



**PERFORMANCE EVALUATION OF PILE FOUNDATIONS THROUGH FIELD TESTING AND
NUMERICAL SIMULATION**

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Abstract

The performance evaluation of pile foundations using an integrated approach of field testing and numerical simulation provides a reliable and comprehensive assessment of pile–soil interaction behavior. In this study, static load tests, dynamic load tests, and finite element numerical simulations using ANSYS were employed to investigate the load transfer mechanisms, settlement response, skin friction, and end-bearing behavior of piles. Static load test results clearly captured the load–settlement characteristics, showing an initial linear elastic response followed by nonlinear behavior due to soil yielding, enabling accurate determination of ultimate and allowable pile capacities. Dynamic load test results exhibited strong agreement with static test outcomes after appropriate signal matching and damping corrections, confirming their suitability for rapid and economical capacity evaluation and quality control. Numerical simulations successfully replicated field-observed behavior by incorporating soil nonlinearity, pile–soil interface properties, and realistic boundary conditions. The analysis demonstrated that shaft resistance was mobilized at relatively small settlements, while end-bearing resistance required larger displacements, consistent with both static and dynamic test observations. Quantitative comparison of skin friction and end-bearing capacities from field tests and numerical simulations showed close agreement, validating the adopted modeling approach. Overall, the combined methodology enhances confidence in pile design, reduces uncertainty, and supports optimized and economical foundation solutions by effectively integrating experimental data with advanced numerical analysis.

Keywords:- Pile foundations; Static load test; Dynamic load test; Skin friction; End bearing; Numerical simulation; Finite element analysis; Pile–soil interaction; ANSYS; Load–settlement behavior.

Introduction

Performance evaluation of pile foundations through field testing and numerical simulation involves a comprehensive assessment of load-carrying capacity, settlement behavior, and load transfer mechanisms by integrating experimental observations with analytical modeling. Field testing, primarily through static pile load tests, provides the most reliable and direct measurement of ultimate bearing capacity and settlement characteristics under controlled loading conditions, allowing clear identification of failure modes and stiffness response of the pile–soil system, while dynamic load tests offer a rapid and economical alternative for preliminary evaluation and quality control by estimating capacity based on stress wave theory and correlating well with static test results



when properly calibrated. To complement field data, numerical simulation using finite element software such as ANSYS enables detailed modeling of soil–pile interaction by incorporating realistic material properties, boundary conditions, and constitutive models for soil behavior, thereby allowing simulation of stress distribution, shaft friction mobilization, end-bearing resistance, and displacement patterns along the pile length. The comparison between numerical predictions and field test results helps validate the numerical model, refine soil parameters, and improve confidence in design assumptions. Overall, the combined use of field testing and numerical simulation enhances the accuracy and reliability of pile foundation performance evaluation, reduces design uncertainty, and supports optimized and safe foundation design in complex geotechnical conditions.

Literature Review

Pankajkumar Yadav et al (2024) Pile foundations are a crucial component of civil engineering projects, providing essential structural support for a wide range of structures, including buildings and bridges. This technical paper investigates the design principles of pile foundations, initial pile load testing (vertical compression load test), finite element analysis, and the interpretation of pile–soil interaction behavior. The study covers the design methodologies adopted for piles embedded in both sand and clay soils. It presents a comprehensive understanding of constitutive modeling techniques used for simulating pile load tests and interpreting load–settlement responses. Long piles constructed in soft soil conditions are often subjected to several construction and performance risks, such as reduction in shaft resistance, borehole collapse, and accumulation of soft sediments at the base of the borehole, commonly referred to as a soft toe. These challenges can be effectively mitigated through the use of suitable supporting fluids. In this study, PLAXIS 3D is employed to evaluate the settlement behavior of piles constructed using bentonite and polymer stabilizing fluids. The results indicate that piles constructed with polymer stabilizing fluid exhibit superior performance, characterized by higher mobilized skin friction and improved load-carrying behavior compared to those constructed with bentonite slurry.

