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INNOVATIONS IN DEEP FOUNDATION SYSTEMS: A SYSTEMATIC REVIEW OF DESIGN APPROACHES AND PERFORMANCE MONITORING

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Abstract

As infrastructure demands increase in complex geotechnical environments, the need for reliable, efficient, and sustainable deep foundation systems has intensified. This study presents a systematic review of thirty peer-reviewed articles published between 2010 and 2025, focusing on innovations in deep foundation design and performance monitoring. The review explores how recent advances, ranging from machine learning algorithms and enhanced numerical simulations to real-time sensing and digital twin frameworks, are transforming traditional foundation engineering paradigms. Articles were sourced from ASCE, Scopus, and ScienceDirect using a structured PRISMA protocol, with rigorous screening and inclusion criteria emphasising methodological novelty, empirical validation, and relevance to design–monitoring integration. Results reveal a strong emphasis on performance-based design approaches, including site-calibrated p–y curve models, hybrid pile systems, and AI-driven settlement predictors. Likewise, innovations in performance monitoring, such as fibre-optic instrumentation and fatigue simulation, offer enhanced insight into in-service foundation behaviour. However, only a minority of studies demonstrated closed-loop frameworks where monitoring data informed adaptive design updates, highlighting a critical gap in design–monitor–update (DMU) integration. Key challenges include limited field-scale validation, underutilization of monitoring data, and the absence of standardised metrics for cross-study comparison. The paper concludes by recommending future directions that include open-access databases, multi-hazard modelling, sustainability assessment, and digital twin implementation. These steps are essential to transitioning from static, empirical methods toward intelligent, resilient, and performance-verified foundation systems.

Keywords: Deep Foundations, Design Innovation, Performance Monitoring, Machine Learning in Geotechnics, Digital Twin Frameworks

Introduction

Deep foundation systems play a critical role in supporting superstructures subjected to high axial and lateral loads, particularly in geologically complex terrains and offshore environments.(Gamage et al., 2021). As infrastructure expands into challenging soil conditions, such as compressible alluvium in urban settings or soft marine clays in offshore zones, innovations in both design approaches and performance monitoring of deep foundations are essential to ensure reliability, efficiency, and sustainability.(J. Wu et al., 2023).

Historically, the design of deep foundations has relied heavily on empirical relationships, simplified load-transfer models, and conservative safety factors.(Salem et al., 2021). While effective in general terms, these traditional approaches often lack the fidelity to account for nonlinear, site-specific soil-structure interactions. In layered or sensitive soils, such as soft marine clays and silt seams, the limitations of these deterministic models become especially pronounced, affecting the accuracy of settlement predictions, lateral load response, and cyclic behavior(Song et al., 2023).

Recent years have witnessed a significant shift toward data-rich and physics-informed modelling approaches. Advanced constitutive models, artificial neural networks (ANNs), finite element simulations, and hybrid design strategies have emerged as tools to capture the complex interaction mechanisms at play more effectively. For instance, frameworks like PISA (Pile Soil Analysis) and the use of AI surrogates have demonstrated substantial gains in optimising pile geometry and reducing material usage.(Quevedo-Reina et al., 2024)At the same time, the development of real-time monitoring technologies, such as fibre-optic sensors, embedded instrumentation, and digital twin systems, has enabled engineers to collect in situ performance data during both construction and operation.(Alselami et al., 2025). This creates unprecedented opportunities to calibrate, validate, and continuously improve the predictive accuracy of design models.

Despite these advancements, a disconnect still exists between design innovations and monitoring practices. Many experimental or numerical innovations remain confined to research without large-scale validation. At the same time, data from performance monitoring systems is often underutilised in updating design parameters or improving reliability-based codes.(Augarde et al., 2021). Bridging this gap requires a systematic understanding of how design and monitoring technologies have evolved and interacted in recent studies.

This paper presents a systematic review of thirty peer-reviewed articles published between 2010 and 2025 that focus on innovative approaches to the design and performance monitoring of deep foundation systems. These articles were identified from a pool of 2002 records extracted from

Scopus, ASCE, and ScienceDirect. A rigorous screening process involving title and abstract reviews, year and language filters, and duplicate elimination yielded a final set of 30 articles: 5 from ASCE, eight from Scopus, and 17 from ScienceDirect.

