

Numerical Evaluation of Axial Capacity and Settlement of a Bored Pile Foundation for a Hospital Building Using Finite Element and AllPile Analyses

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ABSTRACT: The performance of bored pile foundations for hospital buildings must satisfy both axial capacity and serviceability requirements, as excessive settlement may adversely affect structural and non-structural components, sensitive medical equipment, and overall building functionality. This study evaluated the axial bearing capacity and displacement response of a single bored pile at point P-86 of an Integrated Oncology Hospital Building project by comparing two numerical approaches, finite element method (FEM) analysis and AllPile Vertical Analysis, against field measurements obtained from a Pile Driving Analyzer (PDA) test. The investigated pile had a diameter of 0.80 m, an embedded length of 25 m, and a working load of 918 kN. Subsurface conditions were characterized using borehole BH-2 data, with groundwater encountered at approximately 10.5 m below ground level. The FEM analysis predicted an ultimate axial capacity of 985.98 tons and a displacement of 6.00 mm, whereas AllPile predicted an ultimate capacity of 1,365.21 tons, an allowable compressive capacity of 455.17 tons, and a settlement of 3.119 mm. In comparison, the PDA test indicated an ultimate capacity of 429 tons and a displacement of 7.60 mm. Relative to the PDA results, the FEM and AllPile ultimate capacities were higher by 129.83% and 218.23%, respectively, while the corresponding displacement differences were 21.05% and 58.96%. Thus, FEM provided predictions closer to the PDA results for both axial capacity and displacement, although a substantial discrepancy remained in the predicted ultimate capacity. The pile nevertheless satisfied the adopted working-load and serviceability requirements. These findings demonstrate that numerical predictions require site-specific calibration and validation against field measurements. Moreover, PDA-derived capacity should be interpreted as a dynamic field reference rather than as a direct substitute for conventional static pile load testing.

KEYWORDS: Axial capacity; bored pile; finite element analysis; load–settlement response; PDA test; soil–structure interaction

1. Introduction

Deep foundations are commonly adopted when near-surface soils lack sufficient strength or stiffness to safely support structural loads. Among these systems, bored piles are widely used

for large and heavily loaded structures because they can transfer axial loads to deeper and more competent soil layers through a combination of shaft and base resistance. Their performance, however, is governed by complex soil–pile interaction involving soil stiffness and strength, stratification, groundwater conditions, pile geometry, interface behavior, stress history, and construction effects. For critical facilities such as hospitals, reliable foundation performance is particularly important because excessive total or differential settlement may affect not only structural and non-structural components but also architectural finishes, mechanical and electrical systems, medical utilities, sensitive equipment, and the continuous functionality of healthcare services.

The axial resistance of a bored pile is primarily developed through shaft resistance along the pile–soil interface and base resistance beneath the pile tip. These resistance components are progressively mobilized and may require different levels of displacement before reaching their ultimate values. Consequently, pile performance cannot be adequately characterized by ultimate bearing capacity alone; the associated load–settlement response must also be considered to ensure compliance with both ultimate and serviceability requirements. Previous studies have demonstrated that axial pile behavior is highly sensitive to nonlinear soil response, soil stratification, stiffness assumptions, interface characteristics, construction conditions, and the relative mobilization of shaft and base resistance [1–6]. Accurate prediction of these mechanisms therefore remains an important challenge in geotechnical foundation design.

Finite element method (FEM) analysis provides a numerical framework for representing the interaction between the pile and surrounding soil and for evaluating the development of stresses, strains, and displacements under applied loading. Compared with conventional analytical approaches, FEM can explicitly incorporate soil layering, groundwater conditions, constitutive soil behavior, pile–soil interfaces, and nonlinear stress–deformation relationships within a unified numerical model. Recent studies have demonstrated the effectiveness of FEM for evaluating pile and foundation load–settlement behavior under various geotechnical conditions [3, 7–9]. Nevertheless, the reliability of FEM predictions depends strongly on the quality and representativeness of soil parameters, constitutive models, interface properties, boundary conditions, mesh configuration, and other modelling assumptions. Consequently, a sophisticated numerical model does not necessarily provide an accurate representation of field pile behavior when these parameters are insufficiently calibrated to actual site conditions.

In engineering practice, specialized pile-analysis programs such as AllPile provide a more computationally efficient alternative for estimating axial bearing capacity and settlement using established analytical and semi-empirical procedures. Such approaches require fewer modelling decisions than continuum-based FEM and are therefore attractive for routine foundation assessment and design. However, their simplified representation of soil–pile interaction may not fully reproduce the stress redistribution, progressive resistance mobilization, and deformation mechanisms occurring in heterogeneous ground conditions. The use of different analytical frameworks can consequently produce substantially different estimates of ultimate capacity and settlement even when the same pile geometry and subsurface information are adopted.

This methodological uncertainty creates an important engineering problem. Numerically predicted pile capacity and settlement may differ considerably from the response measured under field conditions, making it difficult to determine whether a design model provides a sufficiently realistic representation of actual pile performance. This issue is particularly

relevant to bored piles because their field behavior is influenced not only by the inherent properties of the surrounding soil but also by construction-related factors, including drilling disturbance, borehole stability and cleaning, groundwater conditions, sediment accumulation at the pile base, slurry management, and concrete placement [5, 6]. These effects are difficult to reproduce completely in numerical or semi-empirical models and can alter the mobilization of both shaft and base resistance. Field measurements are therefore essential for assessing the extent to which calculated pile responses represent actual site behavior.

Despite the extensive application of numerical and analytical methods in pile foundation design, project-specific studies that directly compare continuum-based FEM and practical AllPile Vertical Analysis using identical pile geometry, loading conditions, subsurface data, and a common field-test reference remain limited. Previous investigations have generally demonstrated the capabilities of individual modelling approaches, whereas less attention has been given to quantifying the magnitude of disagreement between different prediction methods and field observations for the same bored pile [3, 7–9]. Moreover, comparisons based solely on ultimate capacity provide an incomplete assessment because a model may adequately predict bearing resistance while providing a substantially different estimate of settlement. An integrated comparison of both axial capacity and displacement is therefore required to evaluate the practical reliability of alternative modelling approaches.

The present study addresses this gap through a project-specific assessment of a single bored pile at point P-86 of an Integrated Oncology Hospital Building project. The investigated pile has a diameter of 0.80 m and an embedded length of 25 m. Its axial response is evaluated using two distinct approaches: a two-dimensional FEM model and AllPile Vertical Analysis. Predictions from both methods are compared with the reported Pile Driving Analyzer (PDA) test response for the same pile. The novelty of the study lies not in proposing a new numerical formulation, but in providing an integrated evaluation of two commonly applied engineering approaches against a project-specific field reference while simultaneously considering ultimate axial capacity and displacement. This comparison enables the magnitude of prediction discrepancies to be quantified and provides a basis for examining the potential influence of modelling assumptions, subsurface characterization, construction conditions, and field-test interpretation.

