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Analysis of The Effect of The Number And Depth of Bored Pile Groups on The Settlement of Building Foundations in Soft Soil

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Abstract

This study investigates the influence of bored pile group size and pile depth on the settlement of building foundations constructed on soft soil in the Pakunden area, Semarang City. The analysis considered bored piles with a diameter of 0.8 m, spacing of 2.4 m, group configurations of 2 × 2, 3 × 3, and 4 × 4 piles, and depths of 10 m, 16 m, and 24 m. Elastic settlement was evaluated using the Vesic analytical method, while consolidation and total settlement were analyzed numerically using PLAXIS 2D V22 with the Hardening Soil Model. The results indicate a nonlinear relationship between pile number, pile depth, and settlement. The smallest numerical settlement was 0.04107 m for the 3 × 3 group at 10 m depth, whereas the largest was 0.17625 m for the 4 × 4 group at 24 m depth. Increasing pile number or depth did not consistently reduce settlement. Foundation performance was controlled by soil stratification, load distribution, pile-group interaction, and the extent of compressible soil mobilized under loading. These findings support integrated analytical and numerical evaluation for design.

Keywords: *Bored pile, Pile depth, Pile group, Settlement, Soft soil.*

INTRODUCTION

The rapid development of high-rise buildings has increased the demand for foundation systems capable of safely transferring structural loads to soil layers with adequate bearing capacity. In areas characterized by low soil bearing capacity, shallow foundations may be unable to satisfy strength and deformation requirements, making deep foundation systems a more appropriate alternative. One of the most widely applied deep foundation types is the *bored pile*, which transfers structural loads through a combination of end-bearing resistance and shaft friction along deeper soil strata. The performance of bored piles is governed not only by axial capacity but also by deformation behavior and soil–pile interaction, both of which directly influence foundation settlement (Bandyopadhyay & Teng, 2024; Oteuil et al., 2022).

Soft soil is generally characterized by relatively low shear strength, high compressibility, and a strong tendency to undergo substantial deformation under structural loading. These characteristics may induce both immediate settlement and consolidation settlement, the latter developing progressively as excess pore-water pressure dissipates over time. Studies on foundations constructed in clayey soils have demonstrated that settlement behavior is strongly influenced by soil compressibility, drainage conditions, stress distribution, and the load-transfer mechanism between the foundation and the surrounding soil (Bhartiya et al., 2022; Senjuntichai et al., 2023). Consequently, settlement control is a critical aspect of foundation design because excessive deformation may impair structural serviceability even when the ultimate bearing capacity has not been exceeded.

Bored pile foundations are commonly installed in groups, and their behavior therefore cannot be evaluated solely on the basis of the response of individual piles. The number of piles within a group influences the extent of the stress zone, load distribution mechanisms, group efficiency, and the degree of pile–soil–pile interaction. Increasing the number of piles does not necessarily lead to a proportional reduction in settlement because the stress zones generated by adjacent piles may overlap and produce a collective response that differs substantially from that of a single pile. Previous studies have demonstrated that pile configuration and arrangement are important parameters governing load distribution and long-term settlement of pile groups in clayey soils (Hoang et al., 2024; Khatti et al., 2024; Xiong et al., 2024).

In addition to pile quantity, bored pile depth is an essential design parameter because it determines the length of the pile–soil interaction interface and the position of the pile tip relative to stronger soil strata. Increasing pile depth may enhance shaft resistance and facilitate load transfer toward deeper layers with greater stiffness and bearing capacity. Nevertheless, the relationship between pile length and settlement is not necessarily linear, particularly in layered soil profiles characterized by significant variations in stiffness and compressibility with depth. Numerical and field investigations indicate that pile length, stratigraphic conditions, and the mobilization of end-bearing and shaft resistance must be evaluated simultaneously to obtain a representative prediction of settlement behavior (Nguyen et al., 2024; Pham et al., 2024; Wang et al., 2024).

Soil–pile interaction becomes increasingly complex when multiple piles act simultaneously within a group founded on soft soil. Group loading may generate a broader stress influence zone, causing deformation not only around individual piles but also within the soil mass located between and beneath the entire foundation system. In clayey soils, consolidation further intensifies this behavior over time and may alter the distribution of load among piles throughout the service life of the structure. Previous analyses of pile foundations in soft clay have confirmed that the interaction among pile number, pile arrangement, soil properties, and loading conditions has a direct influence on the resulting settlement pattern (Li & Deng, 2023; Modak & Singh, 2023; Senjuntichai et al., 2023).

Advances in numerical analysis have enabled more detailed assessment of pile-group behavior compared with simplified analytical approaches. The finite element method can represent stress redistribution, soil deformation, soil–structure interaction, and consolidation processes while incorporating constitutive models that reflect the nonlinear behavior of soft soils. Numerical studies have shown that variations in pile dimensions, pile number, pile length, and pile configuration may result in different settlement responses because the interaction between the foundation and the surrounding soil develops in a nonlinear manner (Elsawwaf et al., 2022; Modak & Singh, 2022; Teji & Ashango, 2023). Therefore, combining analytical and numerical approaches is necessary to ensure that settlement evaluation considers not only bearing capacity but also the deformation response of the soil–foundation system under applied loading.

