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Numerical Modeling and Parametric Study of Piled Rafts Foundations Using Finite Element Software PLAXİS 2D

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Abstract- This study presents a series of 2D analyses of piled rafts by varying the length, spacing, and diameter of the piles in the group. The simulated piled rafts are square in plan, and they are loaded vertically with a uniform load. The soil profile utilized for analysis represents the Avcılar district of Istanbul. The soil is treated as elasto-plastic material and idealized using the Mohr-Coulomb model in a drained condition, whereas the piles are modeled as embedded volume elements. For optimization purposes, a total of 64 different designs were created by varying pile diameter, pile length, and pile spacing as variables in pile raft foundation systems. To investigate how each variable affects deformation, modeling was carried out for pile diameters of 0.8, 1, 1.2 and 1.6 m and lengths of 15, 20, 25, and 30 m using 2D, 2.5D, 3D, and 4D ranges. As a result, the design with "D=0.8m, L=30, S/D=4" was found to be the optimal choice in terms of both price and performance.

Keywords Deep foundation, Piled raft foundation, Optimization, Plaxis 2D.

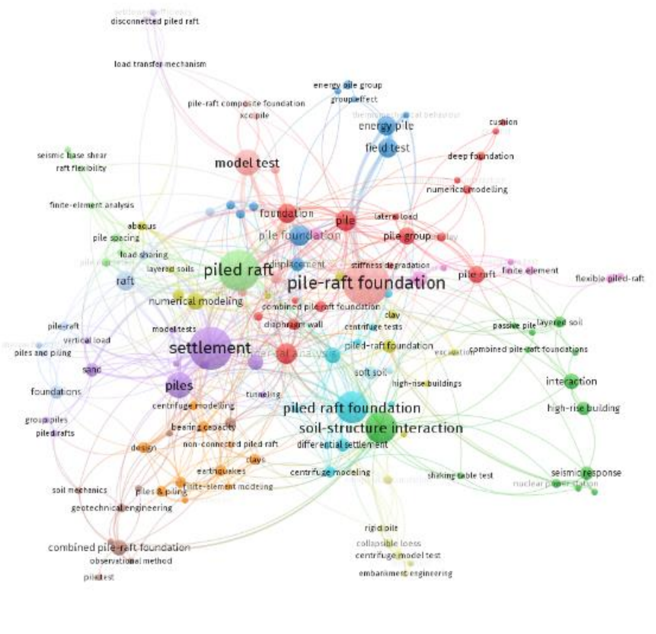
1. Introduction

In foundation engineering, pile raft foundations are the most used form of foundation for tall buildings or unusual structures [1]. Piles can be made of various materials, including wood, concrete, and steel. Pile raft foundations are used to transfer column loads and are often used to construct structures such as high-rise buildings, offshore platforms, defense facilities, dams, and transmission towers on soils with poor bearing capacity. Pile raft foundations reduce permeability, shrinkage, and swelling pressure and increase the bearing capacity of the soil [2]. The use of piled raft foundations is an excellent technique for reducing both total settlement and differential settlement, increasing the bearing capacity of shallow foundations, and economically reducing internal stresses and moments within the raft [3].

In practice, the design of piled raft foundations assumes that the piles will carry the entire load, and the cap is a rigid platform to distribute the load onto the piles [4]. The design of pile groups usually includes piles of the same diameter and length with equal axle spacing between them. The reason for this design is to facilitate fabrication and minimize errors during fabrication [5]. A limited number of piles can improve the ultimate bearing capacity, settlement, and differential settlement performance of the raft and reduce the required thickness of the raft. Many researchers have studied this foundation system (pile raft) to evaluate its bearing capacity and settlement.