Accordingly, this study aimed to evaluate the axial performance and serviceability of the P-86 bored pile by comparing FEM and AllPile Vertical Analysis predictions of axial bearing capacity and settlement with the reported PDA field response, thereby quantifying model–field discrepancies and assessing the suitability of the investigated pile under the adopted working-load and settlement criteria. The AllPile procedure is referred to throughout this study as *AllPile Vertical Analysis* rather than *p–y curve analysis*. The p–y method is primarily used to characterize the lateral soil–pile response, whereas the present AllPile model applies vertical axial loading with zero applied shear force and bending moment. Accordingly, the scope of this study is restricted to axial compression behavior and does not include an assessment of lateral pile capacity.

2. Materials and Methods

2.1. Study Data and Foundation Geometry.

This study employed secondary project data comprising the BH-2 borehole investigation, geotechnical parameters, bored pile geometry, design working load, AllPile output, finite element method (FEM) output, and Pile Driving Analyzer (PDA) test results. The analysis focused on a single bored pile located at point P-86 and subjected to axial compression. The investigated foundation consisted of a 0.80 m diameter bored pile with an embedded length of 25 m and a cross-sectional area of 0.503 m². The applied vertical working load was 918 kN, equivalent to approximately 93.61 tons. The principal geometric, loading, and field-reference parameters are summarized in Table 1.

Table 1. Main foundation and loading parameters.

Parameter	Value
Analysis point	P-86
Foundation type	Bored pile
Pile diameter, D	0.80 m
Embedded length, L	25 m
Cross-sectional area	0.503 m ²
Working vertical load	918 kN
Working load	93.61 tons
Groundwater level	10.5 m
Field reference	PDA test

The subsurface profile was established from borehole BH-2 and consisted predominantly of silty clay in the upper strata, followed by silty sand and increasingly dense sandy materials at greater depths. The Standard Penetration Test (SPT) resistance and interpreted soil stiffness generally increased with depth, indicating progressively stronger and stiffer foundation materials. Groundwater was encountered at approximately 10.5 m below ground level. Because BH-2 was the only borehole available for the present analysis, its profile was adopted as representative of the subsurface conditions at P-86. This assumption introduces uncertainty because soil strength, stiffness, stratification, and groundwater conditions may vary spatially within the same construction site. The BH-2 profile was therefore treated as a project-specific representation of the investigated pile location rather than a complete characterization of the entire hospital foundation area [10–12].

2.2. Analytical Framework.

The axial performance of the investigated bored pile was evaluated in terms of ultimate bearing capacity, allowable capacity, and settlement. Ultimate axial resistance was considered to comprise shaft resistance developed along the pile–soil interface and base resistance mobilized beneath the pile tip. The relative contribution of these components depends on soil properties, interface conditions, pile displacement, and the progressive mobilization of resistance along the pile [1, 4]. Previous field and numerical investigations have also demonstrated that pile-base resistance can be strongly influenced by settlement, construction conditions, and the degree of resistance mobilization [3, 5, 13–15]. For the AllPile analysis, allowable axial capacity was determined using the factor-of-safety procedure adopted in the original project

calculation. Factors of safety of 3.0 and 2.0 were applied to shaft and base resistance, respectively. These values were retained to reproduce the original project analysis and should therefore be regarded as project-specific engineering assumptions rather than universal design factors applicable to all bored piles.

The assessment also considered pile deformation because satisfactory ultimate capacity does not necessarily ensure acceptable serviceability performance. The project adopted an allowable settlement criterion of 80 mm, corresponding to 10% of the pile diameter. This value was treated exclusively as the project-adopted serviceability criterion and not as a universal settlement limit prescribed by SNI 8460:2017. Numerical predictions were compared with the PDA field reference in terms of ultimate axial capacity and reported displacement. The percentage difference between each numerical result and the corresponding PDA value was calculated as:

$$\text{Percentage difference} = \frac{|\text{Numerical result} - \text{PDA result}|}{\text{PDA result}} \times 100\% \quad (1)$$

The investigated pile was considered satisfactory under the analyzed loading condition when the applied working load remained below the adopted allowable axial capacity and the predicted settlement remained below the project-adopted settlement criterion. Because PDA testing derives pile response from dynamic measurements, the PDA result was treated as a project-specific field reference rather than as a direct equivalent of a conventional static axial pile load test. This distinction is important because field and numerical studies have demonstrated that pile response depends on the adopted loading and interpretation procedures [16–18].

2.3. AllPile Vertical Analysis.

The pile was modeled in AllPile as a drilled shaft with a diameter of 0.80 m and an embedded length of 25 m. The concrete surface was defined as rough, and the pile was assumed to be vertical and subjected to single-pile axial compression without pile-cap interaction. A vertical working load of 918 kN was applied at the pile head, while shear force, bending moment, and torsional moment were set to zero. The AllPile simulation therefore represented axial compression exclusively and was not intended to evaluate lateral pile behavior. The soil profile was defined according to the BH-2 investigation at depths of 0, 1.5, 5.5, 10.5, 14.5, and 30 m. The principal soil inputs included unit weight, cohesion, internal friction angle, deformation modulus, SPT-related parameters, and soil classification. These parameters controlled the analytical and semi-empirical estimation of shaft and base resistance. SPT-based approaches remain widely used for estimating pile load-transfer behavior where detailed laboratory or advanced in situ measurements are unavailable [1]. The factors of safety adopted in the original AllPile calculation were 3.0 for shaft resistance and 2.0 for base resistance. The AllPile analysis produced an ultimate compressive capacity of 1,365.21 tons and an allowable compressive capacity of 455.17 tons. Given a working load of approximately 93.61 tons, the predicted allowable capacity was approximately 4.86 times the applied working load. The model geometry, subsurface profile, and axial loading configuration are illustrated in Figure 1. The AllPile procedure is referred to throughout this study as *AllPile Vertical Analysis* rather than *p–y analysis*, because p–y formulations are principally associated with lateral pile–soil interaction under horizontal loading [17].

