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Influence Of Pile Length On Settlement Behaviour Of Pile Raft Foundation In Soils Of Low Strength

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Abstract: This study investigates the numerical modelling of a pile-raft foundation system on soft clay and loose sand using PLAXIS 2D. The main goal is to assess settlement behaviour in pile-raft systems with variations in pile lengths, soil cohesion, and internal friction angles. Two distinct soil profiles are analyzed: one with a soft clay layer over medium-dense sand, and another with loose sand over medium-dense sand. The simulation captures undrained behavior for clay and drained behavior for sand to better understand the soil-pile raft interaction. By utilizing the embedded pile model in PLAXIS 2D, the study examines the interaction between piles, rafts, and the underlying soils, offering insights into settlement behaviour. Results showed that extending pile length from 9 m to 15 m achieved significant settlement reduction (around 25.62%), with a notable quadratic trend between pile length and settlement. However, changes to raft thickness have minimal effect on settlement, suggesting that optimizing pile length is a more effective design strategy. Additionally, the study highlights that increased soil cohesion and higher internal friction angles further reduced the settlement, stressing the importance of considering both soil characteristics and design variables in pile-raft foundation optimization. These results offer practical insights for engineers, emphasizing that pile length and soil properties are critical factors for effective settlement control in foundation design.

***Keywords* –** Soft clay, loose sand, pile raft, settlement behaviour, cohesion, internal friction angle.

1.INTRODUCTION

The rising demand for urban land has increased construction on soft clay soils, which poses challenges due to high compressibility and excessive settlement. Piled raft foundations, combining load-distributing rafts and supportive piles, offer an effective solution to these issues (Poulos, 2001; Wulandari et al., 2015). Interactions among the raft, piles, and soil to assess settlement reduction and load-bearing capacity are crucial in the PLAXIS analysis (Kwon JayMin et al., 2016). Understanding and design of piled raft foundations in challenging soil conditions is very essential. Pile-raft foundations combine the load-distributing function of a raft with the support of piles, enhancing load-bearing capacity and efficiency, especially in challenging soil conditions. Unlike traditional foundations that depend on either piles or a raft, pile-raft systems share loads, reducing the need for extra piles or thicker rafts, thereby lowering costs (Bisht et al., 2012). These foundations are particularly effective in soft soils prone to settlement, improving stability and minimizing differential settlement, making them ideal for urban structures like skyscrapers and bridges.

When designing pile raft foundations in clayey soils, engineers must account for soil low bearing capacity and compressibility. In soft clay, piles carry most vertical loads while the raft distributes stresses to minimize settlement. Factors like undrained cohesion and consolidation influence interactions among the raft, piles, and clay (Ahmed et al., 2020). Short piles stabilize the raft, while longer piles reach deeper, stable layers. As the clay consolidates, load distribution alters, requiring finite element analysis, such as PLAXIS, to ensure long-term stability (Ural et al., 2020; Aligholi and Hossein Zoriyeh, 2024). In sandy soils, pile raft foundations leverage the high bearing capacity and low compressibility of sand, allowing the raft to support substantial loads while reducing the number of piles needed. The piles utilize end-bearing resistance and skin friction for effective load transfer, while the raft stabilizes the structure (Khan Zehra and Abhishek Sharma, 2023; Ahmed et al., 2022; Modak, 2022). Pile raft foundations are commonly used in high-rise buildings and bridges and these foundations effectively manage settlement and utilize dense sand strength. However, design considerations must include friction angle, soil density, and liquefaction risks in loose layers during seismic events, often using modelling tools to predict load-settlement behaviour.

Pile-raft foundations offer key benefits in civil engineering, reducing construction costs by decreasing the number of piles and distributing loads between the raft and piles (Al-Khalidi and Evan Emad, 2024). A pile raft would control differential settlement effectively (Ali et al., 2023) and it would provide stability in soft or varying soil conditions (Jin Hyung Lee et al., 2012). The adaptable design allows for adjustments in pile length, spacing, and raft thickness to meet the specific conditions of the project, making them suitable as foundations for residential buildings, bridges and power plants (Shukla et al., 2013). Pile-raft design is simple provided one knows soil-structure interaction and computational tools. Load-settlement analysis can be performed using PLAXIS software and it helps determine load distribution by accounting for non-linear soil behaviour and consolidation effects. Bearing capacity analysis is vital for safety considerations of pile rafts (Munaba et al., 2022). The performance of piled raft foundations with geo-foam coatings in soft clay showed that hydrostatic uplift significantly reduced the settlement (Alhassani et al.,2020). Accurate determination of pile-soil-raft interaction is essential for actual load distribution, influenced by pile stiffness, spacing of piles, length of piles, and soil properties (Karim et al., 2020).