Reference [6] states that the addition of piles can reduce settlement. The study includes finite element analysis using PLAXIS 2D to analyze the settlement of raft and piled raft foundations. The design process for pile raft foundations consists of three stages: evaluation of the required raft thickness, evaluation of the required pile length, and determination of the optimum number of piles. The preliminary stage involved varying raft thickness, the second stage involved varying pile length, and the final stage determined the optimum number of piles. The main findings of the study are that there is a point where adding piles to the raft foundation can reduce the settlement, but increasing the number of piles does not significantly reduce the settlement. It is important to consider the optimum number of piles in a piled-raft foundation system for economic design based on allowable settlements [6]. Reference [7] performed several numerical analyses using different pile lengths and pile configurations. The bearing behavior of the pile raft was also predicted using relatively stiff soil properties and different loading types. The influence of pile-soil shear on pile raft bearing capacity was investigated based on the results. In addition, the load sharing between the raft and the piles in the ultimate state and the relationship between settlement and the overall safety factor were evaluated. The results show that both the bearing capacity and settlement behavior of the raft can be improved by using a limited number of strategically located piles [7]. Reference [8] concluded that the load carried by the raft increases as the pile length and number of piles decrease. They also found that the optimum settlement ratio (%S/B) for the pile raft settlement mitigation design is 0.7% [8]. Reference [9] investigated the effect of pile raft foundation geometry and the stiffness ratio between pile material and clay on the performance of the foundation system in soft soils. The results of the study show that the performance of pile raft foundations in soft soils is significantly influenced by pile spacing. As the S/D ratio increases, the ultimate capacity of the pile-raft foundation decreases. However, when this ratio exceeds 10 (S/D > 10), the piles have little or no effect on the ultimate capacity of this foundation system [9]. Reference [10] used Plaxis 2D two-dimensional finite element software to investigate the settlement, swelling, and structural behavior of foundations during soil settlement and swelling on different soil profiles under different load combinations and geometric conditions. It was found that, due to the soft and low stiffness of the soil, the pile raft could not withstand higher loads and exceeded the settlement limits. The pile raft increases the load-bearing capacity of the soil, and the subsoil layer on which the piles rest has a higher stiffness and reduces significant settlement [10].

Fig. 1.(a) shows the output of the keywords generated as a result of the search for 'piled raft' from the SCI index database using the VOS viewer algorithm. Fig. 1.(b) shows the number of publications by year. According to Fig. 1.(b), it is seen that there is an increase in the number of studies on 'piled rafts'.



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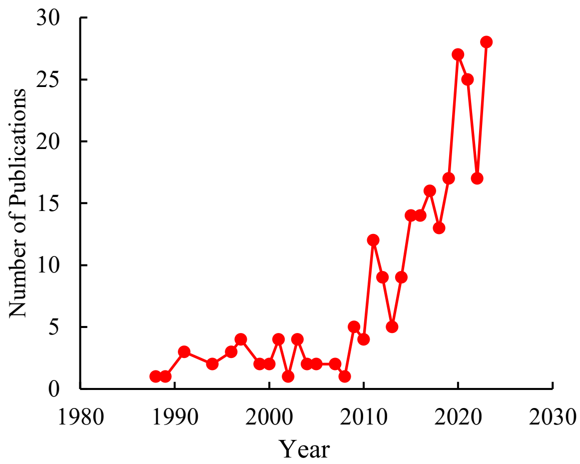


(b)

Fig. 1. Total keywords used in the SCI index database literature based on (a) piled raft and (b) progress over time span of the conducted literature.

As can be seen, there are many factors that influence the performance of pile foundations; therefore, it is of great importance to know the effective factors in advance in order to make reliable predictions at the design stage. In this study, settlement-based optimization of pile foundations was carried out on a soil profile representative of Istanbul's Avcilar district. In order to investigate how each variable affects the displacement, modeling was performed for pile diameters of 0.8, 1, 1.2 and 1.6 m and lengths of 15, 20, 25, and 30 m with 2D, 2.5D, 3D, and 4D ranges. Since the number of piles was only changed on one axis of the pile groups in the study, a 2D analysis program was used. The 64 different designs were modeled and analyzed in the finite element analysis program Plaxis 2D, and the displacement values were determined. After the design and analysis, the cost values for each model were calculated. As a result of the designs, modeling, analysis, and cost calculations, the optimal deformation-based design for a pile foundation was determined.

2. Materials and Method

2.1. Description of The Study Area

Avcılar District is situated approximately 25 km west of Istanbul, between Küçükçekmece and Büyükçekmece Lakes, bordered by the Sea of Marmara (refer to Fig. 2). The prevalent geological formations in this region are detailed in the soil profiles found in Table 1 [11]. Due to variations in the thickness of the top three formations, Authers conducted an investigation involving eight different combinations of soil layers, encompassing extreme values for layer thickness. The uppermost layer is a soft clay known as the Güngören Formation, with a thickness ranging from zero to 10.00 meters. Below this, there is a relatively sturdy limestone formation (Bakırkoy) dating back to the Upper Miocene, with a thickness varying between 7.5 and 15.0 meters. The third layer beneath the surface consists of the same clayey formation (Guengoeren) with a thickness ranging from 4.0 to 15.0 meters. Beneath this layer is a 15.0 m-thick formation of fine, dense sand (Çukurçeşme) from the Pliocene, characterized by its unconsolidated and partially saturated state. The Standard Penetration Test (SPT) values for this sand layer average N60 = 25. The water table is situated at a depth of 13–15 meters below the surface. Below the Çukurçeşme sand formation lies a hard clay layer (Gürpınar), approximately 300 meters thick. Beneath the Gürpınar hard clay layer is a robust tuff formation.