The present study was conducted in the Pakunden area of Semarang City, where the subsurface profile is predominantly composed of soft soil and consequently requires careful evaluation of deep foundation performance. The analyzed foundation system consists of bored piles with a diameter of 0.8 m and a center-to-center spacing of 3D, equivalent to 2.4 m, while the investigated pile-group configurations consist of 4 piles (2 × 2), 9 piles (3 × 3), and 16 piles (4 × 4). Pile depths of 10 m, 16 m, and 24 m were considered to allow a systematic comparison of the effects of pile number and pile depth on foundation settlement under the same ground conditions. These geometric variables and site characteristics were maintained in accordance with the original research data and were used as the basis for both analytical calculations and numerical modeling.

Previous studies have investigated pile-group behavior, piled-raft systems, load-transfer mechanisms, and settlement in clayey soils; however, the simultaneous effects of pile number and bored pile depth remain highly dependent on site-specific soil conditions and foundation configuration (Khatti et al., 2024; Wang et al., 2024; Zheng et al., 2023). This condition highlights the need for a systematic investigation in which different pile-group configurations and pile depths are evaluated within a single soft-soil profile to establish a consistent relationship among the principal design variables. Accordingly, this study analyzes the effects of the number and depth of bored pile groups on building foundation settlement by combining elastic settlement calculations based on the Vesic (1977) method with consolidation settlement analysis using PLAXIS 2D V22. The findings are expected to provide a technical basis for determining bored pile group configurations that satisfy bearing-capacity requirements while simultaneously controlling settlement through a more comprehensive understanding of soil–pile interaction.

RESEARCH METHODS

This study employed a quantitative analytical approach to evaluate the influence of the number and depth of bored pile groups on foundation settlement in soft soil conditions in the Pakunden area, Semarang City. The analyzed bored piles had a diameter of 0.8 m with a center-to-center spacing of

3D, equivalent to 2.4 m, while the pile group configurations consisted of 4 piles (2 × 2), 9 piles (3 × 3), and 16 piles (4 × 4). Three pile depths, namely 10 m, 16 m, and 24 m, were investigated to identify variations in settlement response under different foundation configurations. The soil parameters were derived from field investigations using Standard Penetration Test (SPT) data and laboratory testing, including unit weight, cohesion, internal friction angle, elastic modulus, and Poisson's ratio, while the analytical calculation of elastic settlement was carried out using the Vesic (1977) method for both single piles and pile groups.

In addition to the analytical calculation, a numerical analysis was performed using PLAXIS 2D V22 to simulate the soil–foundation interaction and consolidation behavior of bored pile groups under vertical loading. The *Hardening Soil Model* was adopted to represent the nonlinear deformation characteristics of the soft soil, while the numerical procedure included the development of the soil profile and pile-cap geometry, assignment of soil and structural material properties, generation of the finite-element mesh, initialization of geostatic stresses and groundwater conditions, installation of the bored piles and pile cap, application of axial loading, and subsequent consolidation analysis. The numerical outputs focused on immediate settlement, consolidation settlement, vertical displacement, deformation patterns, and excess pore-water pressure dissipation for each combination of pile number and pile depth. The results obtained from PLAXIS 2D V22 were subsequently compared with the analytical settlement calculations to assess the influence of pile-group configuration and pile depth on the overall settlement response of the foundation system.

RESULTS AND DISCUSSION

Soil–Foundation Model Characteristics, Bearing Capacity, and Elastic Settlement of Bored Pile Groups

The foundation analysis was conducted for the Pakunden area of Semarang City, where the subsurface profile is predominantly characterized by soft soil with relatively high compressibility. The investigated foundation consisted of bored piles with a constant diameter of 0.8 m and a center-to-center spacing of 3D, equivalent to 2.4 m, arranged into 2 × 2, 3 × 3, and 4 × 4 pile groups. Three pile depths of 10 m, 16 m, and 24 m were considered to evaluate the combined influence of pile-group dimensions and penetration depth on foundation response. These variables are relevant because the performance of pile groups in soft ground is controlled by soil stratification, pile geometry, group interaction, and the distribution of structural loads among individual piles (Bandyopadhyay & Teng, 2024; Oteuil et al., 2022).

The soil profile used in the numerical model consisted of several strata ranging from soft clay and soft fine sand in the upper layers to relatively stiffer clay and fine sand at greater depths. Such stratigraphic variability causes piles of different lengths to interact with soil layers having different stiffness, shear resistance, and compressibility characteristics. Consequently, changes in pile depth can alter both the magnitude of shaft resistance and the extent of the soil mass subjected to foundation-induced stresses. Previous studies have similarly demonstrated that accurate assessment of deep foundations requires consideration of soil layering and pile–soil interaction rather than relying exclusively on nominal pile dimensions (Beyruni et al., 2024; Pham et al., 2024).

