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# A REVIEW ON COMPARATIVE STUDY OF PILE FOUNDATION PERFORMANCE BASED ON IN-SITU TESTS AND NUMERICAL ANALYSIS

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## ABSTRACT

Pile foundations are widely used to transfer structural loads to deeper and more competent soil strata, particularly in areas with weak or heterogeneous ground conditions. Accurate prediction of pile performance is essential for safe and economical foundation design. This review paper presents a comprehensive comparative study of pile foundation performance based on in-situ testing methods and numerical analysis techniques. Commonly adopted in-situ tests, such as static pile load tests, cone penetration tests (CPT), standard penetration tests (SPT), and dynamic pile testing, are reviewed with emphasis on their ability to evaluate load–settlement behavior, bearing capacity, and soil–pile interaction mechanisms. The interpretation approaches, advantages, and limitations of these field-based methods are critically discussed. In parallel, numerical modeling techniques using finite element and finite difference methods are examined, focusing on constitutive soil models, boundary conditions, pile–soil interface modeling, and calibration procedures. A comparative assessment highlights the consistency and discrepancies between field test results and numerical predictions, identifying key factors influencing performance such as soil variability, modeling assumptions, and construction effects. The review underscores the importance of integrating in-situ test data with numerical analysis to improve the reliability of pile design and optimize foundation performance. Finally, research gaps and future directions are identified to enhance the accuracy of predictive models and promote performance-based pile foundation design.

**KEYWORDS:** Pile foundation; In-situ tests; Pile load test; Numerical analysis; Finite element method; Soil–structure interaction; Load–settlement behavior; Axial and lateral capacity; Foundation design.

## INTRODUCTION

Pile foundations are extensively used in civil engineering projects to transfer structural loads safely to deeper and more competent soil or rock strata when near-surface soils lack adequate bearing capacity or exhibit excessive settlement characteristics. With rapid urbanization, increasing construction of high-rise buildings, bridges, offshore structures, and industrial facilities, pile foundations have become an indispensable component of modern geotechnical engineering practice. The performance of pile foundations is governed by complex soil–pile interaction mechanisms, which depend on soil stratigraphy, pile material and geometry, installation method, and loading conditions.

Accurate prediction of pile foundation performance—particularly load-carrying capacity, settlement behavior, and load transfer mechanisms—remains a challenging task due to the inherent variability and nonlinearity of soil properties. Traditionally, pile design has relied on empirical and semi-empirical approaches based on field experience and simplified theoretical models. However, these methods often involve conservative assumptions and may not fully capture the actual behavior of piles under in-situ conditions. Consequently, in-situ testing and numerical analysis have emerged as critical tools for evaluating and optimizing pile foundation performance.

### In-Situ Tests in Pile Foundation Evaluation

In-situ tests play a vital role in characterizing subsurface conditions and assessing pile behavior under actual field conditions. Common in-situ tests used in pile foundation studies include the Standard Penetration Test (SPT), Cone Penetration Test (CPT/CPTu), Pressuremeter Test (PMT), Plate Load Test, and full-scale pile load tests such as static compression, tension, and lateral load tests. Among these, static pile load tests are considered the most reliable method for directly determining pile capacity and settlement response, as they provide real-time load–displacement behavior of the pile–soil system.

In-situ tests offer several advantages, including realistic representation of soil stress history, boundary conditions, and construction effects. However, they are often time-consuming, expensive, and limited to a small number of test locations. Moreover, interpretation of test results may vary depending on the adopted criteria, soil heterogeneity, and testing procedures. These limitations necessitate complementary approaches to extend the applicability of field test results.

### Numerical Analysis in Pile Foundation Studies

Advancements in computational power and numerical modeling techniques have enabled the widespread use of numerical analysis tools, such as the Finite Element Method (FEM), Finite Difference Method (FDM), and Boundary Element Method (BEM), for pile foundation analysis. Software packages like PLAXIS, ANSYS, ABAQUS, and FLAC allow detailed simulation of soil–pile interaction by incorporating nonlinear soil constitutive models, interface elements, and construction sequences.

Numerical analysis provides valuable insights into stress distribution, load transfer mechanisms along the pile shaft and base, development of plastic zones in soil, and pile group effects. Parametric studies can be efficiently performed to evaluate the influence of pile geometry, material properties, installation techniques, and soil parameters on pile performance. Despite these advantages, numerical models are highly sensitive to input parameters and assumptions, particularly soil constitutive models and boundary conditions. Therefore, validation of numerical results using in-situ test data is essential to ensure reliability.

