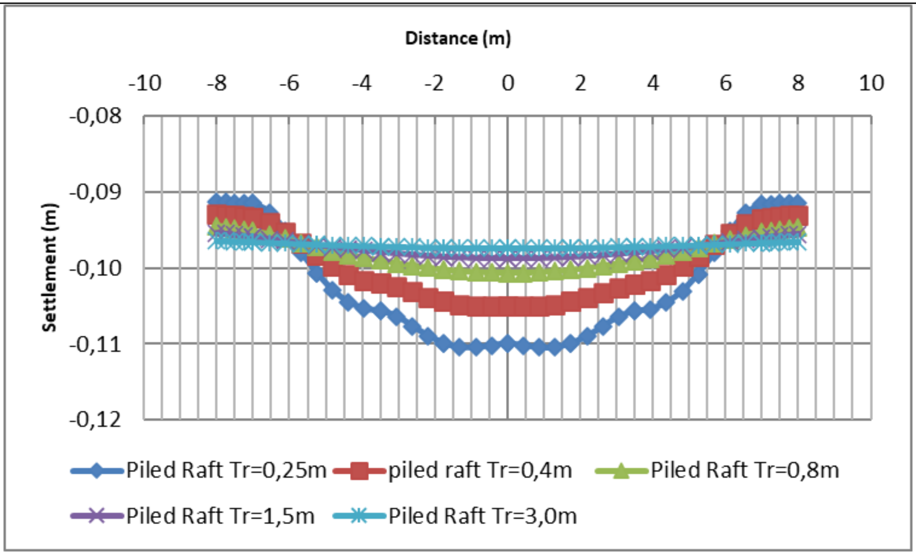


Figure 9. The Result of Foundation System (Differential Settlement)

However, when designing the thickness of the raft, it is also important to consider that the raft thickness can affect the bending moment that occurs when the foundation system is loaded. The thicker the raft is designed, the greater the bending moment that will occur in the raft.

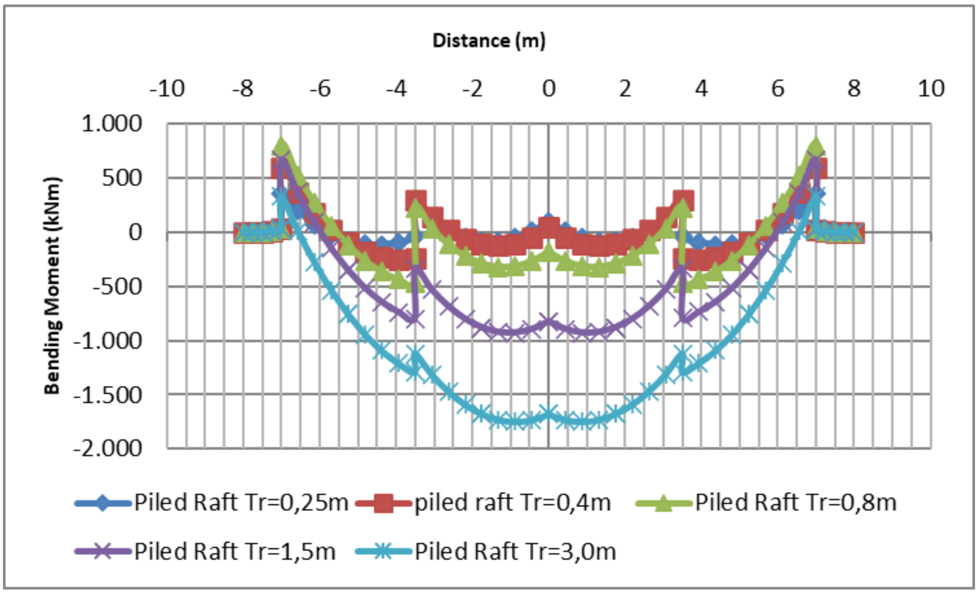
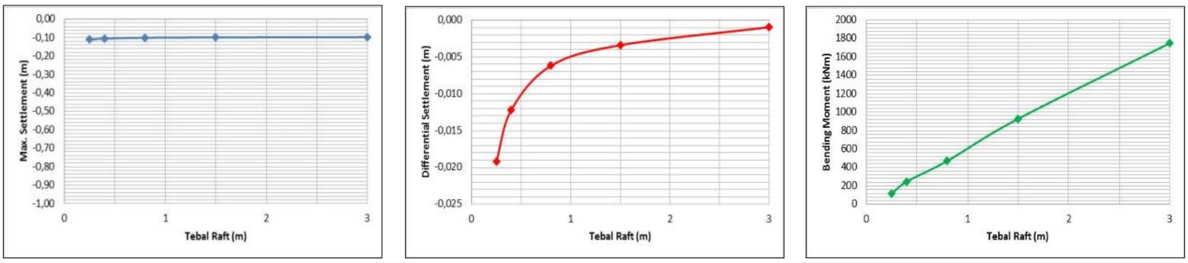


Figure10. The Result of Foundation System (Bending Moment)

The modeling results of the piled raft foundation system with various raft thicknesses are also summarized in graphs showing the relationship between raft thickness and average settlement (Figure.11a), differential settlement (Figure.11b), and bending moment (Figure.11c) that occur in the foundation system. Table 5 below is a summary of the average settlement, differential settlement, and bending moment results for each raft thickness in the foundation system.

Table 5. Resume of The Influence of Raft Thickness

Raft Thickness	Average Settlement	Differential Settlement	Bending Moment
0,25	-0,110	-0,0192	116,60
0,40	-0,105	-0,0122	247,95
0,80	-0,101	-0,0062	471,67
1,50	-0,099	-0,0034	928,52
3,00	-0,097	-0,0009	1749,75



(a) (b) (c)

Figure 11. The Influence of Raft Thickness on Average Settlement, Differential Settlement, and Bending Moment

Figure 11(a) shows that the foundation system with a raft thickness of 0.25m experienced an average settlement of 0.110m, while for a foundation with a raft thickness of 3.00m, the average settlement was 0.097m. The difference in average settlement is only about 0.013m. This concludes that the raft thickness in the foundation system cannot reduce the average settlement. Figure 11(b) shows that the foundation system with a raft thickness of 0.25m experienced a differential settlement of 0.020m, while for a foundation with a raft thickness of 3.00m, there was a very small differential settlement, only about 0.001m. This indicates that raft thickness is very effective in reducing differential settlement. However, it's also important to consider the large bending moment when designing a raft with significant thickness. As seen in Figure 11(c), the bending moment on a raft with a thickness of 0.25m is only 117 kN.m, while the bending moment on a raft with a thickness of 3.00m is 1750 kN.m.

CONCLUSION

From the results of modeling and analysis, several conclusions can be drawn, namely:

1. Piles can function as settlement reducers in raft foundations.
2. The thickness of the raft can reduce differential settlement, but does not significantly affect the average settlement.
3. We need to concern about bending moment when we designed raft with the greater thickness, because it will cause the greater bending moment. Therefore, this needs to be considered in designing a piled raft foundation system with a specific raft thickness.

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