The PLAXIS 2D V22 model incorporated soil parameters derived from field investigation and laboratory testing, including unit weight, effective cohesion, effective friction angle, stiffness parameters, Poisson's ratio, and other variables required by the *Hardening Soil Model*. This constitutive model was adopted because it can represent stress-dependent soil stiffness and nonlinear deformation more realistically than a simple linear-elastic formulation. The material parameters of the bored piles and pile cap were also incorporated to reproduce the interaction between structural elements and the surrounding soft soil. Numerical modeling of piled foundations has demonstrated that appropriate constitutive parameters are particularly important for reproducing settlement and load-transfer behavior in compressible clay deposits (Elsawwaf et al., 2022; Modak & Singh, 2022).

The principal input parameters used in the numerical model are presented in Tables 1–3, covering soil properties, bored pile properties represented by an *Embedded Beam*, and pile-cap properties, respectively. These inputs form the material basis for the subsequent stress, deformation, and consolidation calculations performed in PLAXIS 2D V22. Maintaining the original parameter values is essential because any modification to soil stiffness, strength, or structural properties would alter the predicted settlement response. Accordingly, Tables 1–3 below should be retained exactly as provided in the original research dataset and should not be recalculated or reformatted in a manner that changes their numerical contents.

Table 1. Input Data of Soil Properties

No.	Data input	Lapisan 1	Lapisan 2	Lapisan 3	Lapisan 4	Lapisan 5	Lapisan 6
1.	γsat	19,42 kN/m³	17,91 kN/m³	17,78	18,93 kN/m³	19,57 kN/m³	18,41 kN/m³
2.	γunsat	17,53 kN/m³	17,78 kN/m³	17,14 kN/m³	18,47 kN/m³	18,47 kN/m³	18,04 kN/m³
3.	*E*	5000 kN/m²	7000 kN/m²	7000 kN/m²	28300 kN/m²	37500 kN/m²	43000 kN/m²
4.	ν′	0,2	0,2	0,2	0,2	0,2	0,2
5.	*c*	19,61 kN/m²	20,01 kN/m²	10,01 kN/m²	17,46 kN/m²	17,46 kN/m²	17,46 kN/m²
6.	*ϕ*	31,16°	19,9°	19,91°	20,77°	21,65°	21,65°

Table 2. Input Data of Pile Properties with Embedded Beam

No.	Data input pile properties	Nilai
1.	γbeton	24 kN/m³
3.	E (Modulus Elastisitas)	30459481,3 kN/m²
4.	ν (Poisson ratio)	0,2

Table 3. Input Data of Pile Cap

No.	Data input pilecap	Nilai
1.	γbeton	24 kN/m³
2.	E (Modulus Elastisitas)	25742960,2 kN/m²
3.	H (Tebal pilecap)	1,3 m
4.	I (inersia)	0,325 m⁴
5.	EA (Eref × area pilecap)	33465848,26 m²
6.	EI (Eref × inersia)	8366462,066 m⁴

After the material properties had been assigned, the model geometry was discretized into finite elements through the PLAXIS mesh-generation procedure, followed by initialization of groundwater and geostatic stress conditions. The unit weight of water was maintained at 10 kN/m³, while groundwater conditions were incorporated to establish hydrostatic pore-water pressures and effective stresses throughout the soil profile. The numerical sequence subsequently consisted of the initial stress phase, installation of the bored piles and pile cap, application of axial structural loading, and consolidation analysis. Such staged modeling is important because the stress history and sequence of loading influence both immediate deformation and time-dependent consolidation in saturated soft soils (Bhartiya et al., 2022; Senjuntichai et al., 2023).

Before the numerical calculation was executed, a representative curve point was selected to monitor the relationship between applied loading and foundation displacement. The location of this monitoring point was maintained consistently so that vertical settlement could be evaluated under the same reference condition throughout the calculation phases. The original location used for curve extraction is shown in Figure 1 and constitutes part of the numerical setup employed in the study. This monitoring procedure facilitates the interpretation of load–settlement behavior and provides a consistent basis for comparing foundation responses among the investigated pile configurations (Rizvi et al., 2022; Teji & Ashango, 2023).