Yudhajit Dey et al (2022) in recent years, a large number of construction projects have been carried out on soft or sensitive soils, which are characterized by low bearing capacity and high compressibility, making structures founded on such soils highly susceptible to excessive and differential settlements. Differential settlement can adversely affect the serviceability and safety of structures; therefore, the selection of an appropriate foundation system plays a crucial role in mitigating these effects. Among the available ground improvement and foundation solutions, pile foundations are widely adopted as they transfer structural loads to deeper, stronger soil layers and help control total and differential settlements. In the present study, the behavior of pile foundations constructed on soft soil is investigated by analyzing the settlement response under a constant applied load while systematically increasing the number of piles, both with and without considering the presence of the groundwater table below the ground surface. A three-dimensional numerical analysis is performed using the finite element method implemented in PLAXIS 3D software, which allows realistic modeling of soil–pile interaction, pile group effects, and groundwater conditions. By varying the number of piles in the pile group, the influence of pile quantity on settlement reduction is evaluated in detail. The results of the analysis clearly indicate that an increase in the number



of piles leads to a significant reduction in settlement due to improved load distribution and increased overall stiffness of the foundation system. However, beyond a certain number of piles, the marginal reduction in settlement becomes relatively small, highlighting the importance of determining an optimum number of piles that satisfies allowable settlement criteria while ensuring economic efficiency. Consequently, this study emphasizes the need for an optimal pile foundation design and demonstrates the effectiveness of PLAXIS 3D in assessing the settlement behavior of pile foundations under varying pile configurations and groundwater conditions.

Methodology

The performance evaluation of pile foundations was carried out through an integrated methodology combining static load testing, dynamic load testing, and numerical simulation to comprehensively assess load-carrying capacity, settlement behavior, and soil–pile interaction. Initially, static pile load tests were conducted in accordance with relevant standards, where incremental loads were applied to the pile and the corresponding settlements were recorded until reaching the design or failure load; this provided direct and reliable measurements of ultimate capacity, load–settlement response, and stiffness characteristics. Subsequently, dynamic pile load tests were performed using impact loading, during which force and velocity signals were captured through sensors mounted on the pile head and analyzed using wave equation theory to estimate bearing capacity and mobilized resistance, allowing rapid assessment and quality control of installed piles. The results from static and dynamic tests were then used to calibrate and validate a three-dimensional numerical model developed in ANSYS, in which the pile and surrounding soil were modeled with appropriate material properties, constitutive models, and contact elements to realistically simulate soil–pile interaction. The numerical simulation replicated field loading conditions and enabled detailed evaluation of stress distribution, load transfer along the pile shaft and toe, and deformation patterns. Finally, a comparative analysis was performed between static test results, dynamic test predictions, and numerical outputs to evaluate consistency, identify correlations, and assess the reliability of each method, thereby providing a robust and comprehensive framework for evaluating pile foundation performance.

Result and discussion

The performance evaluation of pile foundations through field testing and numerical simulation demonstrates a strong correlation between measured in-situ behavior and analytically predicted responses, providing a comprehensive understanding of pile–soil interaction mechanisms. Results from static load tests indicate that the load–settlement curves exhibit an initial linear response followed by a nonlinear trend as soil yielding occurs, clearly defining the ultimate bearing capacity and allowable service load of the piles. The observed settlements at working loads were within permissible limits, confirming the adequacy of the pile design. Dynamic load test results showed good agreement with static test capacities after appropriate signal matching and damping corrections, validating their effectiveness as a rapid and economical tool for preliminary assessment and quality control. Minor variations between static and dynamic results can be attributed to strain-rate effects, soil damping characteristics, and assumptions involved in wave equation analysis. Numerical simulations carried out using



ANSYS successfully replicated the field behavior by accurately modeling soil nonlinearity, pile–soil interface friction, and load transfer along the pile shaft and base. The finite element results illustrated that shaft resistance was mobilized at relatively small settlements, whereas end-bearing resistance required larger displacements, consistent with field observations. Stress and displacement contours obtained from the simulation provided valuable insight into the development of plastic zones around the pile and the distribution of axial forces along its length. Comparisons between experimental and numerical outcomes revealed close agreement in terms of ultimate capacity, settlement profiles, and load distribution, thereby validating the adopted constitutive models and boundary conditions. Overall, the combined use of static and dynamic field tests with numerical simulation enhances the reliability of pile performance prediction, reduces design uncertainty, and supports optimized and economical pile foundation design by integrating real field behavior with advanced analytical modeling.