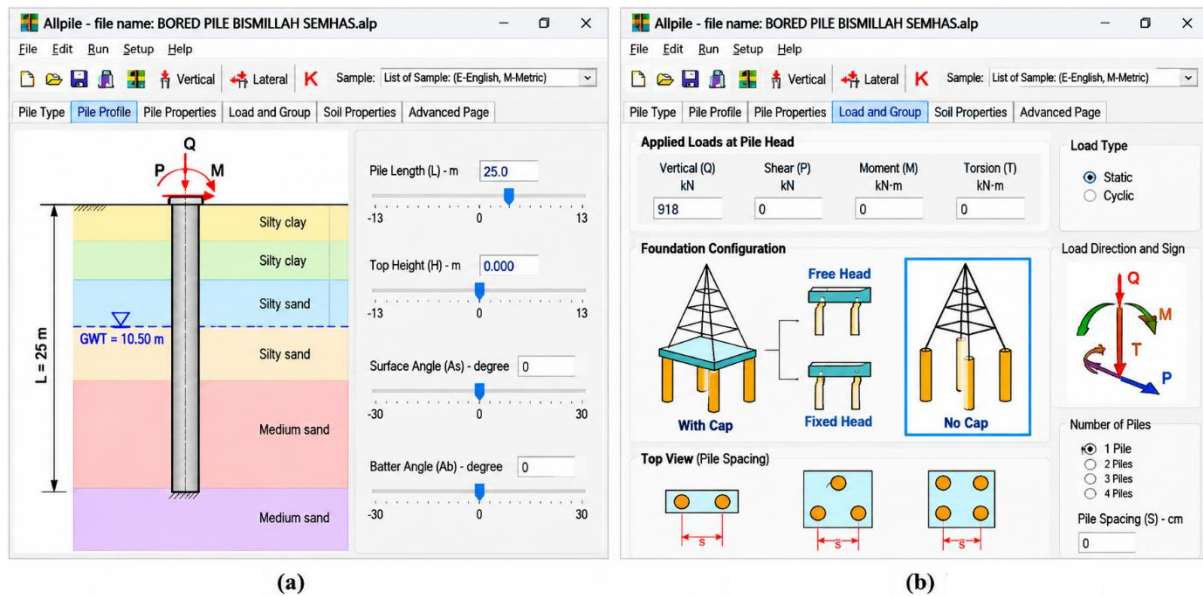


Figure 1. AllPile Model Configuration: (a) Pile Geometry and Soil Profile; (b) Vertical Loading Configuration.

2.4. Finite Element Modeling.

A two-dimensional axisymmetric FEM model was developed to simulate the axial interaction between the bored pile and the surrounding soil. The axisymmetric formulation was selected because the pile had a circular cross-section and was subjected to concentric axial compression. This approach provides an efficient representation of the radial stress and deformation field surrounding a vertically loaded single pile while avoiding the computational requirements of a full three-dimensional model. FEM has been widely applied to investigate pile–soil interaction, load transfer, settlement, and stress redistribution under vertical loading [3, 8, 10, 11].

The numerical soil profile was established from the BH-2 borehole and divided into layers according to changes in soil classification and SPT resistance. The groundwater table was assigned at 10.5 m below ground level. Soil behavior was represented using the Mohr–Coulomb constitutive model because the available geotechnical investigation primarily provided conventional parameters, including unit weight, cohesion, friction angle, and deformation modulus. Although more advanced constitutive models can reproduce nonlinear stiffness behavior in greater detail, their application requires additional parameters that were unavailable in the project dataset. The Mohr–Coulomb formulation was therefore selected as a practical compromise between the available geotechnical information and the requirements of the numerical analysis.

The bored pile was represented as a linear-elastic structural material with a diameter of 0.80 m and an embedded length of 25 m. The concrete was assigned a unit weight of 24 kN/m³, a Young's modulus of 25,000 MPa, and a Poisson's ratio of 0.20. Elastic pile behavior was assumed because the primary objective was to evaluate the axial response of the pile–soil system rather than structural failure of the reinforced-concrete pile.

Pile–soil interaction was represented explicitly using interface elements that permitted relative displacement and shear-stress transfer between the pile and surrounding soil. An interface reduction factor, (*R*_{inter}), of 0.70 was adopted. Accordingly, the interface friction angle and cohesion were defined as 70% of the corresponding soil friction angle and cohesion, respectively. This assumption represented a moderately rough concrete–soil interface and avoided assuming full mobilization of the surrounding soil shear strength at the pile surface.

Explicit representation of pile–soil interface behavior is important because nonlinear interface response can significantly affect predicted shaft resistance and load–settlement behavior [4, 20].

The numerical domain extended 15 m horizontally from the pile axis and approximately 10 m below the pile tip, resulting in a total model depth of 35 m. The vertical boundaries were restrained against horizontal movement while remaining free to deform vertically, whereas the bottom boundary was restrained against both horizontal and vertical displacement. The ground surface remained free, the pile head was subjected to vertical loading, and the pile centerline represented the axis of symmetry.

The domain was discretized using relatively coarse elements away from the pile and progressively refined elements near the pile shaft and base, where the largest stress and displacement gradients were expected. A global element size of approximately 1.0 m was adopted, while the mesh surrounding the pile was locally refined to approximately 0.20–0.30 m. The final model contained approximately 4,500 finite elements. A mesh-refinement assessment was performed by comparing the adopted discretization with a finer mesh, and the resulting difference in pile response remained below approximately 5%. The adopted mesh was therefore considered sufficiently refined for the comparative objectives of this study. The resulting FEM configuration is presented in Figure 2.

The numerical calculation proceeded sequentially through generation of the initial geostatic stress state, establishment of soil layers and groundwater conditions, activation of the bored pile and pile–soil interface, incremental application of the axial working load, continuation of loading toward the numerical ultimate condition, and strength-reduction analysis. During strength reduction, the soil cohesion and friction angle were progressively reduced until the model approached numerical failure. The calculation was considered converged when the global force residual was less than 1×10^{-3} of the reference load and incremental displacement between successive calculation stages became sufficiently small.

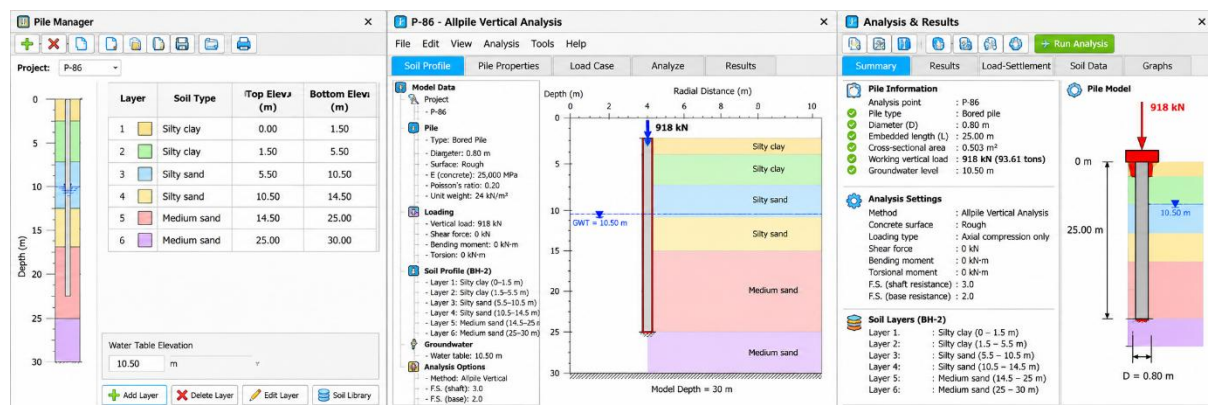


Figure 2. Finite Element Model Showing Soil Stratification, Groundwater Level, Bored Pile, Pile–Soil Interface, Model Boundaries, and Local Mesh Refinement.