### Literature Review

Lei Yan et al (2024) This study addresses the structural and constructional challenges associated with pile foundation underpinning systems, which involve complex force transfer mechanisms and strict construction quality requirements, especially at the interface between new and existing concrete. To enhance the mechanical performance of the underpinning beam—particularly the bond strength, integrity, and load-transfer efficiency at the new–old concrete joint—the paper emphasizes the necessity of introducing epoxy resin reinforcing adhesive for planted rebars. Building on this concept, a novel construction method for pile foundation underpinning beams is proposed, combining "concrete chiseling + prestressed reinforcement + epoxy resin reinforcing adhesive," where chiseling improves surface roughness and mechanical interlock, prestressing optimizes stress distribution and stiffness, and epoxy resin adhesive ensures reliable anchorage and enhanced bonding performance. Taking an actual urban overpass pile foundation underpinning project as the engineering prototype, a scaled physical model with a similarity ratio of 1:6 was designed and fabricated, and a series of repeated progressive static loading tests were carried out to systematically investigate key structural behaviors, including load-carrying capacity, displacement development, stiffness degradation, and overall working performance, as well as to identify typical failure modes of the underpinning structure. Furthermore, based on the prototype structure, a finite element analysis model was established to simulate the stress–strain response and deformation characteristics of the underpinning beam system under actual loading conditions. By comparing the numerical results with the experimental test data, the study verifies the reliability of the finite element model and clarifies the mechanical properties and deformation patterns of the real pile foundation underpinning structure. The combined experimental and numerical findings provide valuable theoretical insights and experimental evidence, thereby offering a solid technical basis and reference for the safe and efficient implementation of similar pile foundation underpinning projects in urban infrastructure engineering.

Runze Zhang et al (2024) This study utilizes static load test results obtained using the self-balancing method on two large-diameter bored piles constructed for the Huaiyang Left Line Special Bridge of the Lianyungang–Zhenjiang Railway to systematically examine the influence of combined tip-and-side post-grouting on the bearing behavior of railway bridge pile foundations. A comparative evaluation of the same individual piles before and after grouting demonstrates that combined post-grouting significantly enhances overall pile performance by densifying the surrounding soil and improving the pile–soil interface conditions. The test results indicate that the ultimate bearing capacity of a single pile increases markedly, with an improvement ranging from 32.99% to 38.42% after grouting, highlighting the effectiveness of the technique. The injected grout forms a compacted grout body around the pile shaft and beneath the pile tip, which strengthens the mechanical properties of the contact surface and leads to a substantial increase in side friction mobilized along the full pile length. At the same time, post-grouting improves the efficiency of tip resistance, enabling it to be mobilized more rapidly with increasing pile tip displacement. Furthermore, the combined tip-and-side post-grouting alters the load transfer mechanism of the pile by increasing the proportion of load carried by tip resistance, thereby achieving a more balanced and efficient distribution of axial load between shaft resistance and end bearing, which is particularly beneficial for large-diameter bored piles in railway bridge foundations.

Yan-Cheng Yu et al (2023) Bored root piles are an advanced pile foundation system designed to enhance load-bearing capacity by hydraulically jacking prefabricated root elements into the surrounding soil through preformed holes in a bored pile shaft, thereby improving soil–pile interaction. In this study, the vertical load-bearing behavior of bored root piles is comprehensively examined by integrating numerical simulations with field testing, allowing both theoretical understanding and practical validation. A three-dimensional numerical model is developed and calibrated using load–displacement data obtained from self-balanced field tests, ensuring the reliability of the simulation results. Once validated, the model is used to analyze the load-transfer mechanism in detail, focusing on the evolution of load–displacement response, axial force distribution along the pile, mobilization of shaft friction, and load-sharing ratios between the pile shaft and root elements. The findings indicate that the prefabricated roots contribute a substantial portion of the applied load, significantly enhancing overall bearing capacity, while the load-sharing behavior among different root layers exhibits clear temporal and sequential characteristics as loading progresses. Furthermore, parametric studies are conducted to assess the influence of various root configurations, such as number, length, and spacing of root layers, on vertical performance. Among these parameters, root layer spacing is identified as the most critical factor governing load-bearing capacity and failure behavior. Based on this observation, three distinct failure modes of bored root piles are proposed according to different root layer spacing conditions. Overall, the results provide valuable insights into the mechanical behavior, optimization, and practical design of bored root piles for engineering applications.

