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Research Article

Bored Pile Foundation Performance: Theoretical and PLAXIS 2D Numerical Analysis of At-Ta'awun Tower

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Abstract
The soft soil condition beneath the At-Ta'awun Tower building of Universitas Muhammadiyah Surabaya requires a careful foundation evaluation that guarantees safety against axial and lateral loads as well as seismic-induced deformation. This study analyzes the axial capacity, lateral capacity, and deformation of bored pile foundations using static theoretical methods and PLAXIS 2D numerical analysis, and compares the results of both approaches. A quantitative case-study design was applied to the 21-story At-Ta'awun Tower, using secondary data comprising Standard Penetration Test (SPT) results, structural drawings, and structural data. Static axial and lateral capacities were estimated using Meyerhof, Decourt, Reese–Wright, and Broms formulations, while nonlinear finite-element analysis was performed in PLAXIS 2D using the Hardening Soil model. Results show that the static methods produced axial capacities that satisfy the upper-structure load demand, with the Meyerhof method giving the largest capacity. The PLAXIS 2D analysis indicated that an eight-pile group configuration satisfies both the axial capacity and allowable settlement criteria. Compared with the static methods, PLAXIS 2D produced a higher axial capacity, with an average deviation of 139.85%, and a smaller settlement, with an average deviation of -2.25%. For lateral capacity, the Broms method produced larger values than PLAXIS 2D, with an average deviation of 97.1%, while lateral deflection from the Broms method was smaller, with an average deviation of -75.2%. These differences are attributed to the ability of PLAXIS 2D to model soil-structure interaction, stress distribution, deformation, and soil nonlinearity in greater detail. Because the Hardening Soil parameters were derived from empirical SPT correlations without independent laboratory verification and the pile group was idealized under a two-dimensional plane-strain condition, the eight-pile, Hardening-Soil-based configuration is recommended as a conservative design-verification reference for similarly soft soil conditions rather than a generalized result. Further research is recommended to validate the results against field load-test data and three-dimensional modeling.

Introduction

A foundation is a substructure component that supports the upper structure and transfers its loads to the underlying soil. The selection of foundation type is influenced by soil conditions, the type and magnitude of the upper-structure load, the surrounding environment, construction time, and cost (Hardiyatmo, 2011). Foundations are generally classified into shallow and deep foundations, with deep foundations selected when the bearing capacity of the soil near the surface is insufficient (Primadaka & Yuwono, 2023; Sopiyanto et al., 2023). Deep foundations are further divided into driven piles and bored piles (Nursabrina & Arifin, 2023).

This study uses a bored pile foundation with a diameter of 50 cm and a depth of 21 m. Bored piles offer relatively good bearing capacity, lower cost, minimal vibration during installation, and flexibility in adjusting pile length. However, the estimation of bored pile capacity is influenced by construction method, concrete quality, soil condition, and pile geometry. In addition, the limitations of analytical models in accurately predicting bearing capacity remain a key motivation for further research in this field (Raisa & Chandrakaran, 2020).

A foundation must be carefully designed to avoid settlement that exceeds the allowable limit (Hamdhan et al., 2021; Primadaka & Yuwono, 2023; Amalia & Minaka, 2024), since excessive settlement endangers the supported superstructure (Rangkite, 2024). The stability and safety of a building depend strongly on the strength of its foundation, particularly for large-scale projects such as high-rise buildings (Saputri et al., 2025). The At-Ta'awun Tower of Universitas Muhammadiyah Surabaya is one of the tallest university buildings in Indonesia, with a height of 80.5 m consisting of 21 floors and a basement used for parking (Erfinanto, 2024). Site investigation using Standard Penetration Test (SPT) at two boreholes to a depth of 45.5 m each revealed a stratigraphy dominated by silty clay with an average N-SPT value below 15, classifying the site as Site Class SE (soft soil) according to SNI 1726:2019. This indicates weak, compressible, and deformation-sensitive soil, requiring a more rigorous foundation analysis to ensure the safety and stability of the supported structure (Mulyono & Agustina, 2022).