The aim of this review is fourfold: (1) to identify the dominant design methodologies being developed and assess their predictive capabilities and limitations; (2) to examine emerging performance monitoring techniques and their application in field settings; (3) to analyze the synergy and disconnect between design models and monitoring outcomes; and (4) to recommend a research pathway toward integrated, evidence-based, and sustainable design-monitor-update workflows in deep foundation engineering.

Materials and Methods

This review employs a rigorously structured yet transparent protocol, aligned with contemporary guidelines for systematic literature reviews in geotechnical engineering. The primary aim was to consolidate advances in two intertwined domains: innovative deep foundation design, encompassing machine learning surrogates, advanced constitutive modelling, and hybrid structural configurations; and state-of-the-art performance monitoring technologies, including embedded instrumentation, full-scale load testing, and digital twin analytics. The review further investigates how these innovation streams have been integrated to support adaptive and reliability-based design frameworks in deep foundation systems.

To build a comprehensive evidence base, we queried three leading scientific databases with strong geotechnical relevance: ASCE Library (n = 744), Scopus (n = 1,118), and ScienceDirect (n = 140), yielding a total of 2,002 records. Boolean operators were applied to search titles, abstracts, and keywords using the following string: ("deep foundation" OR "pile" OR "suction caisson") AND ("design innovation" OR "numerical modelling" OR "machine learning" OR "instrumentation" OR "performance monitoring" OR "digital twin"). Only peer-reviewed, English-language journal articles published between January 2010 and June 2025 were considered.

Duplicate records (n = 338) were removed automatically using EndNote, resulting in 1,664 records. During the initial screening, 798 non-journal publications (468 conference papers, 188 books, 45 standards, and 95 magazine articles) were excluded, leaving 866 for further review. Title screening excluded 614 papers, 601 for being unrelated to the review topic and 13 for being non-English, reducing the pool to 252 articles.

Subsequent abstract screening removed another 196 articles, primarily due to irrelevant outcomes (n = 138) and inadequate evaluation (n = 58). The remaining 83 full-text articles were assessed for eligibility. A total of 53 were excluded for reasons including lack of accessibility (13), absence of research results (11), missing sample data (9), regulatory influence (8), and consulting firm bias (12). Figure 1 shows the PRISMA diagram