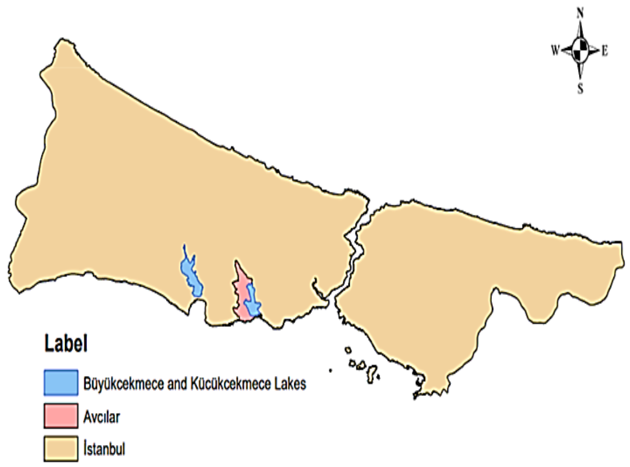


Fig. 2. General view of study area

Table 1. Eight different soil profiles considered for analyses at Avcılar, Istanbul [11].

Formation	Layer Thickness (m)								Soil Parameter	V_s m/sec
	1	2	3	4	5	6	7	8		
ML-CH Clay Güngören Formation	0	10	0	10	0	10	0	10	γ_n=16 N_{30}=20	160
Lime Stone Bakırkoy formation	7.5	7.5	15	15	7.5	7.5	15	15	γ_n=21 N_{30}=Refu q_u=2000 Φ=35	400
ML-CH Clay Güngören Formation	4	4	4	4	15	15	15	15	γ_n=19 N_{30}=20 q_u=50-200 e_0=1	215
SP-GP Sand Çukurçeşme Formation	15	15	15	15	15	15	15	15	γ_n=18 N_{30}=50 Φ=40	275
CH Hard Clay Gürpınar Formation	300	300	300	300	300	300	300	300	γ_n=18 N_{30}=50 q_u=200 e_0=0.75	275
Bed Rock	-	-	-	-	-	-	-	-	γn=23	900

2.2. Geometry Model

In this study, the effect of pile parameters on the settlement of a pile raft foundation system to be constructed in Avcilar district was investigated. For this purpose, a square foundation with dimensions of 50m x 50m and a load of 200 kPa, equivalent to the load of a 20-story building, was applied. The second soil profile presented in Table 1 was used as the soil profile in the study. The geometry model and soil profile were as shown in Fig. 3.

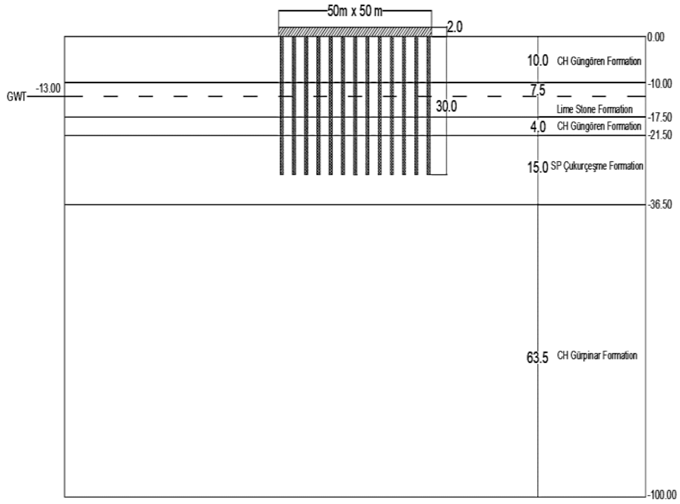


Fig. 3. Geometry Model

2.3. Material Properties

This paper focuses on the integration of the Mohr-Coulomb (MC) model, a widely used nonlinear model for predicting soil behavior. The MC model is known for its simplicity and accuracy in providing reliable results. It incorporates five key input variables: Young's modulus (E), Poisson's ratio (ν), cohesion (c), internal friction angle, and dilatancy angle (ψ). Together, these variables play a critical role in the comprehensive evaluation of soil properties. The MC model can be expressed by the following equation:

$$\tau = c - \sigma \tan\phi \quad (1)$$

where τ presents the shear stress, σ presents the normal stress, c is the cohesion of the soil material and ϕ is the angle of internal friction. MC model parameters of Güngören, Gürpınar, Çukurçeşme and Bakırköy formations were selected according to [12] [13] [11]. Table 2 shows the MC model parameters determined for each formation. The raft was modeled as a linear elastic material, whereas the piles were modeled using the embedded pile model. Modulus elasticity of raft and piles, E, of 2.0 x 10^7 kN/m^2 were used.