This paper presents a specific study of a pile-raft foundation modelled in a soft clay and loose sand layer, examining the settlement with factors such as soil properties, pile length, and raft thickness. The findings presented in the paper can be used to make recommendations for optimizing piled raft foundation designs in soft clay, aiming to improve structural performance and minimize differential settlement.

2. METHODOLOGY

In this study, the uniformly distributed load of 50 kPa was applied to a 40.6 m x 40.6 m raft with 0.3 m diameter piles and was analyzed using the PLAXIS-2D software. A plane strain finite element model was used to model the piled raft foundation. The raft and piles were assumed to be linearly elastic. The Mohr-Coulomb yield criteria were used to represent soil as an elastic-perfectly plastic material. A two-layer soil with no water table was assumed for the study. Here an undrained condition was assumed and the total stress analysis was carried out. The various soil, raft, and pile material properties are presented in Tables 1 to 3. PLAXIS 2D utilizes the two-dimensional finite element analysis to explore either plane strain or axisymmetric conditions, depending on the geometry of the structure. The plane strain approach is suitable when the cross-sectional area is uniform and one axis is significantly longer than the other. This method assumed that deformations or strains perpendicular to the cross-section are minimal compared to those within the cross-section. Fig.1, shows the geometry of the pile raft model on soft soil developed using PLAXIS 2D.

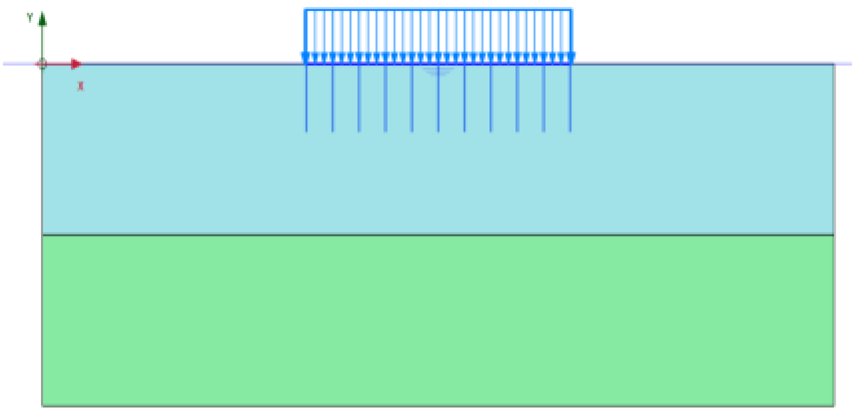

Fig.1 Modeling of the pile raft on soft soil

Table 1: Clay soil parameters

Parameter	Soft clay	Medium dense sand
Thickness of layer, m	20	20
Unit weight, kN/m^3	15	18
Saturated unit weight (γ_{sat}), kN/m^3	18	20
Young's modulus (E) kPa	4000	35000
Poisson's ratio (υ)	0.35	0.3
Undrained cohesion (c), kPa	30	0
Friction angle (ϕ) in Deg	0	35
Dilatancy angle (ψ) in Deg	0	5

Table 2. Sand soil parameters

Parameter	Loose sand	Medium dense sand
Thickness of layer, m	20	20
Unit weight kN/m^3	15	18
Saturated unit weight (γ_{sat}) kN/m^3	18	20
Young's modulus (E) kN/m^2	15000	35000
Poisson's ratio (υ)	0.35	0.3
Undrained cohesion (c)	0	0
Friction angle (ϕ)	28	35
Dilatancy angle (ψ)	0	5

Table 3 Plate properties

Parameter	Raft properties	RC pile properties
Plan Area (mm)	40.6 x 40.6	0.3 x 0.3
Area (m^2)	32.48	0.09
Young's modulus (E), kPa	31.62×10^6	31.62×10^6
Moment of inertia (mm^4)	1.706	6.75×10^{-4}
EA	1.01×10^9	2.84×10^6
EI	53.94×10^6	21.34×10^3
Material model	elastic	elastic
Element type	plate	Plate
Poisson's ratio, v	0.2	0.2
Unit weight, γ (kN/m^3)	25	25
Thickness, t of $raft$ (m)	0.4 m, 0.6 m, 0.8 m, 1.0 m,1.2 m,1.4 m	-
Diameter, d of $pile$ (m)	-	0.3
Length, L of $pile$ (m)	-----	9, 12, 15

3. RESULTS AND DISCUSSION

The results obtained through PLAXIS analysis on pile raft settlements for varied pile lengths of 9 m, 12 m and 15 m, and varied raft thicknesses of 0.4 m, 0.6 m, 0.8 m, 1.0 m and 1.2 m, under different soil conditions such as soft clay and loose sand. Clay cohesion values were considered 30 kPa, 50 kPa, and 70 kPa with soil moduli of 4000 kPa, 8000 kPa, and 12000 kPa respectively. For sand, internal friction angles were taken as 20°, 24°, and 28°, with soil moduli of 5000 kPa, 10000 kPa, and 15000 kPa respectively, simulating conditions commonly encountered in soft clay and loose sand for pile raft foundations.

