Influence of Batter Angle on Settlement of a Piled Raft in Layered Clay

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Abstract:

This study presents a numerical analysis of influence of pile batter angles on the settlement behaviour of piled raft foundations in layered clay deposits. A 3×3 piled raft configuration was modelled in PLAXIS 3D, considering batter angles of 0°, 5°, 10°, and 15°, under vertical load intensities of 200 kPa, 300 kPa, 430 kPa, and 500 kPa and pile length for each case is taken same 12, 14, 16, 18 m respectively as four different cases. The simulation results indicate a consistent decrease in settlement with increasing batter angle. Notably, the configuration with a 15° batter angle achieved the most significant improvement, showing a maximum settlement reduction of approximately 19.3% compared to the vertical pile arrangement (0°). This enhanced performance is attributed to the better mobilization of lateral soil resistance and improved load transfer efficiency due to inclined pile geometry. The findings emphasized the effectiveness of incorporating 15° batter piles in piled raft foundations to control settlement in soft, stratified clayey soils.

Introduction:

In geotechnical engineering, the design of foundation systems in soft and compressible soils remains a critical challenge due to the risks of excessive total and differential settlement. Among the available solutions, piled raft foundations have gained prominence as an efficient and economical option. This hybrid system integrates the load-spreading capabilities of a raft with the deep load-transfer characteristics of piles, allowing the structure to utilize both shallow and deep bearing mechanisms effectively (Poulos, 2001; Wulandari & Tjandra, 2015). The raft primarily helps distribute structural loads over a large area, reducing contact pressure on the underlying weak soil, while the piles bypass the weaker strata to mobilize resistance from stiffer underlying layers, thereby enhancing both bearing capacity and stability (Ghosh & Dey, 2016; Ali et al., 2023).

A more advanced variant of this system incorporates batter piles installed at an inclination to the vertical axis which engage both axial and lateral components of resistance from the surrounding soil mass. Batter piles are known to improve load distribution by providing increased lateral confinement and shear resistance, which can significantly enhance the stiffness of the foundation system and mitigate horizontal displacements and rotational instability (Ural & Gergin, 2020;

Abdel-Azim et al., 2020). This becomes particularly relevant in layered cohesive soils, where the variation in undrained shear strength and compressibility across layers can lead to complex settlement behaviour under structural loading (Ayuluri et al., 2017; Ahmed et al., 2022).

While previous studies have focused extensively on parameters such as pile spacing, pile length, raft thickness, and soil improvement techniques, the specific influence of pile inclination i.e., batter angle on settlement control in layered clay remains under-investigated. Most traditional analyses assume vertical piles, which may not fully exploit the interaction potential between inclined piles and stratified soil profiles (Zoriyeh Aligholi, 2024; Khan & Sharma, 2023). The inclusion of batter piles introduces additional complexity into the load-sharing mechanism among the piles, the raft, and the supporting soil, particularly when subjected to variable loading intensities.

To address this gap, the present study conducts a detailed three-dimensional numerical analysis using PLAXIS 3D, focusing specifically on how different batter angles influence the settlement performance of piled raft foundations in layered clay deposits. The investigation evaluates a 3×3 pile configuration with varying pile batter angle (0°, 5°, 10°, and 15°), subjected to different vertical loading. The outcomes aim to quantify the settlement reduction potential associated with batter piles and identify an optimal inclination angle that enhances foundation performance while ensuring structural safety and cost-effectiveness in soft ground conditions.

2. Methodology

2.1 Numerical Model

In this study, three-dimensional numerical simulations were carried out using PLAXIS 3D to analyse the settlement behaviour of a piled raft foundation embedded in layered clay strata. The model comprised a 10 m × 10 m square raft with a thickness of 1 m, supported by a 3×3 arrangement of circular piles spaced uniformly. To assess the impact of pile inclination, batter angles of 0°, 5°, 10°, and 15° were incorporated. The subsurface profile included three vertically layered cohesive soils—soft, medium stiff, and stiff clay, each characterized using the Mohr-Coulomb constitutive model, which effectively captures elastic-perfectly plastic soil behavior. The piles were modelled as linear elastic embedded beam elements with full interaction enabled between the pile and soil, ensuring accurate load-transfer simulation. The raft was modelled as a rigid plate, allowing realistic load distribution across the pile group and the underlying soil. Boundary conditions and mesh refinement were carefully configured to maintain numerical accuracy and ensure model stability.