2.3. Method of Analysis

In this analysis, a two-dimensional finite element approach is utilized, although a comprehensive three-dimensional study is recommended for enhanced accuracy. It's worth noting that the two-dimensional analysis has a tendency to overestimate pile load by up to 10% and system settlement by up to 30%. However, it offers advantages in terms of time efficiency and simplicity, despite these limitations [14].

Table 2. MC model parameters determined for each formation.

Parameter	Unit	Güngören Formation ML	Bakırköy Formation Limestone	Güngören Formation CH	Çukurçeşme Formation Sand	Gürpınar Formation CH
γ_{sat}	kN/m^3	19	21	19	18	18
γ_{dry}	kN/m^3	16	19	16	16	16
ν	-	0.35	0.2	0.3	0.3	0.2
E_{ref}	MPa	12	582	55	122	113
ϕ	^{o}	7	35	25	40	16
c	kPa	15	40	35	25	45

It's noteworthy that similar methodologies have been employed in other studies [15] [14] [16]. The analysis of an axially loaded piled raft, given its intricate loading and geometry, is typically treated as a three-dimensional problem. However, to simplify and condense the analysis into two dimensions, symmetrical techniques can be applied. PLAXIS 2D utilizes a plain strain model to streamline the representation of a piled-raft foundation. In the context of foundation analysis, a two-dimensional strip-piled raft is often used to simplify and represent a three-dimensional piled raft. In order to investigate the effects of pile properties on the pile foundation system, various models with pile diameters of 0.8, 1, 1.2 and 1.6 meters and lengths of 15, 20, 25 and 30 meters were created in 2D, 2.5D, 3D and 4D. A total of 64 models with different pile properties were prepared. Fig. 4 provides a summary of these models, and an illustrative example of the pile placement model for the "D=1m, S/D=4" model is presented in Fig. 5. In all models, the piles were positioned 1 meter from the edges and 4 meters out of the plane.

L (m)	D (m)	S/D
15 - 20 - 25 - 30	0.8 - 1.0 - 1.2 - 1.6	2.0 - 2.5 - 3.0 - 4.0

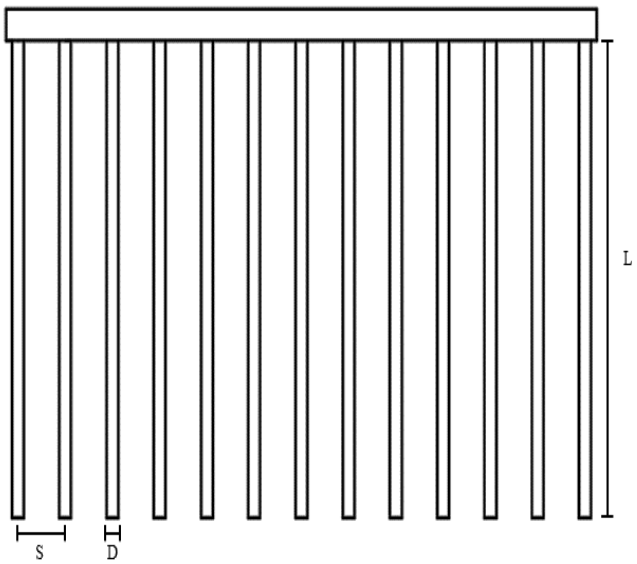


Fig. 4. Different combination of piled-raft foundation.

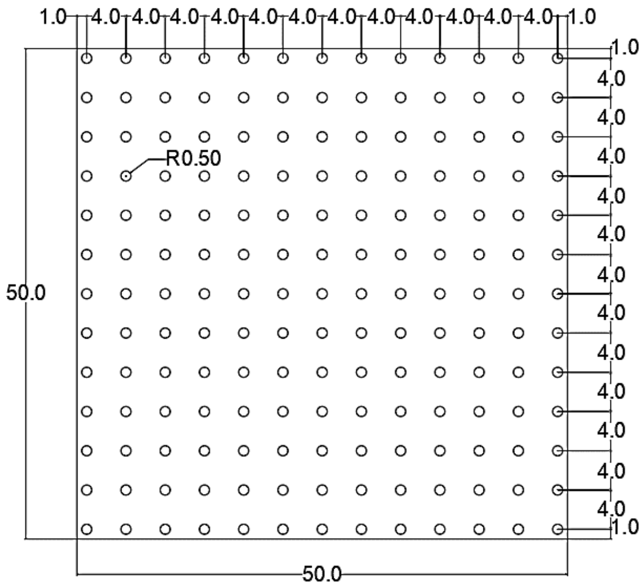
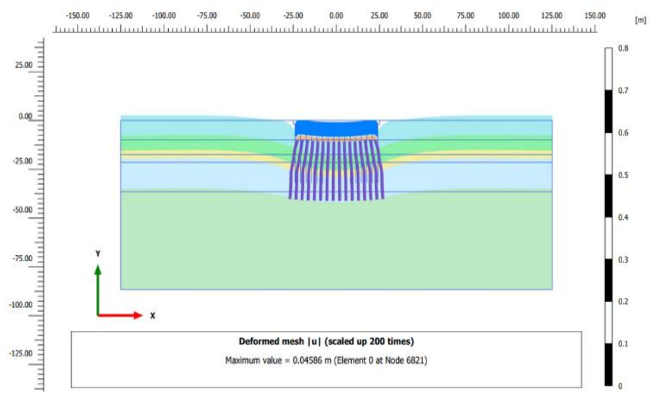


Fig. 5. Example of top view of pile-raft config.urations.