Fig.2 illustrates the displacement distribution for a pile raft foundation with a 9 m pile length in soft clay. The contour plot indicates that maximum settlement occurs directly beneath the centre of the raft and gradually decreases towards the edges. The low undrained shear strength of the soft clay results in substantial settlement, particularly near the tips of the piles, where the load is concentrated. Fig.3 illustrates the settlement variation of a pile raft in clay with a cohesion of 30 kPa for different pile raft thicknesses. It shows that as the length of the pile group increases, the settlement of the pile raft decreases, while varying the raft thickness has minimal impact on settlement. Specifically, for a cohesion of 30 kPa, the settlement decreases by 14.38% as the pile length increases from 9 m to 15 m. Fig.4 displays the relationship between settlement (S) and pile group length (L) for various raft thicknesses in a pile-raft foundation on soft clay with a cohesion of 30 kPa. The results show that as the pile length increases, the settlement decreases, following a quadratic trend represented by the equation:

$$S = -0.1768(L)^2 + 2.9192(L) + 47.475 \text{----------------------- Eqn. 1}$$

The R^2 value of 0.9925 indicates a strong correlation between the variables.

Fig.5 presents a normalized trend between the ratio of settlement to pile diameter (S/D) and the length-to-diameter ratio (L/D) for a pile-raft system with 30 kPa soil cohesion. The negative slope of the linear equation suggests a reduction in normalized settlement as the length-to-diameter ratio increases. With an R^2 value of 0.942, it demonstrates a strong correlation and highlights the effectiveness of increasing pile length to reduce settlement under these conditions.

The trend line obtained is presented in Eqn.2 below.

$$\frac{S}{D} = -1.3231\left(\frac{L}{D}\right) + 239.56 \text{ -------------------------Eqn 2}$$

The corresponding correlation coefficient, $R^2 = 0.942$.

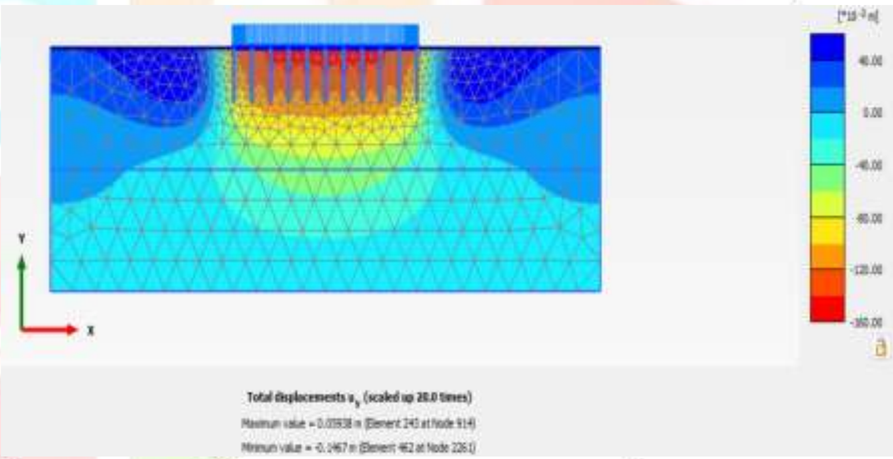

Fig.2. Displacement around pile raft foundation in soft clay for pile length of 9 m modelled in PLAXIS 2D

Fig.6 presents the normalized lines presenting the settlement-to-pile diameter ratio (S/D) against the pile thickness-to-diameter ratio (T/D) for cohesion values of 30 kPa, 50 kPa, and 70 kPa showing that S/D decreases with increasing cohesion for all T/D ratios. This trend is consistent across varying pile lengths (L), emphasizing the importance of soil cohesion in reducing settlement in loaded pile-raft foundations. Higher cohesion minimizes foundation deformation, enhancing load-carrying capacity and decreasing the need for deep pile installations, making these plots valuable for engineers estimating settlement for different lengths, cohesion, and raft thicknesses.