Fig.1 shows a typical 3D pile raft model as generated in PLAXIS 3D, illustrating the spatial configuration of the raft, piles, and surrounding soil.

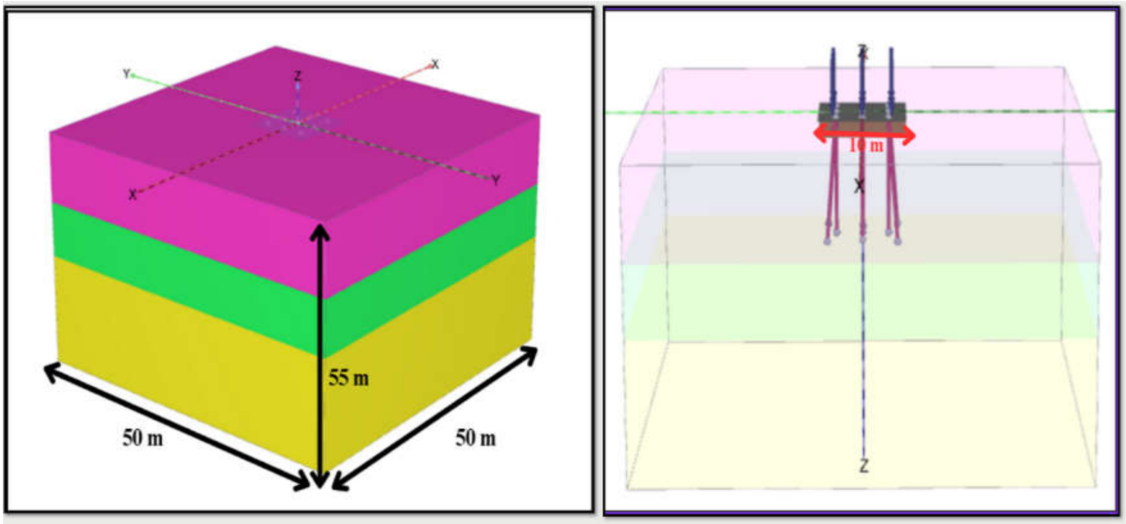

Fig.1 Modelling of the pile raft on layered clay

2.2 Geometry and Soil Conditions

Table 1. Geometry of Piled Raft Foundation

Parameter	Description
Raft Dimensions	10 m × 10 m (square)
Raft Thickness	1 m
Number of Piles	9 (3×3 grid)
Pile Diameter	0.6 m
Pile Lengths (varied cases)	12 m, 14 m, 16 m, 18 m
Batter Angles	0°, 5°, 10°, 15°
Pile Arrangement	Uniform spacing beneath raft (square grid)
Raft Material	Linear elastic
Pile Material	Linear elastic

Table 2. Soil Layer Properties (Mohr–Coulomb Model)

Soil Type (Layered)	Thickness (m)	Unit Weight (γ) kN/m³	Youngs Modulus (E) kPa	Cohesion (kPa)	Angle of Friction (°)	Poisson's Ratio
Soft Clay	9	15	8.0×10^3	10	0	0.4
Medium Stiff Clay	7	18	10×10^3	20	20	0.38
Stiff Clay	14	20	20×10^3	80	25	0.35

3. Result and Discussion

The three-dimensional finite element analysis carried out in PLAXIS 3D evaluated the settlement performance of piled raft foundations incorporating batter (inclined) piles under layered cohesive soil conditions. The study investigated batter angles of 0°, 5°, 10°, and 15°, while maintaining a constant raft thickness of 1.0 m and different pile length 12, 14, 16, 18 m in each case respectively. The subsoil profile comprised vertically stratified clay layers representing typical geotechnical field conditions. To assess the influence of vertical loading, four different load intensities 200 kPa, 300 kPa, 430 kPa, and 500 kPa were applied to the raft foundation model. The simulations were designed to replicate realistic boundary conditions and loading scenarios commonly encountered in practice for structures founded on soft to stiff clay deposits. The results provided insight into how varying the batter angle of piles contributes to enhanced load transfer mechanisms and reduction in total settlement, particularly in stratified weak soil environments.