2.5. Soil Parameters Adopted in the FEM Analysis.

The soil parameters adopted in the FEM model were derived from the BH-2 investigation and interpreted according to the reported soil classification and SPT resistance. Because the available project investigation was predominantly based on field SPT measurements, deformation moduli were estimated using representative correlations with soil type and penetration resistance. Such parameter interpretation is commonly required in numerical

foundation analysis when direct stiffness measurements are unavailable, although the resulting uncertainty should be explicitly recognized because settlement predictions are particularly sensitive to soil stiffness and constitutive assumptions [2, 4, 12]. The adopted parameters are summarized in Table 2. Soil stiffness and friction angle generally increased with depth, consistent with the increasing penetration resistance indicated by the BH-2 investigation. The upper 5.5 m was characterized by silty clay with deformation moduli of 8–12 MPa, whereas the deeper sandy layers exhibited progressively higher stiffness, reaching 55 MPa in the dense sand layer between 30 and 35 m. The groundwater table at 10.5 m was incorporated when determining effective stresses below the groundwater level.

Table 2. Soil parameters adopted in the FEM analysis.

Depth (m)	Soil description	γ (kN/m ³)	c (kPa)	ϕ (°)	E (MPa)	ν	Drainage
0–1.5	Silty clay	16.5	20	18	8	0.35	Undrained
1.5–5.5	Silty clay	17.0	25	20	12	0.35	Undrained
5.5–10.5	Silty sand	18.0	10	28	18	0.30	Drained
10.5–14.5	Silty sand	18.5	8	30	25	0.30	Drained
14.5–25.0	Medium sand	19.0	5	33	35	0.28	Drained
25.0–30.0	Medium sand	19.5	3	35	45	0.28	Drained
30.0–35.0	Dense sand	20.0	2	36	55	0.27	Drained

The deformation moduli in Table 2 should be regarded as representative interpreted values rather than direct laboratory measurements. This constitutes an important source of model uncertainty because soil stiffness strongly controls the predicted load–settlement response [2, 4, 8]. Consequently, uncertainty in the adopted stiffness parameters may contribute to differences between FEM predictions and the field response.

2.6. Pile–Soil Interface and Model Parameters.

The pile–soil interface was explicitly represented using $R_{\text{inter}} = 0.70$, with interface friction and cohesion reduced relative to the corresponding surrounding soil properties. This formulation allowed relative pile–soil displacement while transferring normal and shear stresses across the interface. Such treatment provides a more realistic representation of shaft resistance than imposing complete displacement compatibility between the pile and adjacent soil, particularly because interface behavior can significantly influence the nonlinear load-transfer response of piles [4, 20].

The selected reduction factor was intended to represent the interaction between cast-in-place concrete and the surrounding soil under bored-pile conditions. A perfectly rough or fully bonded interface was not assumed because drilling and construction processes can modify the pile–soil contact condition. Construction-induced disturbance and base conditions have been shown to affect bored-pile resistance and load-transfer characteristics [5, 14]. This interface assumption is also important when comparing FEM with AllPile because the two approaches mobilize shaft resistance differently. AllPile calculates shaft resistance through its analytical and empirical formulations, whereas FEM derives resistance from stresses transferred through the explicitly modeled interface.

The principal numerical assumptions are summarized in Table 3. The same pile geometry, groundwater level, representative BH-2 soil profile, and working load were maintained wherever applicable in both modelling approaches to improve the consistency of the comparison.

Table 3. Summary of FEM Modelling Assumptions.

Parameter	Adopted value
Model type	2D axisymmetric
Soil constitutive model	Mohr–Coulomb
Pile diameter	0.80 m
Pile length	25 m
Groundwater level	10.5 m
Model width from pile axis	15 m
Model depth	35 m
Global mesh size	~1.0 m
Local mesh size around pile	0.20–0.30 m
Approximate number of elements	4,500
Interface reduction factor	$R_{\text{inter}} = 0.70$
Pile Young's modulus	25,000 MPa
Pile Poisson's ratio	0.20
Pile unit weight	24 kN/m ³
Working load	918 kN
Strength-reduction multiplier	4.356
Convergence criterion	Global force residual < 0.1% of reference load
Primary loading mode	Axial compression

2.7. Loading Procedure and Determination of FEM Capacity.

The FEM analysis was initially conducted under the working load of 918 kN to determine the corresponding pile displacement under service conditions. The axial load was applied incrementally to minimize numerical instability and allow progressive development of pile–soil interaction. Following the working-load stage, strength-reduction analysis was conducted to investigate the numerical ultimate condition of the pile–soil system. Strength-reduction procedures progressively decrease soil shear-strength parameters until numerical failure develops and are widely used in finite element geotechnical stability assessment [3, 10, 18].

The strength-reduction analysis produced a numerical multiplier of 4.356. In the original FEM post-processing, the reference pile stress was 4,500 kN/m². For the pile cross-sectional area of 0.503 m², this corresponded to a reference pile force of approximately 2,263.5 kN. The original FEM output subsequently reported an ultimate pile capacity of 985.98 tons. Because the objective of this study was to compare the reported project outputs obtained from FEM, AllPile, and PDA testing, the reported FEM capacity of 985.98 tons was retained throughout the comparative analysis.

Importantly, the strength-reduction multiplier was interpreted as a numerical parameter associated with progressive reduction of soil shear strength toward numerical failure rather than as a conventional pile-design factor of safety. It was also not treated as directly equivalent to the ultimate resistance obtained from a static pile load test. The FEM ultimate capacity was therefore used as a numerical prediction and compared with the AllPile estimate and PDA field reference to quantify the differences among the modelling and field-based approaches.

2.8. Comparative Assessment and Model Limitations.

The performance of FEM and AllPile was evaluated by comparing their predicted ultimate capacities and settlements with the PDA field reference. Absolute and percentage differences were calculated to quantify the magnitude of disagreement among the approaches. Because PDA testing is based on dynamic pile response and signal interpretation, numerical proximity

to the PDA result was interpreted only as relative agreement for the investigated pile and not as proof that one modelling method is universally more accurate than another. Interpretation of pile-test results can itself depend on the testing method and analytical procedure used to derive pile resistance [16].

The modelling framework was designed to maintain consistency in pile geometry, working load, groundwater level, and the representative BH-2 soil profile. Nevertheless, several sources of uncertainty remained. The use of a single borehole limited characterization of spatial subsurface variability, while several soil stiffness parameters were interpreted rather than directly measured. The FEM analysis further relied on the Mohr–Coulomb constitutive model and a prescribed pile–soil interface reduction factor. Actual bored-pile construction effects, including drilling disturbance, borehole cleaning, slurry conditions, base sediment, and concrete placement, were not explicitly simulated, despite evidence that these factors can substantially influence bored-pile resistance [5, 14].

Accordingly, the numerical models were treated as project-specific engineering assessments rather than universally calibrated prediction models. The comparative methodology was intended to determine whether the numerical approaches reproduced the general magnitude of the observed axial response, identify the extent of numerical–field disagreement, and assess whether the investigated pile satisfied the adopted axial capacity and serviceability requirements under the specified working load.