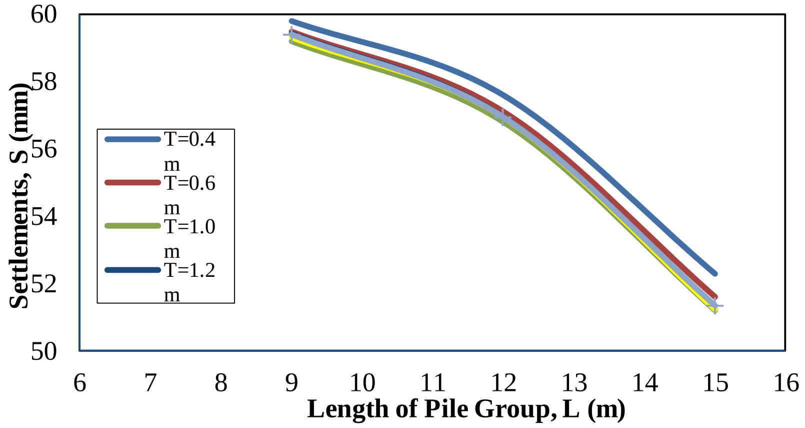

Fig.3 Variation of settlement with length of pile group for different thicknesses of pile raft and cohesion of 30 kPa

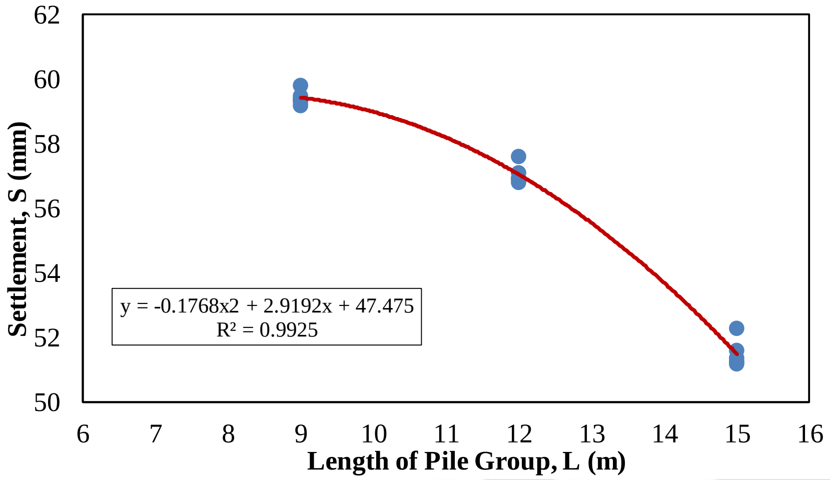

Fig.4 Trend line between settlement and length of pile group for different thicknesses of pile raft and cohesion of 30 kPa

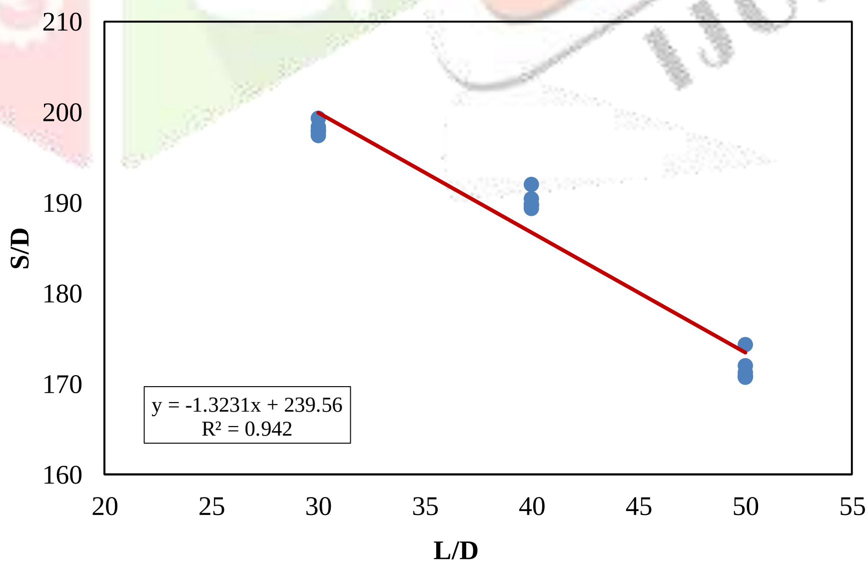

Fig.5 Normalized trend line between S/D and L/D for different thicknesses of pile raft and cohesion of 30 kPa