3. Results and Discussions

In this section, the total vertical displacements obtained for different raft-pile combinations are evaluated using the PLAXIS 2D program. A typical PLAXIS 2D analysis output for D = 0.8 m, L = 30 m, and S/D = 4 is shown in Fig. 6a and 6b. In the following subsections, the analysis results are presente graphically.



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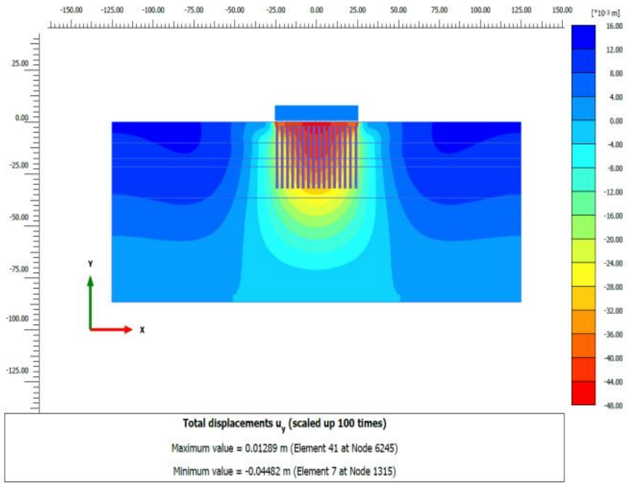

(b)

Fig. 6. A typical PLAXIS 2D analysis output for D=0.8m, L=30 m, S/D=4.

3.1. Effects of Pile Spacing

The impact of four distinct pile spacings on settlement is depicted in Fig. 7 to 10 for various pile diameters. Across all models, an increase in pile length correlates with a reduction in settlement. This improvement is particularly noticeable when extending the pile length from 20m to 25m, showcasing a percentage improvement ranging from 17% to 22%, depending on the pile spacing. Notably, when the pile length is set at 30m for all pile diameters, this represents the scenario where the alteration of pile spacing has the least effect on settlement.

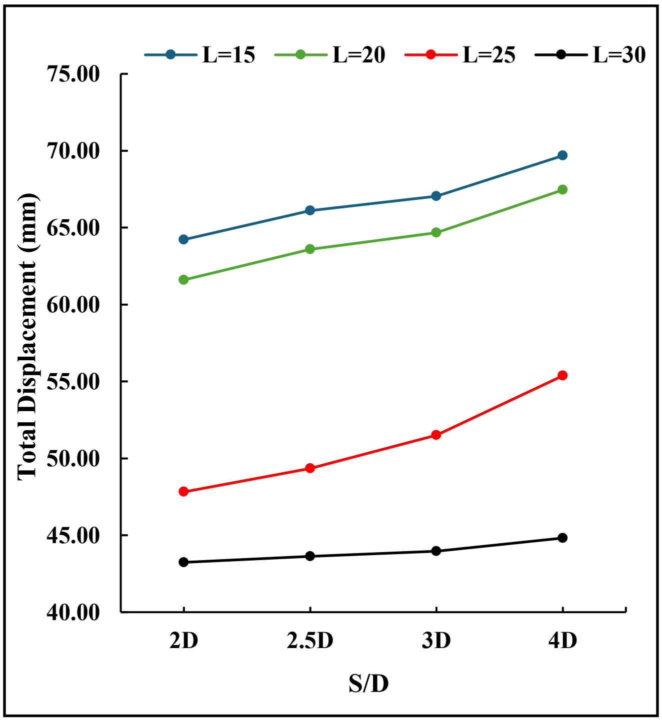

Fig. 7. Effect of S/D and length change for 0.8-meter diameter pile.