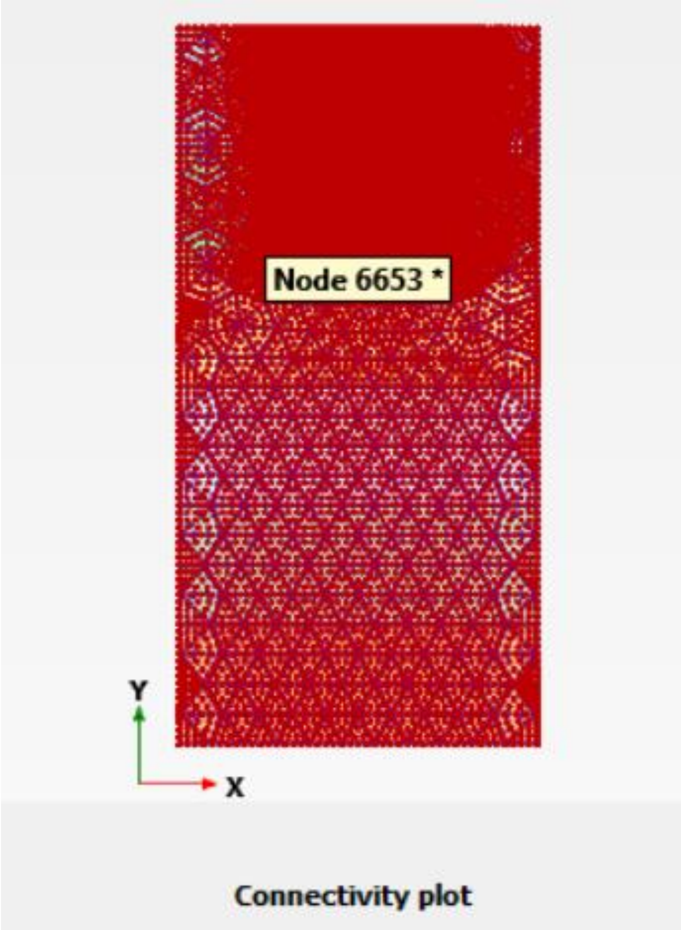

Figure 1. Determination of Curve Point Location

The axial capacity calculation showed that both end-bearing resistance and shaft-friction resistance contributed to the performance of the bored piles. For a single pile at a depth of 10 m with a cross-sectional area of 0.5024 m², the end-bearing capacity (*Qp*) was 150.569 kN and the accumulated shaft resistance (Σ*Qs*) was 572.736 kN, resulting in an ultimate capacity (*Qult*) of 723.305 kN. With a safety factor of 3, the allowable bearing capacity (*Qall*) was 241.101 kN, while the overall allowable capacity of a single pile increased from 90.43 kN at 2 m depth to 2,170.37 kN at 30 m depth. This progressive increase confirms that greater penetration mobilizes additional shaft and tip resistance, although higher bearing capacity does not necessarily imply lower settlement (Dang et al., 2025; Zeng et al., 2024).

The bearing capacity of the pile groups was evaluated using the Converse–Labarre approach to account for group efficiency and pile interaction. For the 2 × 2 configuration, the calculated group efficiency (*Eg*) was 0.795, resulting in an allowable group bearing capacity of 767.177 kN. Although increasing the number of piles increases the cumulative load-resisting components of the foundation system, the mechanical response of a pile group cannot be determined simply by multiplying single-pile capacity because overlapping stress zones modify the mobilization of soil resistance. This group effect has also been identified in full-scale and analytical studies, which show that interaction factors become increasingly important as pile-group dimensions and the number of piles increase (Dai et al., 2012; Jamil et al., 2022).

The Vesic (1977) method was subsequently applied to evaluate elastic settlement by considering deformation of the pile shaft, displacement at the pile tip, and settlement associated with shaft-load transfer. The calculated settlement of a single pile increased from 0.01055 m at 10 m depth to 0.01088 m at 16 m and 0.01220 m at 24 m, indicating a gradual increase rather than a reduction with increasing pile depth. A similar trend was observed for the pile groups, with settlement increasing as both group dimensions and pile depth increased. The complete analytical results are presented in Table 4.10 and Figure 4.9, which should be interpreted as the elastic-response baseline for comparison with the subsequent nonlinear PLAXIS settlement analysis (Khatti et al., 2024; Li & Deng, 2023).

Table 4. Recapitulation of Elastic Settlement of Pile Groups

Pile Depth (m)	Single-Pile Settlement, *Se* (m)	*Sg(e)*, Bg = 3.2 m (2 × 2)	*Sg(e)*, Bg = 5.6 m (3 × 3)	*Sg(e)*, Bg = 8.0 m (4 × 4)
10	0.01055	0.02111	0.02792	0.03337
16	0.01088	0.02176	0.02879	0.03441
24	0.01220	0.02439	0.03227	0.03857