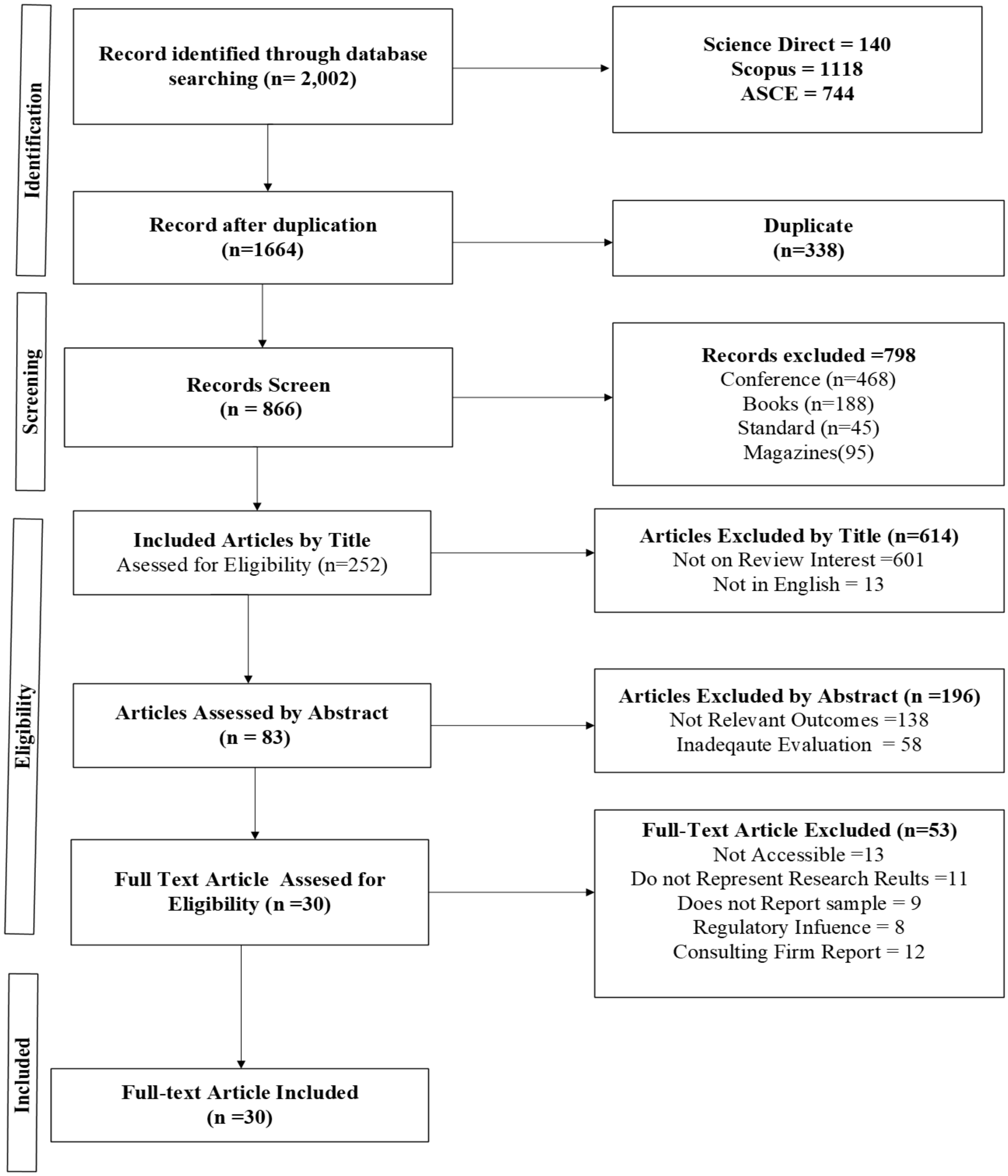

Fig.1. PRISMA flow diagram showing the article selection process

Ultimately, 30 full-text articles met all inclusion criteria. These articles either proposed or validated novel design or monitoring strategies for deep foundations. The final selection included five papers from ASCE, eight from Scopus, and 17 from ScienceDirect. Figures 2 and 3 illustrate the temporal distribution of selected publications (2010–2025) and the proportional contribution from each database, respectively.

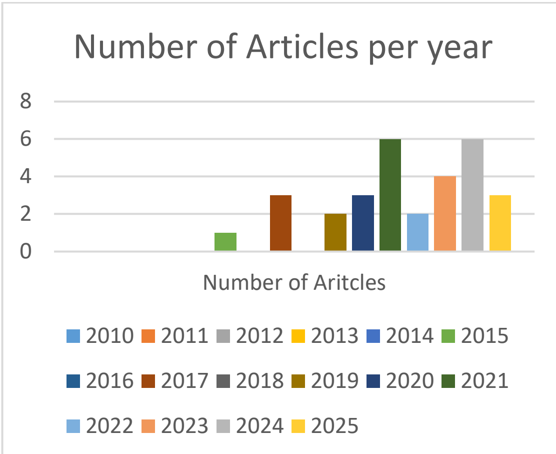

Fig 2. Selected Publish articles based on year

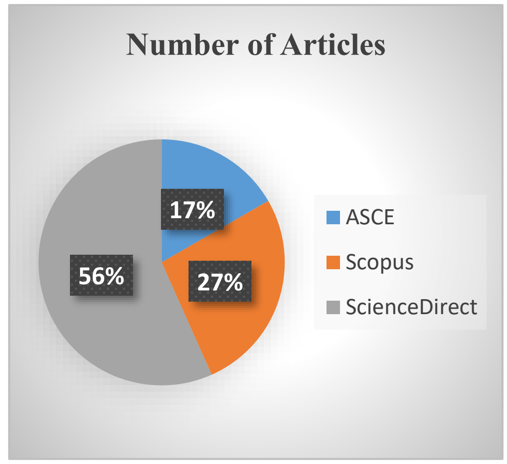

Fig 3. Percentage of articles in database

Inclusion demanded that a study (i) introduced a new design methodology such as an AI model, an upgraded constitutive law or a hybrid pile configuration; (ii) reported a performance-monitoring approach supported by field or laboratory evidence; and (iii) presented quantitative data for axial, lateral, cyclic or environmental responses. We excluded work centred on shallow footing systems, conventional design without innovation, studies lacking numerical or empirical validation, and papers inaccessible through institutional subscriptions.