Fig. 2 presents the settlement contour for a piled raft foundation incorporating 18 m-long piles, subjected to a 430 kPa vertical load and a 15° batter angle, embedded in layered clay strata. The plot reveals that the maximum settlement occurs beneath the central region of the raft, where the applied stress is most concentrated. Moving outward from the centre, the settlement magnitude progressively decreases toward the raft edges. This behaviour reflects typical raft-soil interaction patterns under uniform loading. The presence of soft clay with low undrained shear strength contributes significantly to the observed deformations, particularly near the pile tips, where load transfer is most active. The batter angle enhances lateral resistance but cannot entirely compensate for the compressibility of the underlying weak stratum, leading to measurable settlement accumulation in the central zone.

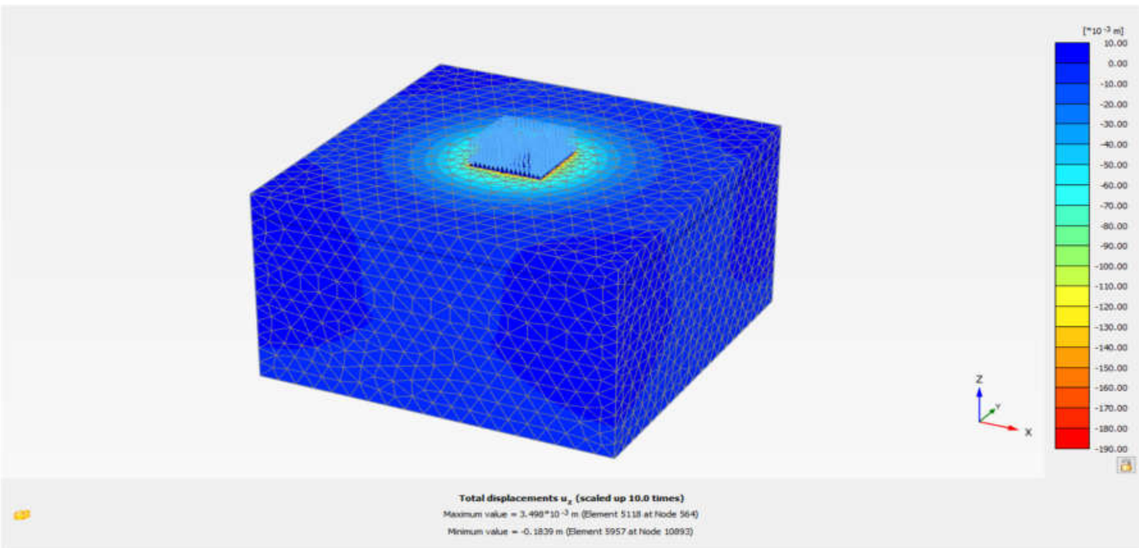

Fig. 2. Settlement profile for a 15° batter piled raft with 18 m piles under 430 kPa load in layered clay

Fig. 3. Shows the effect of increasing load intensities on settlement for a pile raft with different batter angles (0°, 5°, 10°, and 15°) using 12 m long piles. Settlement increases with load across all cases, but higher batter angles consistently result in lower settlement. The best performance is observed at a 15° batter angle, where the settlement at 500 kPa is reduced from approximately 420 mm (at 0°) to about 320 mm—representing a 23.8% reduction. This highlights the effectiveness of inclined piles in improving load transfer and minimizing settlement in layered clay.