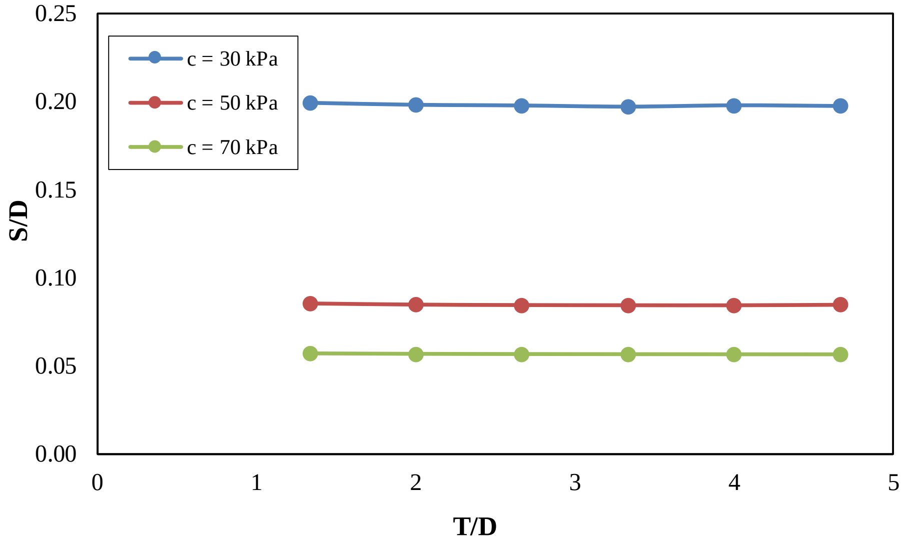

Fig.6 Normalized line between S/D and T/D for different cohesion values and L = 9 m

Fig.7 shows the displacement distribution for a pile raft foundation with a pile length of 9 m in loose sand. The maximum settlement is observed beneath the centre of the raft, where the load is concentrated. The lower stiffness of the loose sand results in more pronounced deformation compared to dense sand or clay. Fig.8 shows that as pile group length increases, settlement decreases for different raft thicknesses (0.4 m to 1.4 m) with an internal friction angle of 20°, particularly notable in shorter piles (up to 16 mm for 8 m piles), while longer piles (14 m) result in similar settlement values (around 9 mm), suggesting that lengthening piles is more effective for controlling settlement in loose sands than increasing raft thickness. Fig.9 presents a polynomial trend line showing that settlement (S) decreases non-linearly with increasing pile group length (L) for an internal friction angle of 20°, following the equation.

$$S = -0.0606(L^2) + 0.6495(L) + 12.846 \quad \text{--Eqn.3}$$

and achieving an excellent regression coefficient of $R^2 = 0.9938$, indicating that longer piles significantly reduce settlement in loose sands, particularly for lengths over 10 m.

Fig.10 illustrates the normalized relationship between the settlement-to-diameter ratio (S/D) and the length-to-diameter ratio (L/D) for an internal friction angle of 20°. The linear equation

$$S/D = -0.8058(L/D) + 70.714 \quad \text{---Eqn.4}$$

demonstrates that as the length-to-diameter ratio increases, normalized settlement decreases significantly, supported by a strong correlation indicated by an R^2 value of 0.9772, emphasizing the crucial role of pile length in managing settlement in loose sands with lower friction angles.

Fig. 11 presents the analysis of the settlement-to-diameter ratio (S/D) and the thickness-to-diameter ratio (T/D) for friction angles of 20°, 24°, and 28° across different pile lengths (9 m, 12 m, and 15 m) reveals that raft thickness (T) has minimal impact on normalized settlement, indicating that in loose sands, factors like pile length and soil friction angle are more critical for settlement performance than increasing raft thickness. These normalized lines provide valuable insights for practitioners.

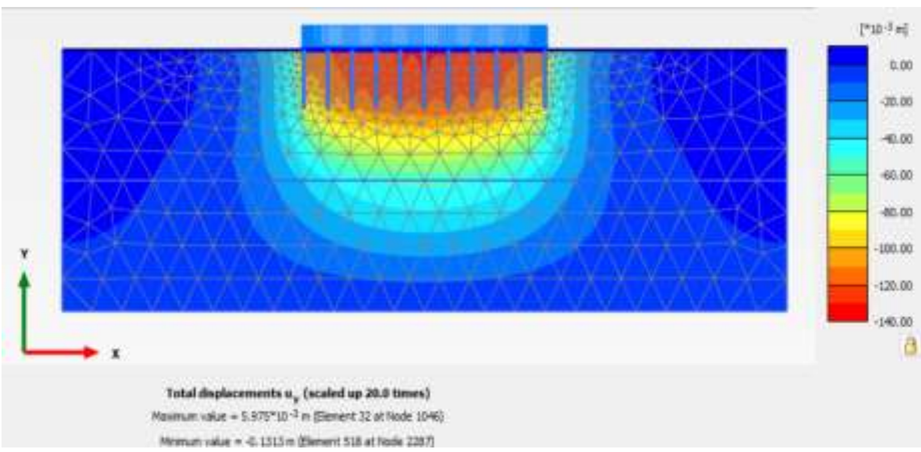

Fig.7 Displacement around the pile raft foundation in loose sand varied pile length at 9 m