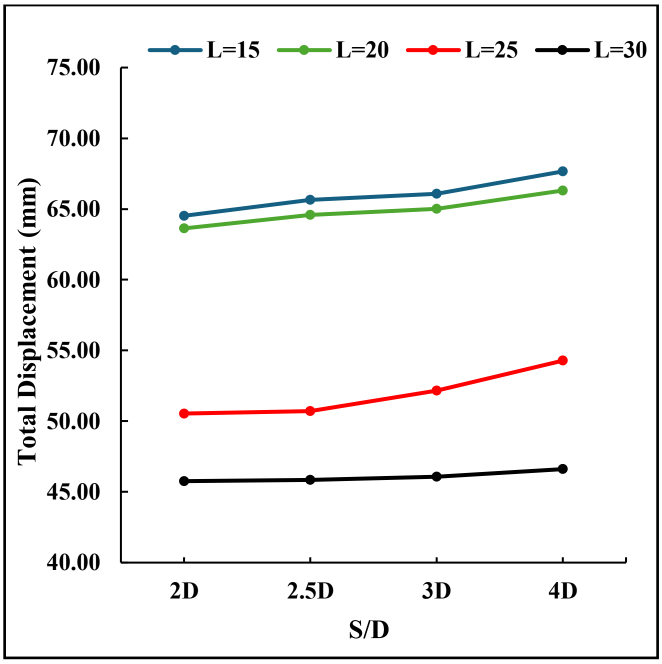

Fig. 8. Effect of S/D and length change for 1 meter diameter pile.

For pile diameters of 1.2m and below, an increase in pile spacing resulted in an increase in displacement, as indicated in the findings. However, examining Fig. 10, with a pile diameter of 1.6m, increasing the pile spacing across all pile lengths led to a decrease in displacement. This behavior can be attributed to the overlapping stress isobars of adjacent piles. When piles are grouped, there is a potential for the stress isobars of neighboring piles to overlap. In regions of overlap, the soil experiences higher stress levels, and with sufficient overlap, either the soil may collapse or the pile group could undergo excessive settlement as the combined pressure bulb extends to a significant depth below the pile base.

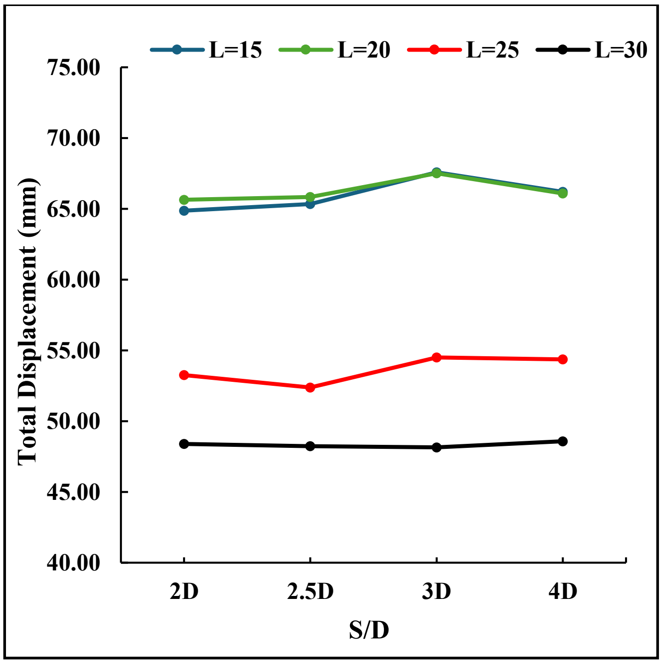

Fig. 9. Effect of S/D and length change for 1.2-meter diameter pile.

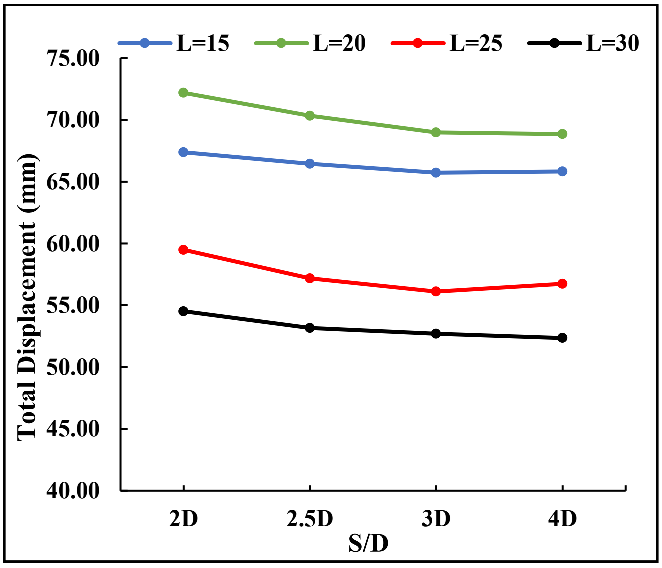

Fig. 10. Effect of S/D and length change for 1.6-meter diameter pile.