Manpreet Kundra et al (2022) With rapid urbanization, the utilization intensity of underground spaces in major cities has increased significantly, leading to congestion and a growing need for safer and more efficient foundation systems capable of withstanding extreme loading conditions such as blast effects. In this study, a comparative evaluation was carried out between the proposed pile foundation material and conventional materials to assess their structural performance under varying blast load intensities. A parametric optimization approach was adopted to establish effective relationships between dependent variables (displacement and stress response) and independent variables (blast load and applied pressure), using Taguchi design methodology and ANOVA techniques to identify the most influential parameters and their optimal combinations. The results clearly indicate that displacement intensity in all pile design configurations increases proportionally with an increase in blast load intensity, with the maximum displacement recorded as 3.98 mm under a blast load of 2495 N, compared to only 1.238 mm at a lower blast load of 195 N. Similarly, the stress intensity exhibited a rising trend with increasing blast loads, reaching a peak stress of 2460 N/mm² at the maximum blast load of 2495 N, whereas a comparatively lower stress of 212 N/mm² corresponded to the 195 N load condition. Further analysis using Pareto charts revealed that the applied blast load has a significantly greater influence on the structural response than the surface pressure, particularly in terms of maximum structural deviation, highlighting blast load intensity as the dominant governing factor in the performance and safety assessment of pile-supported underground structures.

Guozhu Zhang et al (2021) this study highlights that the long-term thermal behavior of precast high-strength concrete (PHC) energy piles is strongly governed by soil–pile thermal interactions, which have not been widely explored in existing research. By integrating field experiments with numerical simulations, the authors demonstrate that thermophysical properties of layered ground conditions increasingly influence temperature evolution over time, particularly in long-term operation. Soils with higher thermal conductivity enable more efficient heat dissipation, leading to a gradual rise in ground temperature near the pile and a delayed thermal response at locations farther from the pile center due to slower heat diffusion. The results further show that enhancing the thermal conductivity of the backfill material significantly improves both short- and long-term heat exchange performance of the PHC energy pile, with heat transfer gains being more pronounced in the short term but still substantial over longer durations; however, changes in the specific heat capacity of the backfill have a negligible effect on thermal response. In addition, the initial ground temperature plays a critical role in determining the pile’s heat transfer capacity and the extent of ground temperature variation during operation. Overall, the findings confirm that ground thermal conductivity is a key parameter controlling long-term thermal response, exerting a much stronger influence over extended operation periods than in short-term conditions, thereby emphasizing the importance of proper thermal characterization of soil and backfill materials in the design and performance optimization of PHC energy pile systems.

Chen et al (2013) carried out detailed three-dimensional Finite Element analyses to study the behavior of piles installed near slope crests, with particular emphasis on how slope inclination and the distance of the pile from the slope crest influence the lateral resistance and the corresponding p–y curves of the soil–pile system. In their study, various slope angles and pile positions were systematically analyzed to capture changes in soil stress distribution, mobilized passive resistance, and pile deflection patterns under lateral loading. The results indicated that the presence of a slope significantly reduces lateral soil resistance when the pile is located close to the crest, due to the loss of confinement and reduced passive soil pressure on the slope side. However, as the pile is placed farther away from the slope crest, the stress conditions around the pile gradually approach those of level ground. Chen and Martin observed that for slope angles less than 45°, the reduction in ultimate lateral load capacity becomes negligible—less than about 10%—once the pile is located at a distance greater than six times the pile diameter from the slope crest. Beyond this distance, the shape and magnitude of the p–y curves closely resemble those for horizontal ground conditions, indicating that the slope no longer has a significant influence on pile behavior. Consequently, they concluded that for practical design purposes, the slope effect can be safely neglected for piles installed beyond six pile diameters from the crest when the slope angle is less than 45°.