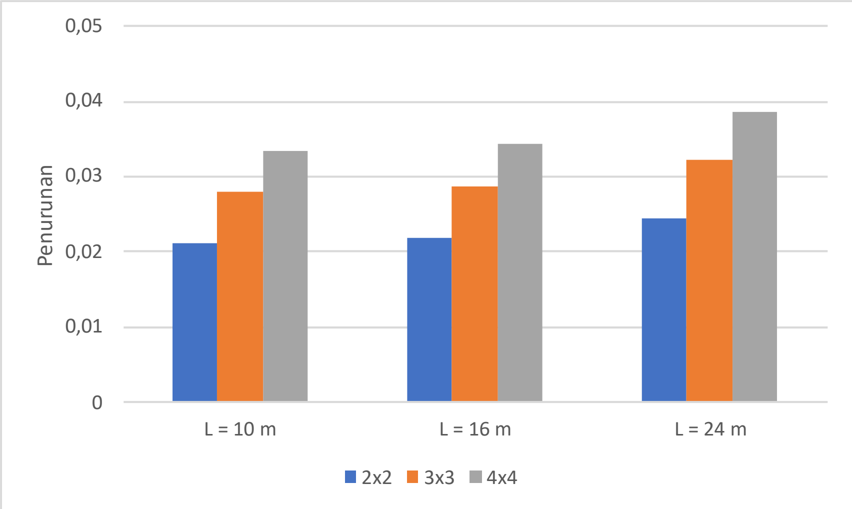

Figure 2. Results of Elastic Settlement Analysis Using the Vesic (1977) Method

The effect of pile-group size is evident from the analytical values, particularly when groups of different widths are compared at the same pile depth. At 10 m depth, the elastic settlement increased from 0.02111 m for the 2 × 2 group to 0.02792 m for the 3 × 3 group and 0.03337 m for the 4 × 4 group, while the same progressive pattern was observed at 16 m and 24 m. These results indicate that increasing the number of piles enlarges the effective group width and the volume of soil influenced by the applied load, thereby increasing the calculated group settlement despite the simultaneous increase in total bearing capacity. This behavior reinforces the principle that pile-group serviceability is governed by collective soil–pile interaction rather than by the resistance of individual piles considered independently (Kumar & Kumar, 2024; Bandyopadhyay & Teng, 2024).

Overall, the analytical results establish an important distinction between bearing-capacity improvement and settlement control for bored pile groups founded in soft soil. Greater pile depth increased the calculated axial resistance, yet the Vesic-based elastic settlement also increased gradually, reaching 0.03857 m for the 4 × 4 pile group at 24 m depth. The findings therefore demonstrate that increasing pile number or penetration depth does not inherently guarantee improved deformation performance, particularly when the resulting foundation geometry influences a larger volume of compressible soil. These analytical results provide the reference condition for the subsequent PLAXIS 2D V22 analysis, where nonlinear soil behavior, pore-water pressure dissipation, consolidation, and more complex group interaction are incorporated into the assessment (Xu et al., 2020; Modak & Singh, 2023).

Numerical Settlement Response and Effect of the Number of Bored Piles

The numerical analysis using PLAXIS 2D V22 was conducted to evaluate the settlement response of bored pile groups while explicitly considering nonlinear soil deformation and soil–foundation interaction. The investigated configurations consisted of 4 piles (2 × 2), 9 piles (3 × 3), and 16 piles (4 × 4), with pile depths of 10 m, 16 m, and 24 m. All configurations retained the same pile diameter of 0.8 m and were subjected to vertical structural loading through the pile cap. Numerical modeling is particularly important for pile groups in soft soil because collective deformation, stress redistribution, and pile–soil interaction may generate settlement behavior that differs substantially from predictions based solely on individual pile response (Elsawwaf et al., 2022; Teji & Ashango, 2023).

The PLAXIS model incorporated the *Hardening Soil Model* to represent the stress-dependent stiffness and nonlinear deformation characteristics of the soft soil layers. Settlement was evaluated after the sequential simulation of initial stress generation, foundation installation, axial loading, and consolidation, thereby allowing the response of the foundation to reflect both immediate and time-dependent deformation mechanisms. In saturated soft soil, the dissipation of excess pore-water pressure may progressively alter effective stress and increase vertical deformation after the structural load has been applied. Previous studies of piled foundations in clayey soils have similarly demonstrated that consolidation and time-dependent interaction can significantly influence long-term settlement and load redistribution within pile groups (Bhartiya et al., 2022; Senjuntichai et al., 2023).

The results indicate that the number of bored piles had a substantial but non-monotonic influence on total settlement. Increasing the number of piles did not consistently reduce foundation deformation because the relative performance of the 2 × 2, 3 × 3, and 4 × 4 configurations changed with pile depth. This behavior suggests that pile quantity cannot be interpreted independently of the soil profile, group dimensions, and stress interaction among adjacent piles. Similar findings have been reported for pile and piled-raft foundations, where pile arrangement and interaction factors exert a major influence on load distribution and settlement performance (Hoang et al., 2024; Jamil et al., 2022).

At a depth of 10 m, the 2 × 2 pile group produced a total settlement of 0.04743 m, while the 3 × 3 configuration produced the smallest value of 0.04107 m. Increasing the pile number further to the 4 × 4 configuration resulted in a settlement of 0.04851 m, which was greater than the settlements obtained for both the 2 × 2 and 3 × 3 groups. Thus, the reduction achieved by increasing the group from four to nine piles was not maintained when the number was increased to sixteen piles. This pattern is consistent with the concept that pile-group settlement is strongly affected by overlapping stress zones and collective deformation of the soil enclosed by and surrounding the piles (Khatti et al., 2024; Li & Deng, 2023).

A more pronounced group effect was observed at a depth of 16 m, where the 2 × 2 configuration produced a settlement of 0.04704 m, whereas the 3 × 3 and 4 × 4 configurations produced settlements of 0.09572 m and 0.09501 m, respectively. The two larger groups therefore exhibited settlements approximately twice as large as that of the four-pile configuration, despite containing considerably more foundation elements. This result indicates that increasing pile-group dimensions may enlarge the volume of compressible soil subjected to overlapping stresses and consequently produce greater collective deformation. Numerical investigations of pile groups have likewise shown that the interaction among piles can enlarge the effective deformation zone and significantly modify the load-transfer mechanism relative to an isolated pile (Shakeel & Ng, 2018; Bandyopadhyay & Teng, 2024).