For every eligible article, we extracted metadata, authors, year, test sample and boundary conditions, methodological framework, principal findings, declared limitations and the study's relevance to the design–monitoring feedback loop and collated these data in a master spreadsheet. Quantitative model-assessment metrics (e.g., root-mean-square error and coefficient of determination) were noted wherever predictive tools were evaluated. A thematic synthesis then distilled recurrent patterns, emerging trends and points of divergence, with special emphasis on how monitoring evidence is or is not fed back into design recalibration. Table 1 below shows the summary of the related study.

Table 1: Summary of the related study

Author/Year	Sample	Methodology	Findings	Gap/Limitation	Relevance to Review
(Beuckelaers et al., 2017)	Monopile in sand	Kinematic hardening soil model + aeroelastic simulations	Captures realistic stiffness reduction and damping increase under cyclic loads	Calibrated only for monotonic loading in sand	Demonstrates a leap in monopile design modelling for fatigue life prediction
(Mehravar et al., 2019)	Suction caisson with silt substratum	Seepage-mechanical coupling in numerical analysis	Low permeability layers affect the tip and frictional resistance significantly	Assumes normalised geometry, lacks site validation	Improves prediction accuracy for caisson installation in layered seabeds
(Byrne et al., 2019)	PISA test sites	Site-specific p–y curve framework	Cuts steel requirement by 30% over API standards	Geographically limited to UK soils	Anchors the shift toward site-calibrated offshore monopile design
(Rabiei & Choobbasti, 2020)	Piled raft systems	Artificial Neural Network (MLP)	Predicts settlements and raft moments efficiently	Requires extensive training data	Presents a data-driven approach to optimise raft foundation layouts

Author/Year	Sample	Methodology	Findings	Gap/Limitation	Relevance to Review
(Trojnar, 2021)	Full-scale hybrid pile	Simplified design method for hybrid pile–soil systems	Lateral displacements reduced by up to 70%	Still in early application; validation needed	Introduces a viable preliminary design framework for hybrid monopiles
(W. Lu et al., 2021)	Centrifuge tests (V-H loads)	Model tests for coupled vertical–horizontal loading	Axial loading alters p–y curve steepness	Small-scale tests in sand only	Challenges separate V and H design; supports integrated p–y formulation
(Huang et al., 2022)	Offshore East China Sea CPT data	CPT-based vs API method	CPT offers more reliable capacity predictions	Fatigue and plug effects are unaccounted for	Advocates' use of site data to improve offshore pile design
(Du et al., 2021)	RBB pile dataset (1008 cases)	FE + Evolutionary Polynomial Regression	Closed-form equations predict capacity reliably	Ignores lateral capacity	Reinforces AI-based design standardisation for enlarged base piles
(D. Wu et al., 2021)	Full-scale energy pile	Field test + numerical modelling	84% thermal energy stored; intermittent mode is more effective	Limited to short-term and single pile	Provides quantified data for energy pile thermal performance monitoring
(Al-Jeznawi et al., 2022)	Pile in layered sand	Static–dynamic analysis of seismic kinematic loading	Peak bending occurs in upper loose sand	Uses simplified saturation assumptions	Enhances seismic design by locating the critical depth for bending
(Amlashi, 2023)	Offshore monopiles	Reliability-based ULS design format	Model bias affects the structural safety level	Focused on the ultimate limit state only	Reinforces the importance of harmonising probabilistic design in offshore piles
(Hong et al., 2024)	Suzhou deep pit	BPNN + NSGA-III	Finds optimal stiffness for cost–safety trade-off	One-case demonstration	Integrates multi-objective AI in foundation pit design
(Soomro et al., 2025)	375 batter pile fault models	Ensemble ML (LightGBM, RF, CatBoost, etc.)	Achieves $R^2 > 0.90$ in damage prediction	No real-world deployment yet	Offers a predictive monitoring model for fault-impacted pile behaviour
(B. Lu et al., 2024)	Ultra-deep pit excavation	Enhanced DLSM + MCC	Captures staged deformation with high fidelity	High computational demand	Provides a scalable tool for pit deformation monitoring in deep foundations
(Feng et al., 2024)	Model pile in sand	DEM + lab validation	Force chain distributions align with test data	Applicable only to uniform sand	Enables particle-scale visualisation in pile penetration design
(Kalovelonis et al., 2025)	Offshore monopile (CP system)	ISO 24656 BEM numerical model	Highlights design differences from ISO defaults	Electrochemical behaviour assumptions need refinement	Provides an integrated design pathway for durability against corrosion
(Jindal et al., 2024)	Offshore monopiles	Comparative study of p–y curves (API, ISO, PISA)	Identifies cyclic and damping modelling gaps	Field validation missing	Assists refinement of foundation models under cyclic offshore loading
(B.-N. Zhang et al., 2024)	Rock-socketed pile	FDEM numerical simulation	Interface failure reduces horizontal capacity sharply	Conventional FEM underestimates failure	Demonstrates rock damage propagation in pile design
(Shirani, 2024)	3XL monopile lowering	Hydrodynamic modelling (Morison vs BEM)	Diffraction effects become dominant	Needs experimental validation	Improves offshore pile transport safety and lifting design
(John et al., 2025)	OLE pile cap	Full instrumentation (strain, wind, vibration)	Captures structural load transfer to the pile cap	Pilot-scale; no long-term monitoring yet	Reinforces the value of live instrumentation for dynamic performance