3.2. Effect of Pile Length

The effect of pile diameter and pile length on fixed pile spacing is illustrated in Fig. 11 to 14. For pile spacings of 2D and 2.5D, as depicted in Fig. 11 and 12, an increase in pile diameter leads to an elevation in displacement. As mentioned in the previous section, this effect is attributed to the overlapping stress bulbs of the piles intensifying with the larger diameter. However, this effect diminishes with increasing pile spacing, as evident in Fig. 14. With a pile spacing of 4D, the general trend is that an increase in pile diameter results in a decrease in displacement.

In models with a pile diameter exceeding 1 meter, the increase in pile length from 15 meters to 20 meters causes an increase in displacement at 2D and 2.5D pile spacings, primarily due to changes in the soil layer. The increase in pile spacing generally leads to an improvement, except for a pile diameter of 1.6 m. Furthermore, extending the pile length beyond 20 meters results in a reduction in displacement for all pile diameters and S/D ratios.

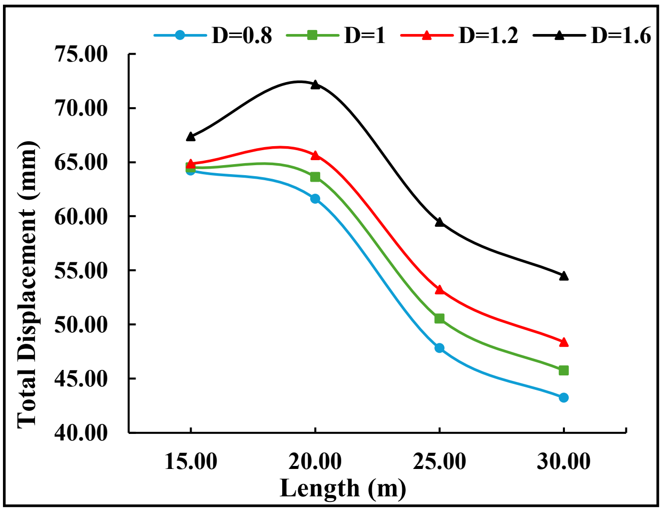

Fig. 11. Effect of pile diameter and length variation in 2D pile spacing models.

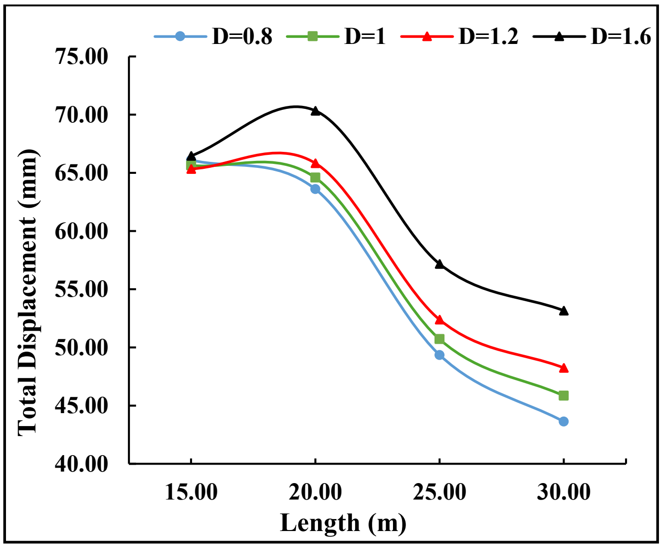

Fig. 12. Effect of pile diameter and length variation in 2.5D pile spacing models.

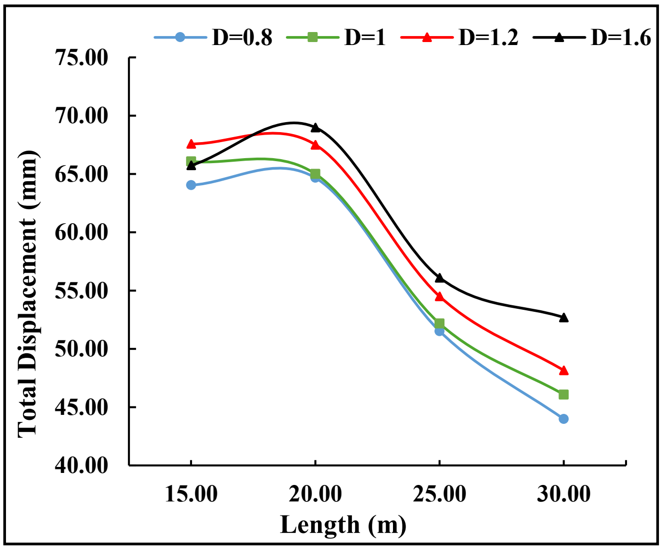

Fig. 13. Effect of pile diameter and length variation in 3D pile spacing models.