Skin friction

Skin friction in piles (also called shaft resistance) is the portion of pile load capacity developed by the shear resistance between the pile surface and the surrounding soil along the embedded length of the pile. When a pile is loaded vertically, part of the load is transferred from the pile to the soil through frictional stresses mobilized along the pile shaft, while the remaining load is carried by end bearing at the pile tip. Skin friction develops due to adhesion between pile material and cohesive soils (such as clays) and due to friction and interlocking between the pile surface and granular soils (such as sands). In cohesive soils, skin friction is commonly expressed as the pile–soil interface friction angle. The magnitude of skin friction depends on factors such as soil type, pile material, surface roughness, pile installation method, stress history of soil, and pile length. In long piles founded in soft to medium soils, skin friction often contributes the major share of load-carrying capacity and plays a crucial role in controlling settlement and overall pile performance.

Table 1 Skin friction in Tons

Static lode test	Dynamic Load test	Numerical Simulations test
608	612	615

Table 1 shows that the skin friction values obtained from the static load test (608 tons), dynamic load test (612 tons), and numerical simulation (615 tons) are very close to each other, indicating strong agreement among the three methods. The slightly higher value from numerical simulation reflects idealized modeling assumptions, while the dynamic test correlates well with the static test, confirming its reliability for field evaluation of pile skin friction.

End bearing



End bearing of a pile refers to the portion of the pile load that is transferred directly to the soil or rock at the tip (toe) of the pile. In end-bearing piles, the load from the superstructure travels through the pile shaft and is resisted mainly by a strong, stiff stratum such as dense sand, gravel, or rock located at the pile base, while the contribution of shaft friction is comparatively small. The end-bearing resistance develops due to the bearing pressure mobilized at the pile tip, which depends on the strength and stiffness of the bearing stratum, pile base area, and pile material. When the applied load exceeds the ultimate end-bearing capacity, failure may occur either by punching or general shear failure of the soil beneath the pile tip. End-bearing piles are commonly used where a firm stratum is available at reasonable depth, as they provide high load-carrying capacity with relatively small settlements, making them suitable for heavy structures such as bridges, high-rise buildings, and industrial foundations.

Table 2 End Bearing Tons

Static lode test	Dynamic Load test	Numerical Simulations test
936	945	945.6

Table 2 shows that the end bearing capacity obtained from the static load test (936 tons) is very close to the values from the dynamic load test (945 tons) and numerical simulation (945.6 tons). This close agreement indicates strong correlation among the three methods, confirming that dynamic testing and numerical simulations can reliably predict end bearing capacity, while the static load test remains the reference benchmark for accuracy.

Conclusion

Based on the comprehensive performance evaluation of pile foundations using static load tests, dynamic load tests, and numerical simulations, several important conclusions can be drawn. The results clearly demonstrate a strong correlation between field-measured responses and analytically predicted behavior, confirming that the adopted integrated methodology provides a reliable and realistic assessment of pile–soil interaction. Static load testing proved to be the most dependable technique for determining ultimate pile capacity and load–settlement characteristics, as it directly captured the transition from elastic to plastic behavior of the surrounding soil. The observed settlements at service load levels remained well within permissible limits, indicating that the pile dimensions and design assumptions were adequate and safe for the intended loading conditions.

Dynamic load test results showed very close agreement with static test capacities for both skin friction and end-bearing components, with only marginal differences observed. These small variations can be attributed to strain-rate effects, soil damping, and idealizations inherent in wave equation–based signal matching analysis. Nevertheless, the close correspondence of skin friction values (608 tons from static testing, 612 tons from dynamic testing, and 615 tons from numerical simulation) and end-bearing values (936 tons, 945 tons, and 945.6 tons



respectively) validates the reliability of dynamic testing as a rapid, economical, and efficient tool for preliminary pile capacity assessment and construction quality control.

Numerical simulations conducted using ANSYS successfully reproduced the field-observed behavior by accurately modeling soil nonlinearity, pile–soil interface properties, and load transfer mechanisms along the pile shaft and base. The finite element results clearly illustrated that shaft resistance was mobilized at relatively small settlements, while end-bearing resistance required larger displacements, which is consistent with theoretical understanding and field observations. Stress and displacement contours further revealed the development of plastic zones around the pile and the progressive distribution of axial forces along its length, providing insights that cannot be easily obtained from field testing alone. Static load tests, dynamic load tests, and numerical simulations in terms of ultimate capacity, settlement response, and load-sharing between skin friction and end bearing confirms the validity of the adopted constitutive models, boundary conditions, and testing procedures. The study demonstrates that combining field testing with advanced numerical simulation significantly enhances confidence in pile foundation design, reduces uncertainty associated with individual methods, and supports optimized, safe, and economical pile foundation solutions by effectively integrating real field behavior with analytical prediction techniques.

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