3. Results and Discussion

3.1. Axial Bearing Capacity.

The ultimate axial capacities obtained from the analytical methods, numerical analyses, and PDA test are compared in Table 4. The results show considerable variation among the different approaches, indicating the sensitivity of predicted pile capacity to the calculation method and the assumptions used to represent soil–pile interaction. Among all methods, the Meyerhof method produced the highest ultimate capacity of 1,720.79 tons, followed by AllPile at 1,365.21 tons, Reese and Wright at 1,108.35 tons, and FEM at 985.98 tons. In contrast, the PDA test yielded a substantially lower ultimate capacity of 429 tons. The AllPile analysis also provided an allowable compressive capacity of 455.17 tons. Given the working load of 918 kN, equivalent to approximately 93.61 tons, the AllPile allowable capacity was approximately 4.86 times the applied working load.

Table 4. Comparison of Ultimate Axial Pile Capacity Obtained Using Different Methods.

Method	Base resistance, Q_p (tons)	Shaft resistance, Q_s (tons)	Ultimate capacity, Q_u (tons)	Difference from PDA (%)
Meyerhof	1,165.16	555.63	1,720.79	301.12
Reese and Wright	205.06	903.29	1,108.35	158.36
AllPile	871.73	493.48	1,365.21	218.23
FEM	—	—	985.98	129.83
PDA test	40.00	389.00	429.00	0.00

As shown in Table 4, all analytical and numerical methods overestimated the ultimate capacity relative to the PDA field reference. The FEM prediction exceeded the PDA result by 556.98 tons, corresponding to a difference of 129.83%, whereas the AllPile prediction was

936.21 tons higher, representing a difference of 218.23%. The analytical methods produced even larger discrepancies, with Reese and Wright and Meyerhof exceeding the PDA result by 158.36% and 301.12%, respectively. Among the two numerical approaches evaluated in detail, FEM therefore produced the capacity estimate numerically closest to the PDA result. Nevertheless, a difference of 129.83% remains substantial and should not be interpreted as close agreement between the numerical prediction and field reference.

Several factors may explain these numerical–field discrepancies. First, the BH-2 borehole was adopted as the representative subsurface profile for P-86, although local soil conditions may vary spatially within the project area. Variations in soil strength, stiffness, stratification, and groundwater conditions over relatively short horizontal distances can substantially influence both shaft and base resistance. Consequently, reliance on a single borehole introduces uncertainty into the numerical representation of the actual ground conditions surrounding the tested pile.

Second, actual bored-pile construction conditions may differ considerably from the idealized conditions represented in the numerical models. Drilling can disturb the soil along the pile shaft, while inadequate borehole cleaning may leave sediment at the pile base and reduce the mobilized end-bearing resistance. Groundwater, slurry conditions, and concrete placement can further modify the pile–soil interface. Previous studies have demonstrated that construction-induced disturbance and pile-base sediment can substantially affect the bearing behavior of bored piles [5, 6].

Third, several numerical soil parameters were interpreted from field investigation data and correlations rather than obtained from direct measurements at the P-86 location. Pile capacity is particularly sensitive to soil shear strength, interface resistance, stiffness, and the properties of the bearing layer. Consequently, even moderate uncertainty in these parameters may produce substantial differences in calculated ultimate capacity.

Fourth, FEM and AllPile represent soil–pile interaction differently. FEM treats the soil and pile as an interacting continuum and allows stresses and deformations to redistribute throughout the numerical domain. AllPile, in contrast, employs analytical and semi-empirical relationships to calculate shaft and base resistance. These differences in formulation influence the predicted mobilization and distribution of pile resistance and partly explain the discrepancy between the two approaches.

A particularly important difference can be observed in the resistance components reported in Table 4. AllPile predicted a base resistance of 871.73 tons and a shaft resistance of 493.48 tons, whereas the PDA interpretation indicated only 40 tons of base resistance and 389 tons of shaft resistance. Thus, the discrepancy in shaft resistance was relatively moderate compared with the very large difference in base resistance. The AllPile base resistance was more than 20 times the PDA-derived value, indicating that the assumed mobilization of pile-tip resistance was the principal contributor to the high AllPile ultimate capacity. This observation is consistent with studies demonstrating that bored-pile base resistance is particularly sensitive to pile-tip conditions, construction-induced disturbance, base sediment, and the degree of resistance mobilization [2, 5, 6].

A further source of discrepancy is the fundamental difference between the PDA test and the numerical procedures. PDA testing evaluates pile response dynamically and derives resistance through the interpretation of stress-wave measurements, whereas FEM and AllPile estimate pile behavior under idealized numerical or analytical loading conditions. The PDA

result should therefore be regarded as a project-specific dynamic field reference rather than as a direct equivalent of static numerical capacity. Exact agreement among these approaches should not be expected.

The overall differences in ultimate capacity are illustrated in Figure 3, which clearly shows that all analytical and numerical predictions exceeded the PDA field reference. The figure also confirms that FEM produced the lowest predicted ultimate capacity among the calculation methods and was therefore numerically closest to the PDA result. However, the remaining discrepancy emphasizes that increasing numerical sophistication alone does not guarantee agreement with field observations. Reliable pile-capacity prediction requires appropriate site characterization, realistic soil and interface parameters, consideration of construction effects, and calibration against relevant field measurements.

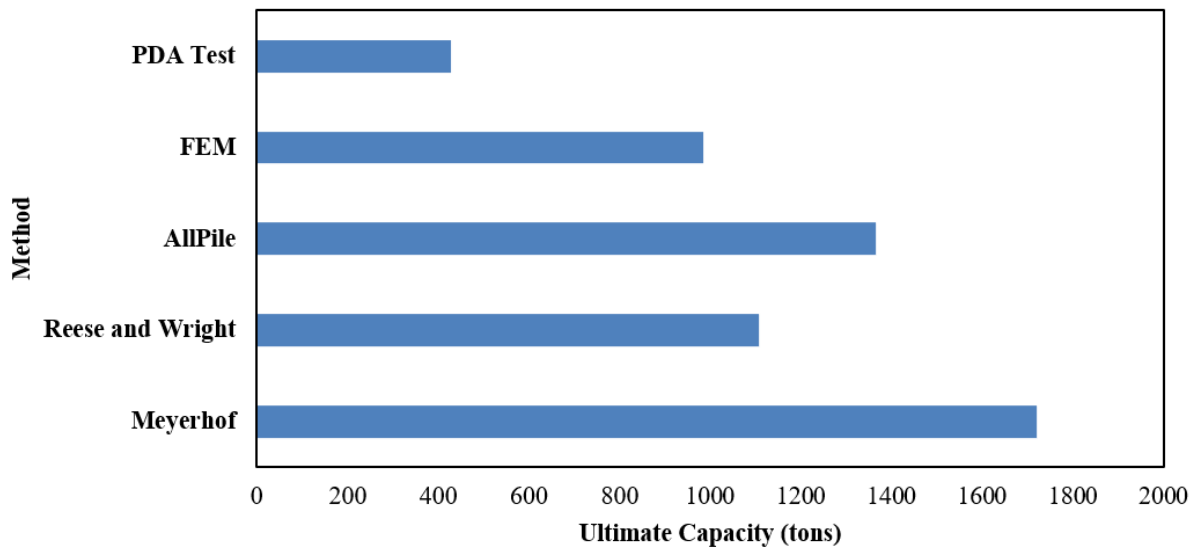


Figure 3. Comparison of Ultimate Axial Pile Capacities Obtained From Analytical, Numerical, and PDA methods.