Foundation performance can be evaluated using various approaches, including static methods and finite element methods (Prilia et al., 2021). Static methods are calculated theoretically based on soil engineering properties, typically obtained from field tests such as SPT and differentiated by soil type (Muthmainnah, 2021). This study applies the static theories of Meyerhof (1976), Luciano Decourt (1982), and Reese and Wright (1977). However, significant discrepancies in pile design procedures and uncertainties in applying standard principles, together with the many parameters that must be considered, mean that alternative analytical approaches are needed to describe pile behavior more accurately (Momin et al., 2024). The finite element method has therefore become a reliable approach for determining the geotechnical capacity of bored piles that cannot be adequately analyzed using conventional design methods (Momin et al., 2024).

The finite element method is capable of accounting for soil nonlinearity, soil continuity, and soil-pile interface interaction, making it an effective tool for soil-structure interaction analysis, albeit at a relatively high computational cost (Choi et al., 2013). PLAXIS 2D is a finite-element-based program used for geotechnical analysis, in which soil models represent field soil behavior to obtain the relationship between load and pile settlement (Nursabrina & Arifin, 2023), and is also used to analyze deformation, stability, and bearing capacity in geotechnical problems (Rangkite, 2024). A prior comparison study by Momin et al. (2024), covering 15 different sites in Bangladesh, found that pile capacities from static load tests and numerical analysis achieved approximately 94% convergence, indicating that numerical analysis results can be sufficiently reliable and accurate.

PLAXIS 2D employs constitutive soil models to represent the stress-strain relationship. The Mohr-Coulomb (MC) model is one of the simplest and most commonly recommended models for preliminary geotechnical analysis (Dahal et al., 2024). The Hardening Soil (HS) model additionally considers the variation of soil stiffness with stress level and the different soil response under loading and unloading conditions, allowing it to represent soil deformation more realistically than the MC model, particularly for deep excavation and soil-structure interaction analysis (Dahal et al., 2024). Hacini et al. (2025) found that the HS model consistently outperformed the MC model in representing wall deflection, deformation pattern, and boundary conditions, with an error below 12%, whereas the MC model tended to overestimate displacement. Similarly, Pratiwi and Winoto (2025) evaluated axial capacity, lateral capacity, and settlement of bored piles using PLAXIS 3D with both MC and HS models compared against field Pile Driving Analyzer (PDA) and Static Loading Tests, finding that the HS model produced results closer to the Static Loading Test.

Despite this growing body of work, most existing comparisons between static analytical methods and PLAXIS-based numerical analysis have examined either a limited number of static formulas, driven or precast piles rather than bored piles, or soil profiles different from the deep, soft clayey silt encountered in the Surabaya region; comparative studies that jointly evaluate several established static methods against a Hardening-Soil-based PLAXIS model for a high-rise building foundation on such soft soil remain scarce. Moreover, several of the comparative studies cited above, including Momin et al. (2024), Suradi et al. (2024), and Pratama et al. (2018), were based on the Mohr-Coulomb rather than the Hardening Soil model, so the magnitude of deviation they reported may not be directly transferable to Hardening-Soil-based analyses such as the present one. This gap motivates the present study, which jointly evaluates axial capacity, lateral capacity, and deformation using four established static methods together with a Hardening-Soil-based PLAXIS 2D model calibrated to site-specific SPT data, for both a 4-pile and an 8-pile group configuration.

Based on the above, this study focuses on analyzing the performance of a bored pile foundation using both a theoretical approach and PLAXIS 2D numerical modeling, and evaluating the extent to which the two methods provide consistent results that can serve as a basis for foundation design consideration on soft soil, using the At-Ta'awun Tower of Universitas Muhammadiyah Surabaya as the case study. Specifically, the research addresses (1) the axial capacity, lateral capacity, and deformation of the bored pile foundation based on static methods; (2) the same performance parameters based on PLAXIS 2D numerical analysis; and (3) the differences between the two methods. The novelty of this study lies in the direct comparison of four established static methods with a Hardening-Soil-based PLAXIS 2D model for a high-rise building on soft clayey silt soil, providing practical insight for foundation design verification in similar soft-soil conditions in the Surabaya region.

Research Method

This study applies both a theoretical and a finite-element numerical approach (PLAXIS 2D) to analyze bored pile foundation performance, expressed in terms of axial capacity, lateral capacity, lateral deflection, and settlement, and to compare the results obtained from both approaches.