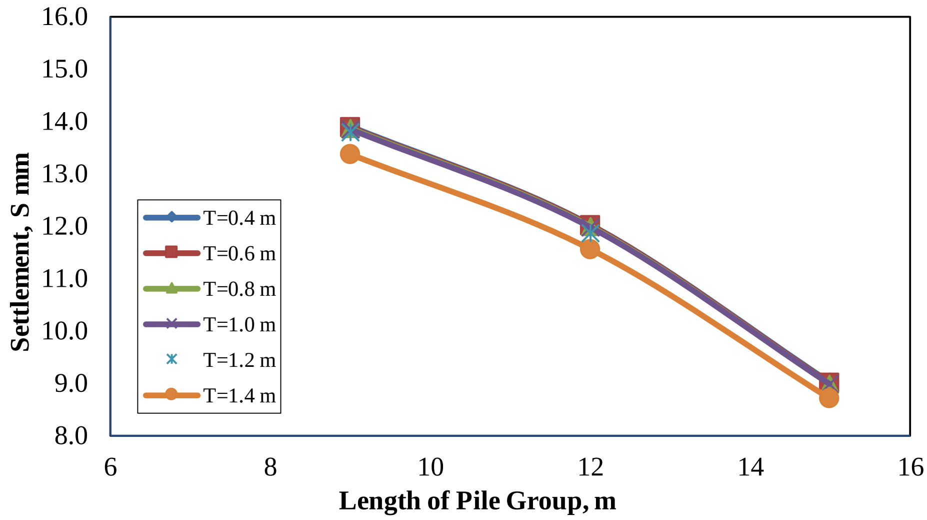

Fig.8 Variation of settlement with length of pile group for different thicknesses of pile raft and angle of internal friction 20°

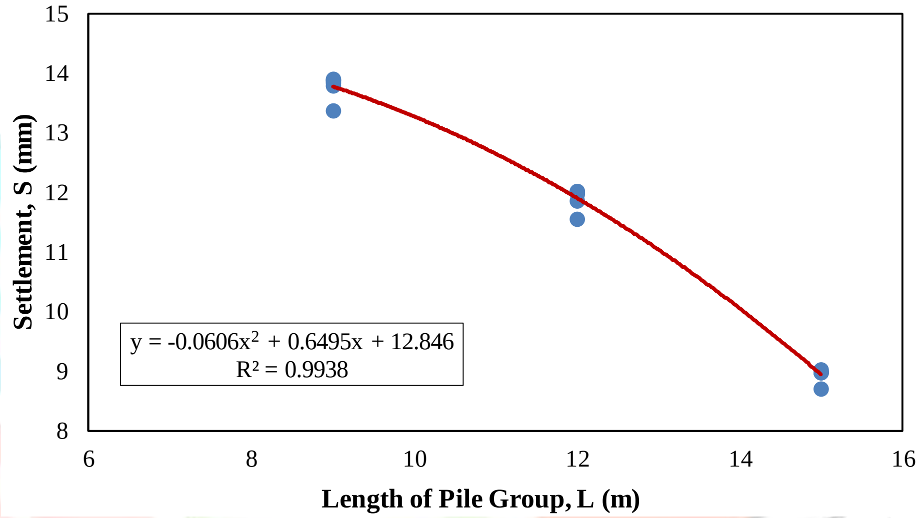

Fig.9 Trend line between settlement and length of pile group for different thicknesses of pile raft and angle of internal friction 20^0