Emilios M. Comodromos et al (2009) Capacity-based design of pile foundations commonly simplifies soil–structure interaction by focusing primarily on the bearing capacity of the pile group, often neglecting the structural and load-sharing contribution of the raft, which can lead to conservative and uneconomical designs. Conversely, a fully coupled nonlinear three-dimensional numerical analysis that rigorously accounts for soil nonlinearity, structural nonlinearity, and pile–soil–pile interaction effects is computationally intensive and requires advanced numerical resources, making it impractical for routine engineering applications. To address this limitation, a hybrid design methodology based on the concept of sub-structuring is proposed, combining experimental observations with targeted nonlinear 3-D numerical analyses to achieve an efficient, accurate, and cost-effective foundation design for bridge structures. The approach begins with a detailed back-analysis of a static pile load test, through which key soil parameters such as shear strength, deformation modulus, and the degree of shear strength mobilization at the soil–pile interface are calibrated to realistically represent field behavior. These calibrated parameters are then employed in numerical models to simulate the response of 2 × 2 and 3 × 3 pile group configurations, allowing for an evaluation of load-sharing mechanisms and the interaction between the raft and individual piles within the group. The numerical results provide insight into how vertical loads are distributed between the raft and characteristic piles under different configurations, highlighting the beneficial contribution of the raft that is often ignored in conventional design. Based on these findings, a rational design strategy is proposed for pile-raft foundations subjected to non-uniform vertical loading, enabling optimized foundation layouts that balance safety, performance, and economy while maintaining realistic consideration of soil–structure interaction effects.

## METHODOLOGY

The methodology for a review on the comparative study of pile foundation performance based on in-situ tests and numerical analysis involves a systematic collection and critical evaluation of published experimental, field, and numerical studies related to pile behavior under axial and lateral loading. First, relevant in-situ test methods such as static pile load tests, dynamic load tests, PDA, SPT, CPT, and pressure meter tests are reviewed to understand their role in estimating pile capacity, load–settlement response, and soil–pile interaction characteristics. The in-situ test results are reviewed to understand actual load–settlement behavior, failure mechanisms, and soil–pile interaction characteristics, while the numerical models are examined in terms of constitutive soil models, boundary conditions, mesh sensitivity, and pile–soil interface modeling. A comparative analysis is then carried out by correlating field-measured responses with numerically predicted outcomes, highlighting agreements, discrepancies, and influencing parameters such as soil stratification, pile geometry, and material properties. Finally, the strengths, limitations, and applicability of both approaches are synthesized to identify gaps in existing studies and to recommend best practices for reliable pile foundation design and performance prediction. Limitations, and sources of discrepancy. Finally, the review synthesizes key findings to identify trends, reliability of in-situ tests for model calibration, and the effectiveness of numerical analysis in predicting real pile behavior, providing recommendations for integrated use of field testing and numerical modeling in pile foundation design.

## CONCLUSION

This review has presented a comprehensive comparative evaluation of pile foundation performance based on results obtained from in-situ testing methods and numerical analysis techniques. In-situ tests such as static pile load tests, dynamic load tests, SPT-, CPT-, and pressure meter-based evaluations provide reliable and site-specific insight into actual soil–pile interaction, capturing the influence of construction method, soil variability, and boundary conditions. These tests remain the benchmark for validating pile capacity and settlement behavior, particularly for critical and large-scale infrastructure projects.

Numerical analysis methods, including finite element and finite difference approaches, have demonstrated strong potential in predicting pile behavior under various loading and ground conditions when appropriate constitutive soil models and boundary conditions are adopted. Advanced numerical models effectively simulate load transfer mechanisms, stress distribution, group effects, and non-linear soil–structure interaction, offering significant advantages in parametric studies and design optimization. However, the accuracy of numerical predictions is highly dependent on the quality of input parameters, calibration with field data, and the selection of suitable soil models.

The comparative assessment highlights that while numerical analysis can closely match in-situ test results, discrepancies often arise due to soil heterogeneity, simplifications in modelling assumptions, and scale effects. Therefore, numerical models should not be treated as standalone tools but should be validated and refined using field test results to enhance reliability. The integration of in-situ testing and numerical simulation provides a robust framework for improving design confidence, reducing construction risk, and achieving economical pile foundation solutions.

Overall, this review concludes that a combined approach—leveraging the accuracy of in-situ tests and the predictive capability of numerical analysis—offers the most effective strategy for assessing pile foundation performance. Future research should focus on improved soil constitutive models, long-term pile behaviour, and data-driven calibration techniques to further bridge the gap between field observations and numerical predictions.

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