Table 5. Recapitulation of Settlement Results of Bored Pile Groups

Bored Pile Depth (m)	2 × 2 Pile Group (m)	3 × 3 Pile Group (m)	4 × 4 Pile Group (m)
10	0.04743	0.04107	0.04851
16	0.04704	0.09572	0.09501
24	0.11358	0.08474	0.17625

At a depth of 24 m, the influence of pile quantity became even more variable, with settlement values of 0.11358 m for the 2 × 2 group, 0.08474 m for the 3 × 3 group, and 0.17625 m for the 4 × 4 group. The 3 × 3 configuration therefore generated the smallest settlement at this depth, whereas the 4 × 4 group produced the maximum settlement recorded among all nine analyzed configurations. The marked increase associated with the sixteen-pile group indicates that a larger number of piles can intensify the interaction with deeper compressible strata when the resulting stress influence zones become extensively superimposed. Studies on long piles and pile groups in soft deposits similarly demonstrate that settlement depends on the combined effects of pile geometry, soil stratification, shaft resistance, base resistance, and the volume of soil mobilized beneath the foundation (Nguyen et al., 2024; Wang et al., 2024).

The numerical behavior can be interpreted through the development of overlapping stress zones within the pile group. When pile spacing remains constant while the number of piles increases, the overall dimensions of the group and pile cap become larger, thereby extending the loaded area and increasing the volume of soil affected by foundation stresses. In soft and highly compressible ground, adjacent stress zones may merge and generate a group response in which the enclosed soil deforms together with the piles rather than allowing each pile to behave independently. This mechanism explains why an increase in pile quantity may improve total bearing resistance without necessarily producing a corresponding reduction in settlement (Dai et al., 2012; Xiong et al., 2024).

The variation among the three pile-group configurations also indicates that foundation efficiency must be assessed in terms of deformation as well as ultimate capacity. Although a greater number of piles generally provides a larger total resistance, serviceability performance depends on how the applied load is distributed through the pile cap and transferred into the surrounding soil. Installation disturbance, redistribution of effective stress, and interactions among adjacent piles can further modify the response of soft soil under group loading. Recent numerical studies confirm that construction-induced disturbance and pile-group interaction can significantly affect the subsequent deformation characteristics of deep foundation systems (Shao et al., 2025; Zheng et al., 2023).

A comparison with the analytical results presented in Subsection 3.1 further emphasizes the complexity of the group effect. The Vesic calculation produced a systematic increase in elastic settlement as the group dimension increased, whereas the PLAXIS results exhibited a distinctly non-linear pattern in which the 3 × 3 configuration occasionally generated less settlement than both the smaller and larger groups. This difference arises because the numerical model incorporates nonlinear soil behavior, consolidation, and broader stress redistribution that cannot be represented to the same extent by a simplified analytical settlement relationship. Similar discrepancies between simplified analytical predictions and advanced numerical simulations have been reported in studies of layered soil and pile-foundation systems (Modak & Singh, 2023; Pham et al., 2024).

From an engineering perspective, the results demonstrate that increasing the number of bored piles should not be regarded as an automatic strategy for reducing foundation settlement in soft soil. The smallest numerical settlement in the study was 0.04107 m for the 3 × 3 configuration at 10 m depth, whereas the greatest value was 0.17625 m for the 4 × 4 configuration at 24 m depth, demonstrating a wide range of responses across the analyzed models. Selection of the pile-group configuration should therefore consider group size, load distribution, pile spacing, soil compressibility, pile depth, and the resulting interaction between adjacent foundation elements. An integrated design approach based on both bearing capacity and settlement performance is consistent with contemporary research emphasizing settlement-based optimization of pile and piled-raft foundations (Kumar & Kumar, 2024; Xu et al., 2020).

The PLAXIS 2D V22 analysis confirms that the relationship between pile number and settlement is nonlinear under the soft-soil conditions investigated in this study. A larger pile group may either reduce or increase settlement depending on its depth and the characteristics of the soil layers participating in the load-transfer mechanism. The findings therefore demonstrate that pile quantity should be evaluated simultaneously with pile depth and soil stratigraphy rather than treated as an independent design variable. This interpretation provides the basis for the subsequent analysis of the specific effect of pile depth, which is examined separately in Subsection 3.3 without duplicating the numerical table presented in this section (Cho et al., 2012; Modak & Singh, 2022).

Effect of Bored Pile Depth on Settlement and Integrated Interpretation of Foundation Response

Pile depth represents one of the principal geometric parameters governing the settlement behavior of bored pile foundations in soft soil because it controls the length of soil–pile interaction and the soil strata mobilized during loading. In the present study, bored pile depths of 10 m, 16 m, and 24 m were investigated for the 2 × 2, 3 × 3, and 4 × 4 pile-group configurations. The numerical results indicate that increasing pile depth did not consistently reduce total settlement, demonstrating that deeper foundations do not necessarily provide superior serviceability performance under all soil conditions. This behavior is consistent with studies showing that pile length interacts with soil stratification, shaft resistance, base resistance, and stress-dependent soil stiffness rather than functioning as an independent settlement-control parameter (Nguyen et al., 2024; Wang et al., 2024).