3.2. Settlement Response.

The settlement responses obtained from AllPile, FEM, and the PDA test are compared with the project-adopted allowable settlement criterion in Table 5. AllPile predicted the smallest settlement of 3.119 mm, whereas FEM predicted 6.00 mm and the PDA test reported a displacement of 7.60 mm. Relative to the PDA result, the absolute difference was 4.481 mm for AllPile and 1.60 mm for FEM, corresponding to percentage differences of 58.96% and 21.05%, respectively. FEM therefore provided the numerical settlement prediction closest to the reported PDA displacement.

Table 5. Comparison of Pile Settlement.

Method	Settlement (mm)	Difference from PDA (mm)	Difference from PDA (%)	Percentage of allowable settlement (%)
AllPile	3.119	4.481	58.96	3.9
FEM	6	1.6	21.05	7.5
PDA test	7.6	0	0	9.5
Allowable criterion	80	—	—	100

The differences can be related to the different treatment of soil stiffness, nonlinear soil behavior, pile–soil interface, and load-transfer mechanisms. A lower predicted settlement indicates a comparatively stiffer numerical response. The AllPile prediction was approximately 48% lower than the FEM prediction, indicating a substantially stiffer predicted response under the analyzed load. Recent studies have demonstrated that pile settlement is strongly affected by soil stiffness, pile–soil interaction, stress redistribution, and long-term soil response [1–4,7]. Therefore, the lower AllPile settlement should not automatically be interpreted as evidence of higher accuracy; it reflects the assumptions embedded in the adopted analytical formulation. All calculated and reported settlements were substantially below the project-adopted allowable settlement of 80 mm. The FEM settlement represents 7.5% of the adopted limit, while AllPile and PDA correspond to approximately 3.90% and 9.50%, respectively.

The results therefore indicate that total settlement of the investigated pile is not a governing serviceability concern under the specified working load. However, the PDA settlement value must be interpreted carefully because PDA is primarily a dynamic testing technique. It should not be treated as directly equivalent to the settlement measured during a conventional static axial pile load test. The previously reported Vesic analytical settlement of 7.664 mm was also close to the reported PDA value of 7.60 mm. Nevertheless, agreement at a single pile location does not establish general validity throughout the project. Figure 4 shows a comparison of the predicted and reported pile settlements against the adopted allowable settlement criterion.

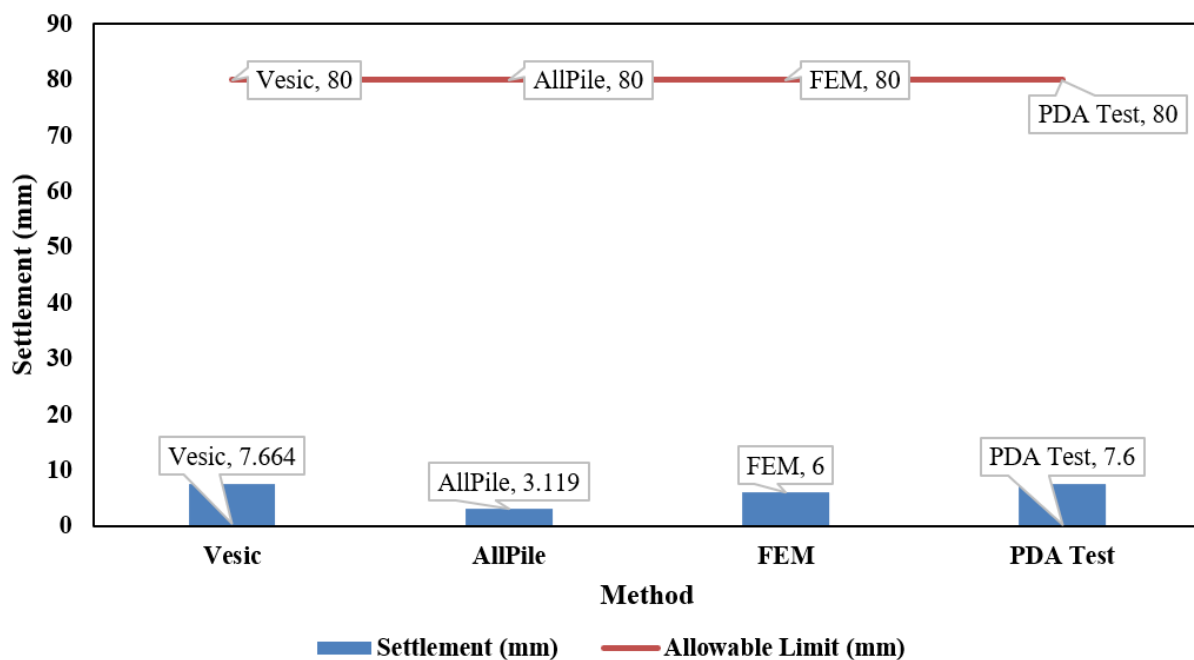


Figure 4. Comparison of Predicted and Reported Pile Settlement with the Adopted Allowable Settlement Limit.

3.3. Axial Stability under Working Load.

The working load of 918 kN is approximately 93.61 tons. The AllPile allowable capacity of 455.17 tons is therefore approximately 4.86 times the working load. This indicates that the applied working load is substantially below the allowable capacity obtained from the AllPile analysis. The PDA ultimate capacity of 429 tons is approximately 4.58 times the working load. However, this comparison should not be interpreted as a formal factor of safety because the

PDA value represents an ultimate field reference rather than an allowable design capacity. The numerical and field results consistently indicate that the working load is substantially below the estimated ultimate capacity. Consequently, axial resistance is not the governing concern for the investigated pile under the specified loading condition. From a serviceability perspective, the maximum reported or predicted settlement is 7.60 mm, which is only 9.50% of the adopted 80 mm settlement criterion. The results therefore indicate a substantial margin against excessive total settlement for the investigated pile.

3.4. Interpretation of Numerical–Field Differences.

The comparison between numerical predictions and field measurements is an important finding of this study. Both AllPile and FEM predicted considerably higher ultimate capacities than the PDA test. The difference was 218.23% for AllPile and 129.83% for FEM. The smaller FEM deviation should not be interpreted as evidence that FEM is universally more accurate than AllPile. It indicates only that, for the investigated pile and the adopted input parameters, the FEM prediction was numerically closer to the reported PDA reference. The substantial difference in capacity may result from the following factors.

3.4.1. Spatial Variability of Soil Conditions.

The numerical analysis used BH-2 as the representative soil profile for P-86. If the tested pile is located at a different horizontal position from BH-2, the local soil strength, stiffness, groundwater condition, and stratification may differ from the borehole profile. This limitation is particularly important because pile capacity is influenced by both the shaft and base soil conditions.

3.4.2. Construction Effects.

The numerical models generally represent idealized pile–soil conditions, whereas actual bored-pile construction involves drilling, borehole stabilization, cleaning, reinforcement installation, and concrete placement. Sediment at the pile base or disturbance along the pile shaft may reduce the mobilized resistance relative to the idealized numerical condition. The substantially higher numerical capacities relative to the PDA reference are also consistent with the sensitivity of bored-pile resistance to pile-base condition and construction effects reported in recent field and numerical studies [5, 6].