Study Area and Data

The case study is the At-Ta'awun Tower of Universitas Muhammadiyah Surabaya, located on Jalan Sutorejo No. 59, Surabaya, East Java. The building is a 21-story reinforced-concrete educational facility with a height of approximately 80.5 m. Secondary data were obtained from the project contractor (PT. Graha Muriatama Indonesia), comprising SPT soil-investigation data from two boreholes (DB-1 and DB-2) to a depth of 45 m, structural working drawings, and ETABS structural output. The weighted average N-SPT value, computed following SNI 1726:2019, was 7.72 for DB-1 and 6.40 for DB-2, confirming a Site Class SE (soft soil) classification at both points. Two column points nearest the boreholes, K1C.B (joint 98, near DB-1) and K1A (joint 126, near DB-2), were selected for evaluation because they best represent the field soil condition. The planned bored pile foundation has a diameter of 50 cm, a depth of 21 m, and concrete quality K500 (41.5 MPa), replacing the existing square precast pile foundation for the purpose of this study.

Upper-Structure Analysis (ETABS)

The superstructure was modeled in ETABS, including geometry definition, structural element definition, seismic and gravity load definition following applicable SNI provisions, and running of the analysis. The resulting joint reactions (axial force, shear force, and moment) at the two evaluated column points were extracted as the design input for the bored pile foundation. The maximum factored axial reactions obtained were 6488.99 kN at joint 98 and 6712.73 kN at joint 126.

Static (Theoretical) Analysis

The axial bearing capacity of a single pile was calculated using the Meyerhof (1976), Decourt (1982), and Reese and Wright (1977) SPT-based correlation methods, each combining end-bearing and skin-friction resistance components derived from the N-SPT profile. Group efficiency and block-failure capacity were then evaluated to obtain the group axial capacity for 4-pile and 8-pile configurations at each column point. Pile-group settlement was estimated using the Vesic (1977) approach and checked against the allowable settlement limits of Sowers (1993), S = L/250, and SNI 8460:2017, S = (15 + b/600)/100. Lateral bearing capacity and lateral deflection of the pile groups were evaluated using the Broms (1964) method for piles in cohesive soil, and checked against the allowable lateral deflection limit of 0.025 m specified for strong seismic design. A safety factor consistent with standard Indonesian geotechnical practice under SNI 8460:2017 was applied to the ultimate static capacities to obtain the allowable pile-group capacity used to determine the required configuration, so that the comparison between static and numerical results in the following section is made on an equivalent design basis.

Numerical Analysis (PLAXIS 2D)

The subsurface was modeled in PLAXIS 2D using the Hardening Soil (HS) constitutive model, with soil parameters derived from empirical correlations based on the SPT data of DB-1 and DB-2 without additional laboratory testing. The HS model was selected because it represents stress-dependent stiffness through three distinct stiffness moduli, namely the triaxial loading stiffness (E50), the unloading-reloading stiffness (Eur), and the oedometer stiffness (Eoed) (Hamdhan et al., 2021), which allows a more realistic representation of nonlinear soil-structure interaction than the Mohr-Coulomb model. Pile elements were modeled as embedded beam/plate elements with properties corresponding to the 50 cm diameter, K500 concrete bored pile. The modeling sequence consisted of geometry modeling, soil parameter definition, structural element definition, load application, mesh generation, staged construction, and calculation for both the 4-pile and 8-pile group configurations at each column point. Model boundaries were positioned at a sufficient lateral and vertical distance from the pile group to minimize boundary effects on the computed capacity and settlement, and a refined 15-node triangular mesh was applied around the piles, following the modeling good-practice recommendations in the PLAXIS 2D materials models manual (Bentley, 2023). Axial capacity, group settlement, lateral capacity, and lateral deflection were extracted from the PLAXIS 2D output and compared directly with the corresponding static-method results. Because the Hardening Soil parameters were obtained from empirical SPT correlations rather than from laboratory triaxial and oedometer testing, some uncertainty in the absolute stiffness values is expected; this limitation is discussed further in the Conclusion.

Results and Discussion

Axial Capacity and Configuration

Table 1 summarizes the group axial capacity obtained from the static methods and from PLAXIS 2D for the two evaluated column points. The Meyerhof (1976) method produced the largest axial capacity, satisfying the structural demand with only a 4-pile configuration, whereas the Decourt (1982), and Reese and Wright (1977) methods required an 8-pile configuration to satisfy the same demand. This is consistent with Yelvi et al. (2022), who reported a higher capacity from the Meyerhof method than from Reese and Wright, and with Al-Atroush et al. (2022), who noted that the classical Meyerhof method tends to overestimate large-diameter bored pile capacity by 14-46% because it assumes full mobilization of end-bearing and skin-friction resistance.