For the 2 × 2 configuration, the total settlement obtained from PLAXIS 2D V22 was 0.04743 m at a depth of 10 m and decreased only slightly to 0.04704 m at 16 m. When the pile depth was increased further to 24 m, the settlement rose markedly to 0.11358 m, indicating that the deeper configuration activated a substantially greater deformation mechanism. This pattern demonstrates that the additional penetration length did not automatically improve settlement performance despite the corresponding increase in axial bearing capacity. Numerical investigations of axial pile behavior have similarly shown that longer piles may mobilize greater resistance while simultaneously interacting with a larger volume of deformable soil (Li, Hu, Li, & Xiong, 2024; Pham et al., 2024).

A different depth-dependent response was observed for the 3 × 3 pile group, where total settlement increased from 0.04107 m at 10 m depth to 0.09572 m at 16 m depth. At 24 m, settlement subsequently decreased to 0.08474 m, although this value remained considerably higher than that obtained at 10 m. The variation demonstrates that the settlement response is governed by the position of the pile group relative to layers with different stiffness and compressibility rather than by pile depth alone. Similar studies on piled foundations in clay have reported that changes in pile length can redistribute load between shaft and base resistance and modify the extent of the stress influence zone within the surrounding soil (Modak & Singh, 2022; Li & Deng, 2023).

The most pronounced depth effect was obtained for the 4 × 4 configuration, where settlement increased from 0.04851 m at 10 m to 0.09501 m at 16 m and finally to 0.17625 m at 24 m. The value of 0.17625 m represents the greatest settlement among all combinations examined in the present investigation. This trend suggests that the interaction of sixteen piles with deeper compressible strata produced a broader stress field and larger cumulative soil deformation beneath the pile group. The response is consistent with findings that group interaction and pile installation effects may become increasingly significant as the number of piles and the depth of the influenced soil mass increase (Xiong et al., 2024; Shao et al., 2025).

The depth-dependent behavior identified in the numerical model also illustrates the importance of evaluating bored pile foundations based on both ultimate capacity and serviceability criteria. Analytical calculations showed that the allowable bearing capacity increased progressively with pile depth, but the corresponding numerical settlement did not follow an inverse relationship. Consequently, a foundation with greater resistance capacity may still experience larger deformation if the additional pile length transfers stress into highly compressible soil layers. Experimental and analytical studies of pile groups likewise emphasize that load-carrying capacity and settlement should be evaluated together because increases in capacity do not necessarily guarantee reductions in displacement (Jamil et al., 2022; Rizvi et al., 2022).

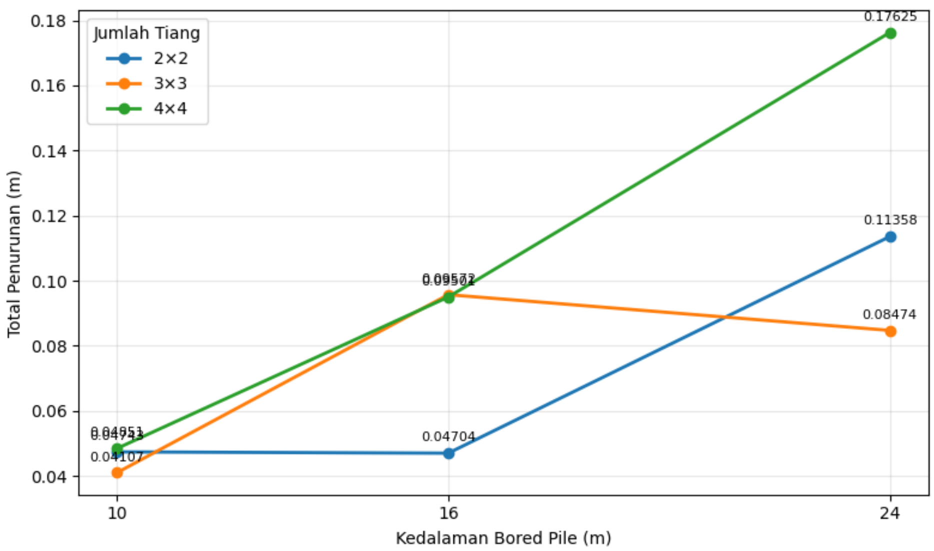

Figure 3. Relationship between Bored Pile Depth and Settlement

When the results are compared across depths, the lowest overall settlement occurred at 10 m for the 3 × 3 configuration, with a value of 0.04107 m. At 16 m, the smallest settlement was obtained for the 2 × 2 configuration at 0.04704 m, whereas the 3 × 3 and 4 × 4 groups produced substantially greater values of 0.09572 m and 0.09501 m, respectively. At 24 m, the 3 × 3 configuration again provided the smallest settlement of 0.08474 m compared with 0.11358 m for the 2 × 2 group and 0.17625 m for the 4 × 4 group. These changes confirm that no single pile quantity remained optimal at every depth, which is consistent with experimental evidence that pile-group response depends on the interaction among geometry, loading, and soil conditions (Jamil, Ahmad, Ullah, Ahmad, Sabri, & Majdi, 2022; Khatti et al., 2024).