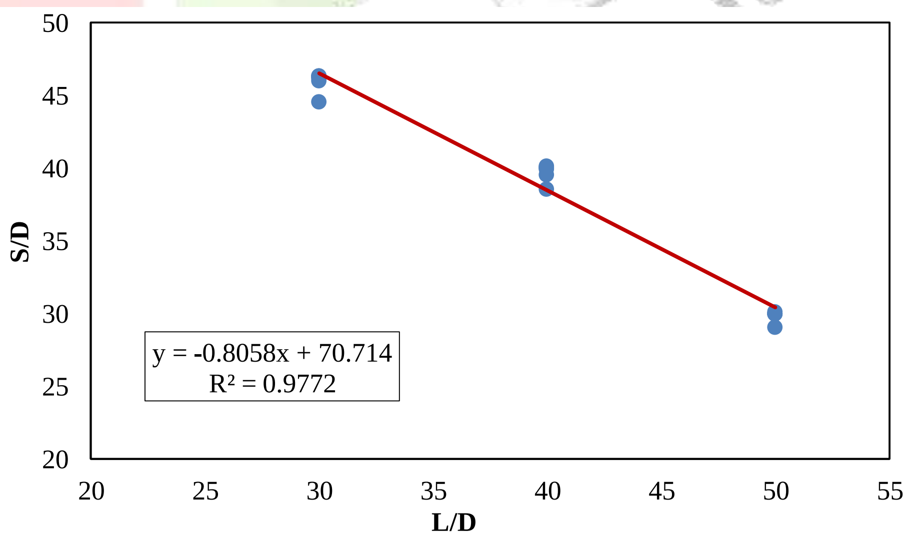

Fig.10 Normalized trend line between S/D and L/D for different thicknesses of pile raft and angle of internal friction 20^0

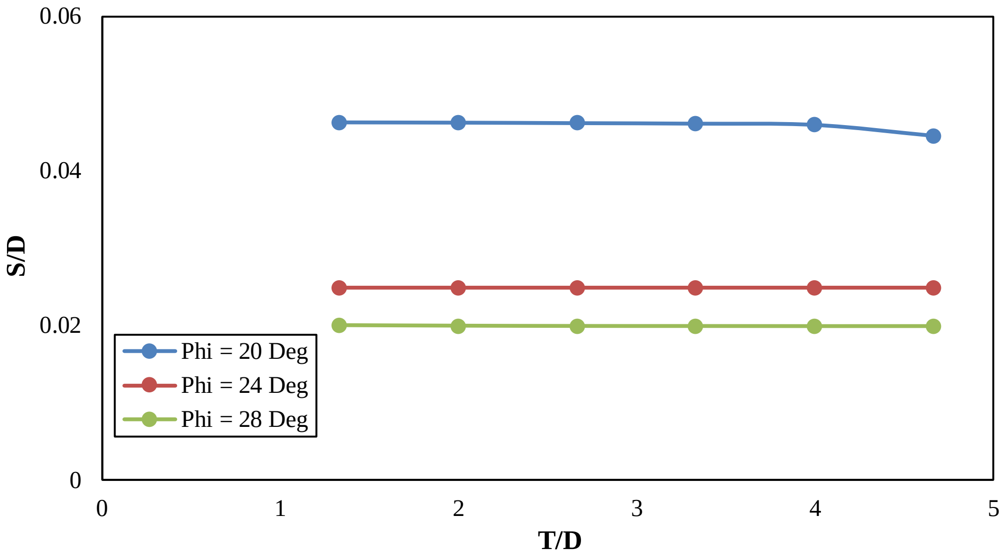

Fig.10 Normalized trend line between S/D and T/D for different angles of internal friction and pile grou[length 9 m

4 Conclusion

Increasing pile length in soft clay (30 kPa cohesion) reduced settlement by 14.38% from 9 m to 15 m; at 50 kPa cohesion, this reduction was 25.62%, and at 70 kPa, it was 18.5%. A quadratic relationship at 30 kPa showed that optimized pile length significantly reduces settlement, with similar results at 50 kPa (R^2 = 0.9994). Higher cohesion also lowers normalized settlement, as presented in the result in the form of S/D and L/D. In loose sands, increasing pile length significantly decreases the settlement, especially in shorter piles, while raft thickness has minimal impact. Higher internal friction angles reduced the settlement more effectively; at 24°, a polynomial trend with R^2 = 0.9988 indicated a strong settlement-pile length relation, while at 28° (R^2 = 0.9872), higher friction angles yielded lower settlement, reducing the need for pile length adjustments. For a 28° angle, normalized settlement showed a limited sensitivity to L/D changes, suggesting other factors affect settlement in high-friction soils. The S/D and T/D relationship across friction angles (20°, 24°, and 28°) confirms that raft thickness has minimal effect on normalized settlement, making these trends valuable in pile raft foundation design.