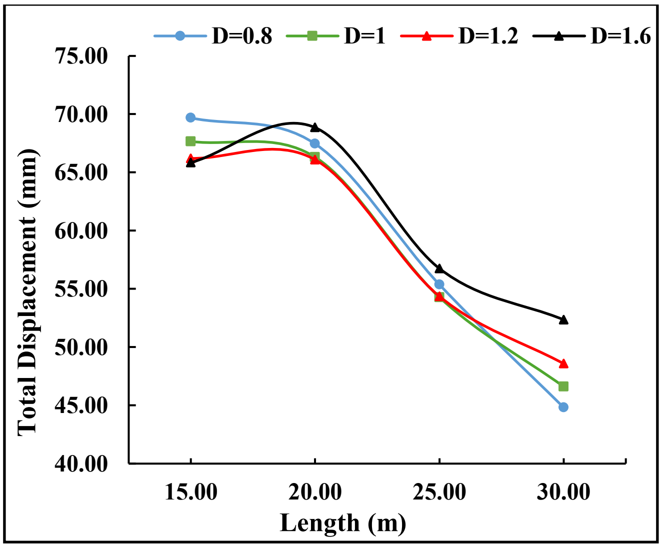

Fig. 14. Effect of pile diameter and length variation in 4D pile spacing models.

3.3. Pile Cost and Displacement Optimization

In order to make optimization between the models in terms of price and performance, the models with displacements below 50 mm, which is the allowable displacement amount of pile raft foundation systems, were determined and cost calculations were made and presented in Fig. 15.

The cost calculations of bored piles were made based on the price list attached to the 2023 construction unit price recipes of the Presidency of the Supreme Science Council of the Ministry of Environment and Urbanization [17]. As seen in Fig. 15, the minimum pile length should be 25 meters in order to be below the allowable limit. Fig. 12 shows that the best design in terms of price and performance is "D=0.8m, L=30, S/D=4".

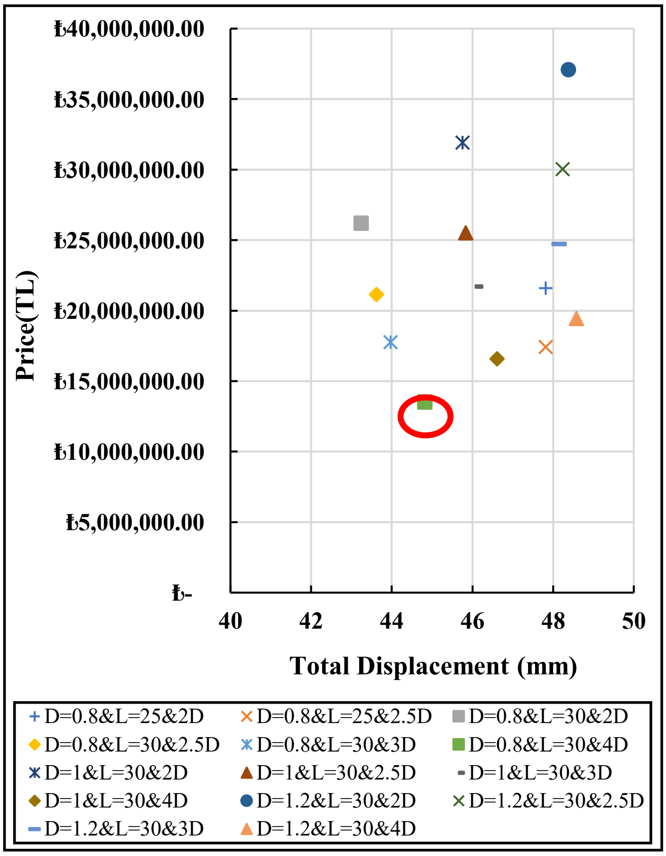

Fig. 15. Displacement and cost comparison.

4. Conclusion

In this study, the effect of pile properties on the performance of pile raft system is investigated through 64 analyses, the results are presented below:

- For all models, increasing pile length resulted in improving settlement.
- The pile length at which the effect of changing the pile spacing is the smallest is 30 m for all pile diameters.
- Raising the pile spacing results in more settlements when the pile diameter is 1.2 m or less. This problem is more noticeable when the pile length is smaller than 30m.
- When the pile spacing is 2D and 2.5D, increasing the pile diameter leads to an increase in the amount of displacement. Except for the 1.6 m pile diameter, increasing the pile spacing resulted in an improvement. These behaviors can be attributed to the overlapping stress isobars of adjacent piles.
- Because longer piles have higher skin friction resistance, increasing the pile length beyond 20m reduced the amount of displacement for all pile diameters and S/Ds. Therefore, as can be seen in Fig. 15, the minimum pile length should be 25 m in order to stay below the allowable limit.

The optimal design in this situation and in terms of cost and functionality is **"D=0.8m, L=30, S/D=4"**.

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