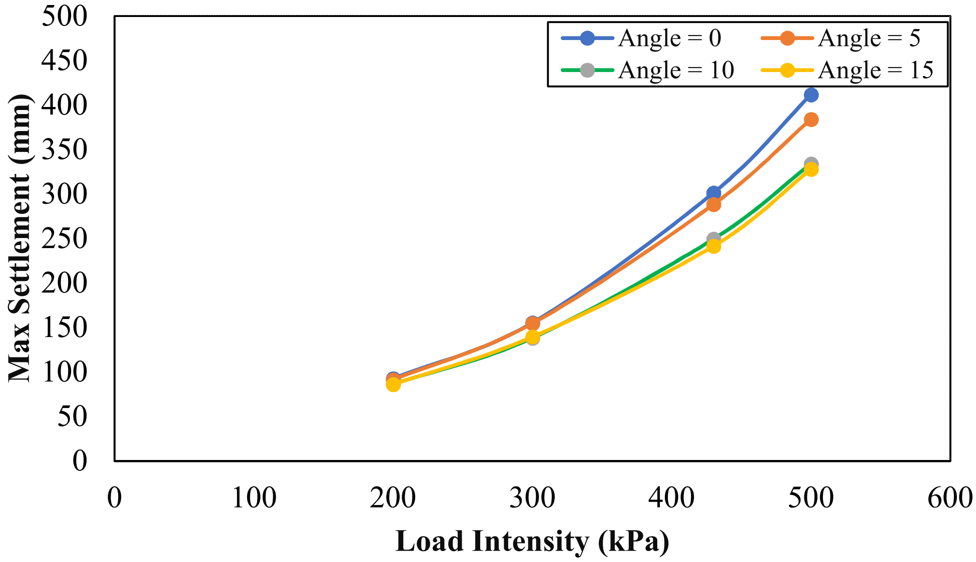

Fig. 3. Settlement variation with load intensity on the pile group in layered clay with constant pile lengths of 12 m and for variable pile batter angles of 0°, 5°, 10°, 15°

Fig. 4. Illustrates the effect of increasing load intensities on settlement for a pile raft foundation with different batter angles (0°, 5°, 10°, and 15°) using 14 m long piles. As with the previous case, settlement increases with load, but higher batter angles result in noticeably less settlement. The best performance is again observed at a 15° batter angle, where the settlement at 500 kPa drops from about 440 mm (at 0°) to 310 mm, showing a 29.5% reduction. This confirms that inclined piles significantly enhance the load transfer and reduce settlement, particularly in layered clay under high loads.

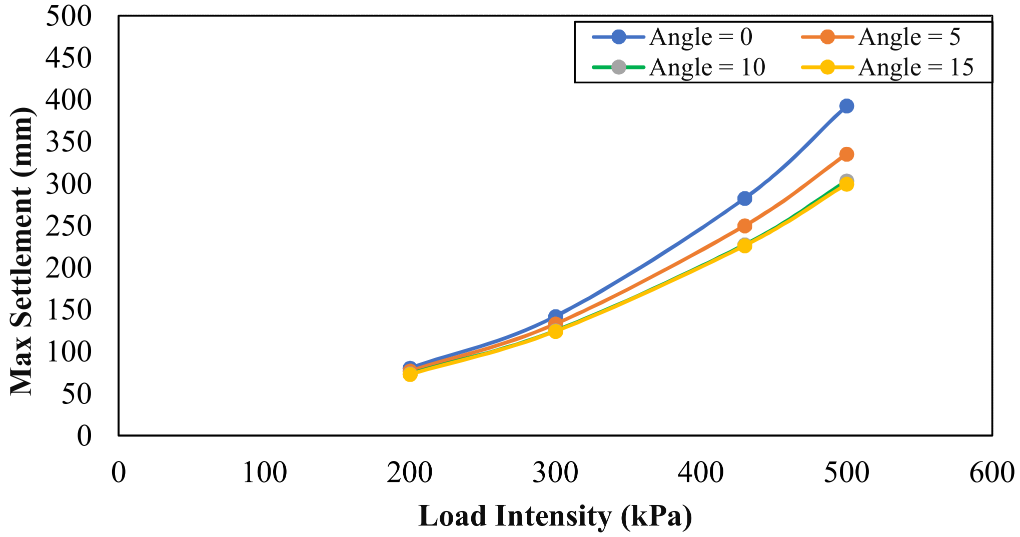

Fig.4 Settlement variation with load intensity on the pile group in layered clay with constant pile lengths of 14 m and for variable pile batter angles of 0°, 5°, 10°, 15°

Fig.5. Shows the effect of increasing load intensities on settlement for a pile raft with varying batter angles (0°, 5°, 10°, and 15°) using 16 m long piles. As with previous figures, settlement rises with load, but inclined piles continue to perform better than vertical ones. At 500 kPa, the maximum settlement decreases from about 435 mm for vertical piles (0°) to around 385 mm at a 15° batter angle—indicating a ~11.5% reduction. Though the improvement is less pronounced than in shorter piles, inclined piles still enhance load transfer and reduce settlement, especially under high loads in layered clay.