Table 1. Group Axial Capacity from Static Methods and PLAXIS 2D (kN)

Method	No. 98 (4 piles)	No. 98 (8 piles)	No. 126 (4 piles)	No. 126 (8 piles)
Meyerhof (1976)	7493.20	-	9049.41	-
L. Decourt (1982)	-	7659.15	-	9251.26
Reese & Wright (1977)	-	7817.60	-	8969.17
PLAXIS 2D	5880.30	18000.67	4253.40	22502.22

For the 8-pile configuration, PLAXIS 2D produced a substantially higher axial capacity than the static methods, with an average deviation of about 139.85%. This is attributed to the ability of the finite element method to model nonlinear soil-structure interaction and to represent stress distribution and soil deformation more realistically, together with the more complex soil parameters used in PLAXIS 2D compared with manual analysis (Suradi et al., 2024). Momin et al. (2024) reported PLAXIS-based capacities about 45% higher than conventional theoretical calculations, and Suradi et al. (2024) reported a difference of about 49%; the larger deviation obtained in the present study is attributed to the use of the Hardening Soil model, which involves three distinct stiffness parameters and therefore produces smaller deformation and a stiffer, higher-capacity response than the Mohr-Coulomb model used in those comparative studies (Pratiwi & Winoto, 2025).

Settlement

The group settlement results are summarized in Table 2. Settlement predicted by the Reese and Wright (1977) method was the largest among the static methods (0.0896 m at point 98 and 0.0875 m at point 126), exceeding the Sowers (1993) allowable limit of L/250 = 0.084 m, although it still satisfies the more permissive SNI 8460:2017 limit of 0.1542 m. PLAXIS 2D settlements were consistently smaller than the static-method settlements, with an average deviation of about -2.25%, and were closest to the Luciano Decourt (1982) results. A similar trend of smaller PLAXIS-based settlement was reported by Pratama et al. (2018) (-34.13%), Kresnohadi and Hamdhan (2015) (-21.76%), and Hasrul et al. (2023) (-27.15%); the smaller deviation obtained in this study is consistent with the correspondingly higher axial capacity computed by PLAXIS 2D, since a stiffer, higher-capacity foundation mobilizes proportionally less settlement under the same working load.

Table 2. Group Settlement from Static Methods and PLAXIS 2D (m)

Method	No. 98 (4 piles)	No. 98 (8 piles)	No. 126 (4 piles)	No. 126 (8 piles)
Meyerhof (1976)	0.0690	0.0690	0.0632	0.0632
L. Decourt (1982)	0.0846	0.0846	0.0819	0.0819
Reese & Wright (1977)	0.0896	0.0896	0.0875	0.0875
PLAXIS 2D	0.0816	0.0798	0.0801	0.0638

Lateral Capacity and Lateral Deflection

The calculated lateral capacities are summarized in Table 3. Only the 8-pile configuration satisfied the lateral load demand under both methods; the 4-pile configuration was inadequate at both column points. The Broms (1964) method produced a substantially higher lateral capacity than PLAXIS 2D, with deviations ranging from 67.8% to 146.9% (average 97.1%), broadly consistent with the 49% deviation reported by Pratama et al. (2018). This occurs because the Broms method relies on simplified assumptions of homogeneous, purely cohesive or purely cohesionless soil and an ultimate force-moment equilibrium that does not explicitly account for progressive soil stiffness degradation, whereas PLAXIS 2D computes the soil-pile response incrementally through nonlinear numerical analysis, in agreement with Kristianto et al. (2017), who found finite-element results closer to lateral load-test data than the Broms method.