References

1. Poulos, H. G. (2001). "Piled raft foundations: design and applications." Geotechnique, Vol. 51, No. 2: pp. 95-113.
2. Wulandari, Paravita Sri, and Daniel Tjandra. (2015) "Analysis of piled raft foundation on soft soil using PLAXIS 2D." Procedia Engineering Vol. 125: pp 363-367.
3. Kwon JayMin, C. P. Weisel, M. T. Morandi and T. H. Stock (2016). "Source proximity and meteorological effects on residential outdoor VOCs in urban areas: results from the Houston and Los Angeles RIOPA studies." pp 954-964.
4. Bisht, Rajendra Singh, and Baleshwar Singh (2012). "Study on behaviour of piled raft foundation by numerical modelling." In SAITM Research Symposium on Engineering Advancements (SAITM–RSEA 2012).
5. Ahmed, Danish, Siti Noor Linda bt Taib, Tahar Ayadat, and Alsidqi Hasan (2022). "Numerical analysis of the carrying capacity of a piled raft foundation in soft clayey soils." Civ Eng J Vol. 8, No. 4: pp. 622-636.
6. Ural, Nazile, and Abdulselam Gergin (2020). "Foundation design on problematic soils with high underground water level." Revista de la Construcción Vol. 19, No. 3: pp 233-245.
7. Aligholi, Hossein Zoriyeh (2024). "Numerical Modeling and Parametric Study of Piled Rafts Foundations Using Finite Element Software PLAXİS 2D." International Journal of Engineering Science and Application Vol. 8, No. 1: pp 14-22.
8. Khan Zehra and Abhishek Sharma (2023). "Numerical Simulation of Piled-Raft Foundation in Cohesionless Soil using ABAQUS." Journal of Mining and Environment Vol. 14, no. 4: 1183-1203.
9. Modak, Rajib, and Baleshwar Singh (2022). "Interaction Effects for Large Piled Rafts in Clay Soil." In Indian Geotechnical Conference, Singapore: Springer Nature Singapore, pp. 11-23.

10. Al-Khalidi and Evan Emad (2024). "Numerical analysis to study the effect of sand columns on bearing capacity of raft foundation in clay soil." In AIP Conference Proceedings, Vol. 2864, No. 1. AIP Publishing.
11. Ali, M., Mahdi, O. Karkush, and Ala N. Al-Jorany (2023). "Numerical modelling of connected piled raft foundation under seismic loading in layered soils." Journal of the Mechanical Behaviour of Materials Vol. 32, No. 1: 20220250.
12. Shukla, S. J., A. K. Desai, and C. H. Solanki (2013). "A dynamic behavioural study of a 25-storey building with piled raft foundation with variable subsoil." Int. J. Struct. Civ. Eng. Res Vol. 2, No. 1: pp. 119-130.
13. Ayuluri, Srinivasa Reddy, B. Vamsi Krishna, and D. Ramulu (2017). "Settlement analysis of Piled Raft Foundation System (PRFS) in soft clay." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Vol. 14, No. 2: pp. 62-68.
14. Wiesner, Terence J., and Peter T. Brown (1980). "Laboratory tests on model piled raft foundations." Journal of the Geotechnical Engineering Division Vol. 106, No. 7: pp. 767-783.
15. Munaba, Christian William, Aswin Lim, and Arif Yunando Soen (2022). "Two-dimensional finite element analysis of piled raft coefficient settlement ratio on clays." Indonesian Geotechnical Journal Vol. 1, No. 2: pp. 27-37.
16. Gultom, Juni, H. Pratikso, Abdul Rochim, and Syahril Taufik (2021). "Behaviour of Piled Raft Foundation in Soft Clay Layer with Geo-Foam Application." Budapest International Research and Critics Institute-Journal (BIRCI-Journal) Vol. 4, No. 4: pp. 9629-9637.
17. Karim, H. H., Z. W. Samuel, and M. A. Hussein (2020). "Investigation of the behaviour of shallow machine foundation resting on a saturated layered sandy soil subjected to a dynamic load." In IOP Conference Series: Materials Science and Engineering, Vol. 888, No. 1, pp. 012055. IOP Publishing,
18. Alhassani, A.M.J. and Aljorany, A.N (2020). “Parametric study on unconnected piled raft foundation using numerical modelling”. *Journal of Engineering*, *26*(5), pp.156-171.
19. Jin-Hyung Lee, Cho, Jaeyeon, Sangseom Jeong, and Jaehwan Lee (2012). "The settlement behavior of piled raft in clay soils." *Ocean Engineering* 53: pp. 153-163.
20. IS: 2950 (Part I-1981). Indian Standard Code of Practice for Design and Construction of Raft Foundations.
21. IS 2911 (Part 1/Sec 1 -2010). Indian Standard Code of Practice of Design and Construction of Pile Foundations, Part 1 - Driven Cast In-situ Concrete Piles.
22. IS 2911 (Part 1/Sec 4 -2010). Indian Standard Code of Practice of Design and Construction of Pile Foundations, Part 1 - Precast Concrete Piles in Prebored Holes.