3.4.3. Soil Stiffness and Interface Assumptions.

The predicted settlement depends strongly on the adopted soil stiffness and pile–soil interface parameters. The FEM analysis explicitly represents the interface, while AllPile uses an analytical representation of load transfer. Recent research has shown that nonlinear interface behavior can significantly influence pile load–settlement response, particularly in layered soils [2].

3.4.4. Difference Between Dynamic and Numerical Field Response.

PDA derives pile response from dynamic measurements and signal interpretation. FEM and AllPile, in contrast, calculate pile response from prescribed soil and pile parameters. Therefore, the PDA result should be regarded as a field reference rather than a direct static benchmark.

The results support the use of field testing as an essential calibration reference. For the investigated pile, FEM produced the closer numerical representation, but the 129.83% capacity difference remains too large to justify treating the numerical result as a direct substitute for field verification.

3.5. Implications for Hospital Foundation Performance.

For the investigated P-86 pile, both the calculated and reported settlements were substantially below the project-adopted allowable settlement criterion of 80 mm. The maximum displacement considered in the analysis was 7.60 mm, corresponding to only 9.50% of the adopted limit. These results indicate that excessive total settlement is unlikely to govern the serviceability performance of the individual pile under the specified working load. In combination with the axial capacity results, the findings suggest that P-86 provides an adequate margin against both axial resistance failure and excessive vertical deformation under the investigated loading condition.

Nevertheless, satisfactory performance of an individual pile does not necessarily demonstrate satisfactory performance of the entire hospital foundation system. This distinction is particularly important for hospital buildings because their functionality depends not only on structural integrity but also on the performance of architectural components, mechanical and electrical installations, medical utilities, and sensitive equipment. Differential settlement between adjacent piles or pile caps may affect these systems even when the absolute settlement of individual piles remains relatively small. Consequently, serviceability assessment should consider both the magnitude and spatial variability of foundation deformation.

A comprehensive project-level assessment should therefore incorporate pile-group interaction, pile-cap stiffness, redistribution of structural loads, differential settlement, long-term soil consolidation, relevant structural load combinations, and potential groundwater fluctuations. The interaction between foundation deformation and settlement-sensitive medical equipment or utility systems should also be considered where appropriate. These factors cannot be evaluated from the response of P-86 alone because group effects and structural interaction may modify the load-transfer mechanisms and settlement behavior observed for an isolated pile.

Accordingly, the present results demonstrate that the investigated P-86 pile satisfies the adopted axial capacity and settlement requirements under the specified working load. However, the findings should be interpreted as a site-specific assessment of an individual pile rather than evidence that all piles within the Integrated Oncology Hospital foundation system will exhibit equivalent performance.

3.6. Model Limitations and Engineering Implications.

Several limitations should be considered when interpreting the findings. First, the subsurface model was developed using only the BH-2 borehole. Although this profile provided the geotechnical basis for both numerical approaches, a single borehole cannot fully represent spatial variations in soil stratification, strength, stiffness, and groundwater conditions across the project site. Additional boreholes and in situ testing near the investigated piles would improve the spatial characterization of the subsurface conditions and reduce uncertainty in the numerical input parameters.

Second, the field reference was obtained from PDA testing. Although PDA provides valuable information on pile resistance and dynamic response, it does not reproduce the loading conditions of a conventional static axial pile load test. A static load test would therefore provide a more direct basis for calibrating the numerical load–settlement response and assessing the mobilization of pile resistance under quasi-static loading. Accordingly, the differences between FEM, AllPile, and PDA should be interpreted with consideration of the fundamentally different loading and analytical frameworks employed by these methods.

Third, the FEM analysis was performed using a two-dimensional axisymmetric model. This formulation is appropriate for a circular single pile subjected to concentric axial compression and provides an efficient representation of the surrounding soil domain. Nevertheless, a three-dimensional model would permit more explicit simulation of spatial stress redistribution, heterogeneous subsurface conditions, pile-group interaction, and non-axisymmetric loading conditions. Such modelling would be particularly relevant for extending the present single-pile analysis to the complete hospital foundation system.

Fourth, uncertainty remains in the adopted soil stiffness and pile–soil interface parameters. Several deformation parameters were estimated from representative correlations rather than obtained directly from laboratory or advanced in situ measurements. Because pile settlement and shaft resistance are sensitive to soil stiffness and interface behavior, uncertainty in these parameters may partly explain the discrepancies between the numerical predictions and PDA results. Future analyses incorporating site-specific stiffness measurements and interface calibration would improve the reliability of the numerical predictions.

Fifth, actual bored-pile construction effects were not explicitly simulated. Drilling disturbance, borehole stability and cleaning, groundwater conditions, slurry management, sediment accumulation at the pile base, and concrete placement can influence the mobilization of shaft and base resistance [5, 6]. These effects are particularly relevant to the present results because the largest discrepancy between AllPile and PDA occurred in the estimated base resistance. Incorporating construction-related effects into future model calibration could therefore improve agreement between predicted and field pile behavior.

Finally, the present investigation was restricted to axial compression. Shear force, bending moment, and torsional moment were set to zero in the AllPile analysis; consequently, the results provide no basis for assessing lateral pile resistance. The p – y method, which characterizes nonlinear lateral soil–pile interaction, was therefore not applicable to the present vertical analysis. Future investigations of lateral foundation performance should employ a dedicated p – y or equivalent lateral soil–pile interaction analysis incorporating horizontal loading, appropriate pile-head boundary conditions, lateral displacement, soil reaction, shear force, and bending moment. These limitations indicate that the present findings should be interpreted as a project-specific evaluation of the axial behavior of P-86 rather than a comprehensive assessment of all possible foundation responses.

4. Conclusions

This study evaluated the axial bearing capacity and settlement response of a 0.80 m diameter, 25 m long bored pile at point P-86 of an Integrated Oncology Hospital Building project using FEM and AllPile Vertical Analysis, with the PDA test serving as a project-specific dynamic field reference. The results demonstrated substantial differences among the prediction methods. AllPile estimated an ultimate axial capacity of 1,365.21 tons and an allowable compressive