Comparison with the Vesic analytical results further demonstrates a clear difference between elastic settlement and the more comprehensive settlement response obtained from PLAXIS. The analytical elastic settlement increased gradually with pile depth, whereas the PLAXIS results exhibited substantially larger and non-monotonic changes, particularly at depths of 16 m and 24 m. This difference can be attributed to the numerical model accounting for nonlinear soil deformation, stress redistribution, pore-water pressure development, and consolidation processes that are not represented in the same manner by the simplified elastic approach. Studies employing finite-element analysis for piled foundations have similarly shown that nonlinear constitutive behavior can produce settlement patterns that differ significantly from predictions based solely on analytical elastic relationships (Elsawwaf et al., 2022; Teji & Ashango, 2023).

The consolidation mechanism is particularly important in explaining the larger numerical settlements obtained for some deeper pile configurations. As structural loading is transmitted into saturated soft soil, excess pore-water pressure develops and subsequently dissipates, resulting in time-dependent volume change and additional settlement. A deeper pile group may influence a larger portion of the compressible profile, thereby generating settlement that cannot be explained only by immediate elastic deformation of the pile and surrounding soil. Time-dependent studies of pile and piled-raft foundations in clay have similarly demonstrated that consolidation significantly affects long-term deformation and may alter the distribution of loads among foundation components (Bhartiya et al., 2022; Senjuntichai et al., 2023).

The observed response also highlights the role of pile-group stress overlap in controlling settlement at greater depths. Increasing pile depth extends the shaft–soil interface, while increasing pile number enlarges the plan area over which stresses from individual piles interact, causing the combined influence zone to extend both laterally and vertically. Under soft-soil conditions, this mechanism can create a block-type response in which the group and the enclosed soil deform collectively rather than behaving as independent pile elements. Field and numerical investigations have demonstrated that such interaction strongly influences load transfer, displacement, and settlement of bored pile groups and other deep foundation systems (Dai et al., 2012; Bandyopadhyay & Teng, 2024; Zheng et al., 2023).

From a design perspective, the results demonstrate that increasing bored pile depth should not be adopted solely on the assumption that deeper piles will always reduce settlement. The selected depth should instead be determined by considering the soil profile, the location of compressible layers, the required bearing capacity, the number and arrangement of piles, and the corresponding soil–pile interaction mechanism. This integrated approach is particularly important for soft-soil foundations because both pile geometry and constitutive soil behavior contribute to the final deformation response (Oteuil et al., 2022; Zeng et al., 2024). Consequently, the most effective bored pile configuration is the one that achieves an acceptable balance between bearing capacity and settlement rather than simply maximizing pile number or penetration depth.

The combined analytical and numerical findings confirm that the influence of both pile number and pile depth on foundation settlement is inherently nonlinear. The results demonstrate that the lowest numerical settlement was 0.04107 m for the 3 × 3 group at 10 m depth, whereas the maximum settlement reached 0.17625 m for the 4 × 4 group at 24 m depth, indicating substantial variation among the investigated configurations. The differences between the Vesic and PLAXIS responses further demonstrate that foundation performance in soft soil is controlled by a combination of elastic pile deformation, consolidation, stress redistribution, pile-group interaction, and soil stratification rather than by pile geometry alone. These findings support the use of integrated analytical and numerical assessment for bored pile group design and are consistent with contemporary research emphasizing settlement-based evaluation of deep foundations in compressible soils (Xu et al., 2020; Cho et al., 2012; Kumar & Kumar, 2024).

CONCLUSION

The analytical results using the Vesic (1977) method show that increasing both pile depth and pile-group dimensions tends to increase the elastic settlement of the bored pile foundation. Single-pile settlement increased from 0.01055 m at a depth of 10 m to 0.01088 m at 16 m and 0.01220 m at 24 m, while the maximum elastic group settlement reached 0.03857 m for the 4 × 4 configuration at a depth of 24 m. These results indicate that an increase in pile depth, although capable of improving axial bearing capacity, does not necessarily improve foundation serviceability in terms of settlement. The settlement response is therefore governed by the interaction between pile geometry, load transfer, group dimensions, and the deformation characteristics of the surrounding soil.

The PLAXIS 2D V22 analysis further demonstrates that the effects of pile number and pile depth on settlement are nonlinear. The smallest total settlement was 0.04107 m for the 3 × 3 pile group at a depth of 10 m, whereas the largest settlement reached 0.17625 m for the 4 × 4 pile group at a depth of 24 m. Increasing the number or depth of bored piles therefore does not automatically reduce settlement because the response is influenced by soil stratification, stress-zone overlap, load distribution, consolidation, and soil–pile interaction. Consequently, the selection of bored pile number and depth in soft soil should be based on an integrated bearing-capacity and settlement analysis rather than solely on increasing pile quantity or penetration depth.

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