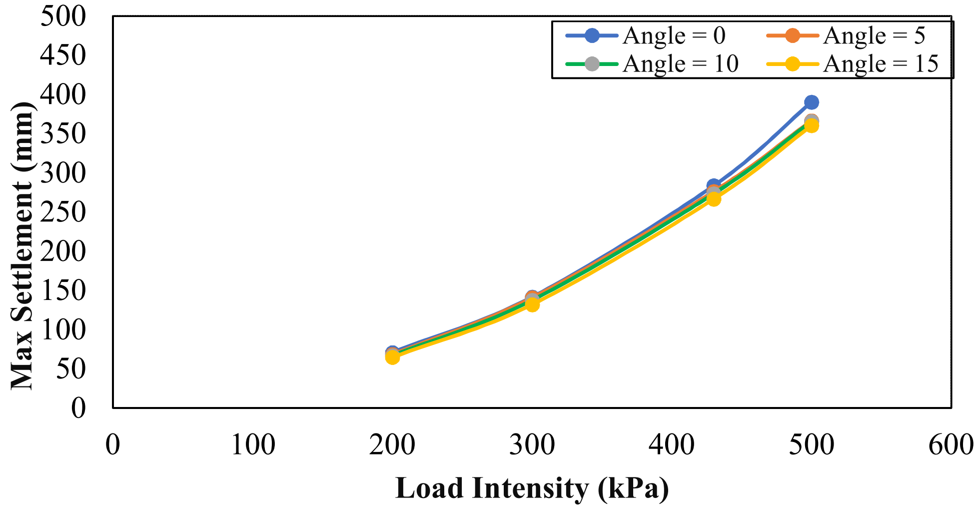

Fig.5. Settlement variation with load intensity on the pile group in layered clay with constant pile lengths of 16 m and for variable pile batter angles of 0°, 5°, 10°, 15°

Fig.6 Illustrates the impact of increasing vertical load intensities on settlement for different batter angles (0°, 5°, 10°, and 15°) using 18 m long piles. As in earlier cases, settlement increases with load, but inclined piles continue to offer improved performance. At a load of 500 kPa, the settlement decreases from approximately 330 mm for vertical piles (0°) to about 260 mm for piles with a 15° batter angle—showing a 21.2% reduction. This demonstrates that even with longer piles, increasing the batter angle effectively enhances load transfer and helps minimize settlement in layered clay under high loading conditions.

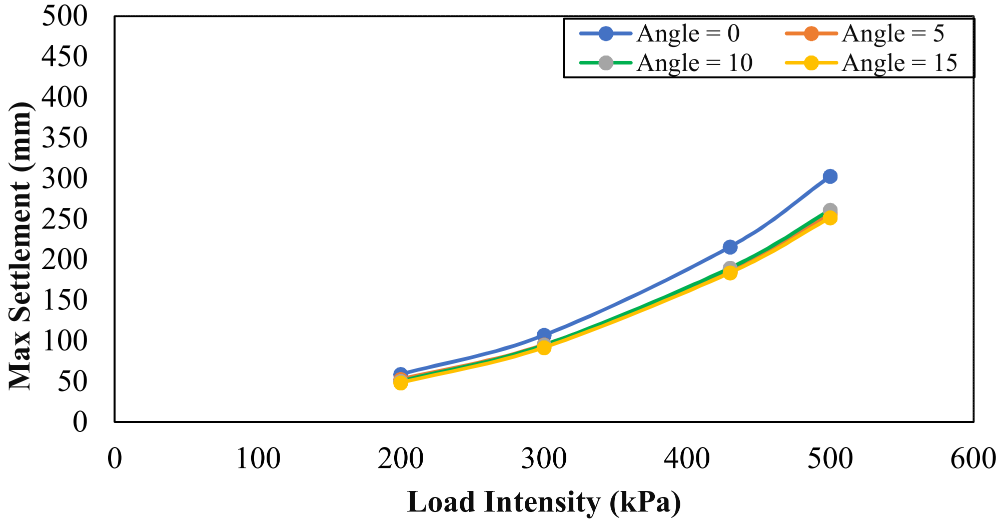

Fig.6 Settlement variation with load intensity on the pile group in layered clay with constant pile lengths of 18 m and for variable pile batter angles 0°, 5°, 10°, 15°

Conclusion:

This numerical study clearly illustrated that the increased pile batter angle reduced the foundation settlement in layered cohesive soils. Relative to the vertical configuration, the maximum settlement under 500 kPa loading decreased: by 12.2% at 5° batter angle, by 17.8% at 10° batter angle, and by 23.3% at 15° batter angle.

These results revealed the importance of optimizing pile inclination as part of piled raft design, especially in soft or stratified soil deposits. A 15° batter angle emerged as the most performing one in minimizing settlement while enhancing load-bearing behavior providing an insight for geotechnical practitioners aiming for performance-based foundation design.

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