Table 3. Group Lateral Capacity from Broms (1964) and PLAXIS 2D (kN)

Method	No. 98 (4 piles)	No. 98 (8 piles)	No. 126 (4 piles)	No. 126 (8 piles)
Broms (1964)	237.19	474.37	238.70	477.39
PLAXIS 2D	96.06	267.14	121.65	284.42

Table 4. Group Lateral Deflection from Broms (1964) and PLAXIS 2D (m)

Method	No. 98 (4 piles)	No. 98 (8 piles)	No. 126 (4 piles)	No. 126 (8 piles)
Broms (1964)	0.01168	0.00584	0.02551	0.01275
PLAXIS 2D	0.03900	0.03257	0.08437	0.06029

The lateral deflections obtained from the two approaches are presented in Table 4. Lateral deflection increased with the number of piles reduced in the group, consistent with Sekhar and Kishan (2025). The Broms method consistently underestimated lateral deflection relative to PLAXIS 2D, with a deviation ranging from -69.8% to -82.1% (average -75.2%), comparable to the -79.29% reported by Maktabipour and Motahari (2015). Because the Broms method idealizes the soil response and does not capture progressive elastoplastic behavior, it produces a stiffer and less deformable response than the numerical model (Maktabipour & Motahari, 2015). Consequently, none of the PLAXIS 2D group configurations satisfied the 0.025 m allowable lateral deflection limit for strong seismic design, whereas all static-method configurations satisfied this limit except the 4-pile group at point 126.

Conclusion

The static analysis shows that the Meyerhof (1976), Decourt (1982), and Reese and Wright (1977) methods all produce an axial capacity sufficient to support the superstructure load, with the Meyerhof method being the most efficient, requiring only a 4-pile configuration, while the other two methods require an 8-pile configuration. The largest static settlement, obtained from the Reese and Wright method (0.0896 m at point 98 and 0.0875 m at point 126), exceeds the Sowers (1993) allowable limit but remains within the SNI 8460:2017 limit. Lateral analysis using the Broms (1964) method shows that only the 8-pile configuration meets the lateral capacity requirement, and lateral deflection satisfies the 0.025 m limit for all configurations except the 4-pile group at point 126.

The PLAXIS 2D numerical analysis with the Hardening Soil model shows that the 8-pile configuration satisfies the axial capacity requirement at both column points, and all configurations satisfy the allowable settlement limit, with the largest settlement of 0.0816 m occurring in the 4-pile group at point 98. For lateral performance, only the 8-pile configuration at point 98 satisfies the lateral capacity requirement, and none of the configurations satisfy the 0.025 m allowable lateral deflection limit for strong seismic design.

The comparison between the two approaches indicates substantial differences in both capacity and deformation. PLAXIS 2D yields a higher axial capacity for the 8-pile configuration, with an average deviation of about 139.85%, and a smaller settlement, with an average deviation of about -2.25%, closest to the Luciano Decourt method. For lateral response, the Broms method yields a higher lateral capacity, with an average deviation of about 97.1%, and a smaller lateral deflection, with an average deviation of about -75.2%, than PLAXIS 2D. These differences arise because the static methods rely on empirical and analytical assumptions of homogeneous soil and simplified soil behavior, whereas PLAXIS 2D accounts for soil-structure interaction, stress distribution, soil deformation, and soil nonlinearity in greater detail through the finite element method. Overall, the 8-pile group configuration with a Hardening-Soil-based PLAXIS 2D model is recommended as the more conservative basis for foundation design verification in this soft-soil case, and further studies are recommended to validate the results against field load-test data and three-dimensional numerical modeling.

These conclusions should be interpreted within the limitations of the present study. The Hardening Soil parameters were derived from empirical SPT correlations without independent laboratory triaxial or oedometer testing, the PLAXIS 2D analysis idealizes the pile group under a two-dimensional plane-strain condition rather than a fully three-dimensional geometry, and the comparison is limited to a single case study, two column points, and four static methods. Consequently, the findings are intended as a design-verification reference for foundation planning under similarly soft soil conditions in the Surabaya region rather than as a generalizable conclusion for all bored pile foundations, and the recommended 8-pile, Hardening-Soil-based configuration should be confirmed against field pile load-test data and three-dimensional numerical modeling before final design adoption.

Author Contributions

Conceptualization, H.V.P.A and N.A.; Methodology, M.F.S.; Software, N.A.; Validation, M.F.S and D.; Formal Analysis, M.F.S.; Investigation, D.; Resources, M.F.S and D.; Data Curation, H.V.P.A.; Writing – Original Draft Preparation, H.V.P.A.; Writing – Review & Editing, H.V.P.A.; Visualization, N.A.; Supervision, N.A.; Project Administration, D.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

The datasets generated during and/ or analyzedduring the current study are available from the corresponding author on reasonable request.

Use of Generative AI

No generative AI was used.

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