capacity of 455.17 tons, while FEM predicted an ultimate capacity of 985.98 tons, compared with 429 tons obtained from the PDA interpretation. Relative to the PDA result, the FEM and AllPile capacities were higher by 129.83% and 218.23%, respectively. Thus, FEM provided the numerically closer capacity prediction, although the remaining discrepancy was too large to indicate close agreement with the field reference. A similar pattern was observed for pile displacement. FEM predicted a settlement of 6.00 mm, compared with 3.119 mm from AllPile and 7.60 mm from the PDA test, corresponding to differences of 21.05% and 58.96%, respectively. Despite these numerical–field discrepancies, the working load of 918 kN, equivalent to approximately 93.61 tons, remained substantially below the AllPile allowable capacity of 455.17 tons. Furthermore, the maximum reported displacement of 7.60 mm represented only 9.50% of the project-adopted settlement criterion of 80 mm. The investigated pile therefore satisfied the adopted axial resistance and serviceability requirements under the analyzed working load. The findings demonstrate that agreement between numerical predictions and field observations depends not only on the analytical method but also on the quality of subsurface characterization, soil stiffness, pile–soil interface assumptions, construction conditions, and the interpretation of field testing. The particularly large difference in predicted base resistance indicates that pile-tip conditions and the degree of end-bearing mobilization are critical sources of uncertainty. Moreover, PDA-derived capacity should be interpreted as a dynamic field reference rather than as a direct equivalent of static pile capacity. Overall, FEM provided a closer representation of the PDA response than AllPile for the investigated pile, particularly for settlement; however, this result should not be generalized as evidence of the universal superiority of FEM. The findings are specific to P-86 and cannot represent the performance of the entire hospital foundation system. Future project-level verification should incorporate additional boreholes, static pile load testing, improved calibration of soil and interface parameters, three-dimensional and pile-group analyses, differential settlement assessment, and long-term consolidation behavior. Such integration of numerical modelling with site-specific field verification is essential for achieving reliable and serviceable foundation design for settlement-sensitive hospital facilities.

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Author Contribution

Rashika Mutia Zahratunisa RH: Conceptualization, Methodology, Data Collection, Data Analysis, Writing—Original Draft. Rudianto Surbakti: Conceptualization, Methodology, Supervision, Writing—Review and Editing. Salsabila Sahfa: Data Collection, Data Analysis, Visualization, Writing—Review and Editing. All authors reviewed and approved the final manuscript.

Competing Interest

The authors declare that they have no conflict of interest.

References

- [1] Bouafia, A.; Laouedj, A. (2024). Construction of the load-transfer curves for piles in sand as a function of the Standard Penetration Test. *Iraqi Journal of Civil Engineering*. <https://doi.org/10.37650/ijce.2024.180201>.
- [2] Wang, Q.; Li, J.; Fang, T.; Yu, S. (2024). Database analysis of long-term settlement behavior of pile foundations in Shanghai soft coastal clays. *Buildings*, 14, 3334. <https://doi.org/10.3390/buildings14113334>.
- [3] Zhang, R.; Guo, Z.; Gong, W.; Wan, Z. (2025). Field test and numerical simulation study of bearing characteristics of combined post-grouted piles for railway bridges. *Applied Sciences*, 15, 335. <https://doi.org/10.3390/app15010335>.
- [4] Zhang, Y.; et al. (2024). Softening-based interface model and nonlinear load-settlement response analysis of piles in saturated and unsaturated multi-layered soils. *Computers and Geotechnics*, 171, 106331. <https://doi.org/10.1016/j.compgeo.2024.106331>.
- [5] Song, W.; Wang, Z.; Zhu, W.; Yang, J.; Zeng, J. (2025). Management of pile end sediment and its influence on the bearing characteristics of bored pile. *Buildings*, 15, 1389. <https://doi.org/10.3390/buildings15081389>.
- [6] Rizky, A.S.; Hastuty, I.P.; Harahap, S.E. (2026). Analysis of the axial bearing capacity and settlement of bored pile foundations using the finite element method: Case study of the construction of the Sumatera Main Stadium. *Jurnal Teknik Sipil Cendekia*, 7. <https://doi.org/10.51988/jtsc.v7i2.540>.
- [7] [Authors missing] (2025). Investigating ageing effects on bored pile shaft resistance in cohesionless soil through field testing. *Geotechnics*, 5, 59. <https://doi.org/10.3390/geotechnics5030059>.
- [8] Yoon, B.; Lee, C. (2025). Simplified method for estimating settlement of disconnected piled raft foundations based on a finite element approach using interaction factors. *Scientific Reports*, 15, 15119. <https://doi.org/10.1038/s41598-025-99859-z>.
- [9] Ahmad, H. (2025). Numerical study of comparing skirt sandpile with deep cement pile to improve load–settlement response of circular footing in layered soils: Centric and eccentric effects. *Heliyon*, 11, e41710. <https://doi.org/10.1016/j.heliyon.2025.e41710>.
- [10] Chang, D.-W.; Cheng, S.-H.; Chiu, M.-C.; Ge, L. (2025). A study on subsoil and pile reactions of embedded piled raft foundations in sandy soils under vertical loads. *KSCE Journal of Civil Engineering*, 29, 100230. <https://doi.org/10.1016/j.kscej.2025.100230>.
- [11] Sui, S.; Zhang, X.; Lu, K.; Li, Z.; Liu, W.; et al. (2024). Finite element analysis of combined bearing characteristics of pile–soil interaction in composite foundation. *Applied Sciences*, 14, 3894. <https://doi.org/10.3390/app14093894>.
- [12] Ter-Martirosyan, A.Z.; Ermoshina, L.Y.; Anzhelo, G.O. (2024). Settlement of a pile foundation considering linear and rheological properties of soils. *Buildings*, 14, 2830. <https://doi.org/10.3390/buildings14092830>.
- [13] Teberik, S.; Celik, F.; Aydin, E. (2025). Influence of bracing systems on pile design parameters: A structure–soil–pile interaction approach. *Buildings*, 15, 764. <https://doi.org/10.3390/buildings15050764>.
- [14] Ahmad, H.; et al. (2025). Influence of construction-induced effects and post-grouting on the performance of mud-protected bored piles: A numerical investigation. *Buildings*, 15, 1457. <https://doi.org/10.3390/buildings15091457>.
- [15] Wang, Q.; et al. (2024). Influence of settlement on base resistance of long piles in soft soil—Field and machine learning assessments. *Geotechnics*, 4, 447–469. <https://doi.org/10.3390/geotechnics4020025>.

- [16] Abualkhair, M.; et al. (2024). Assessment of empirical methods for interpreting bidirectional pile load test results. *Ain Shams Engineering Journal*, 15, 102791. <https://doi.org/10.1016/j.asej.2024.102791>.
- [17] [Authors missing] (2024). A new p-y model for soil-pile interaction analyses in cohesionless soils under monotonic loading. *Soils and Foundations*, 64, 101441. <https://doi.org/10.1016/j.sandf.2024.101441>.
- [18] Goshu, T.; Assefa, E.; Jilo, N.Z.; et al. (2025). Nonlinear dynamic analysis of pile foundation using finite element method. *Scientific Reports*, 15, 37181. <https://doi.org/10.1038/s41598-025-23445-6>.
- [19] Li, W.; Zhang, J.; Chen, H.; Ni, J.; Zhang, D. (2024). Quantitative study on the impact of surcharge on nearby foundations. *Buildings*, 14, 1596. <https://doi.org/10.3390/buildings14061596>.
- [20] Sun, G.; Gu, L.; Li, L.; Huo, Y.; Wang, Z.; et al. (2024). A novel calculate model of shear deformation and relative displacement of pile–soil interface in warm frozen soil foundation. *Buildings*, 14, 1459. <https://doi.org/10.3390/buildings14051459>.



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