Author/Year	Sample	Methodology	Findings	Gap/Limitation	Relevance to Review
(Coleman et al., 2021)	Multiple deep foundation projects	Applied Statnamic, CSL, sonic testing	Reveals cost and schedule benefits of tailored testing	Primarily qualitative and project-specific	Establishes how innovative testing improves foundation performance verification
(Stapelfeldt et al., 2021)	Centrifuge caisson tests in layered soils	Model testing under cyclic tension loads	Shows significant clay plug control on tension capacity	Model-scale only, no field data	Enhances understanding of layered-soil interaction in caisson design
(Abadie et al., 2023)	Foundations under long-term cyclic loads	Fatigue simulation using pseudo-random loads	Predicts long-term capacity evolution under millions of cycles	Requires field validation	Provides a robust method for fatigue-life performance prediction
(Colak et al., 2023)	5 piled raft buildings	Comparative analysis using PLAXIS 2D & 3D	3D analysis offers better settlement and stress accuracy	Higher complexity and computational cost	Validates 3D numerical modelling as a superior design tool in complex conditions
(Favaretti et al., 2015)	Database of full-scale pile tests	Review of advanced p–y formulations	Highlights cyclic, group, and geometric effects overlooked in practice	API models outdated yet widely used	Supports transition to context-specific, updated p–y models
(Chen et al., 2017)	Prestressed concrete energy pile	Field test under thermal cycling	Shaft resistance decreases under heating, increases under cooling	Single-pile study with short-term data	Offers field data for refining thermo-mechanical pile response models
(Shan et al., 2017)	Retrofit of building with new pile supports	Monitored axial force and settlement	Pile–pillar force transfer succeeded; cutting technique critical	Applies to specific retrofit case	Demonstrates monitoring strategy for safety in structural underpinning
(Pujadas-Gispert et al., 2020)	Deep foundation types in Spain	Life-cycle assessment (LCA) with cost analysis	Precast piles reduce CO_2 emissions by 44%	Regional data and assumptions limit generality	Bridges sustainability into deep foundation design choices
(J. Zhang et al., 2020)	Shanghai pile load-test database	Bayesian updating of resistance factors	Site-specific calibration reduces prediction bias	Depends on availability of regional data	Promotes reliability-based design with machine learning enhancements
(Hong et al., 2024)	Offshore suction caisson	FE–based capacity prediction under cyclic tension	Improved model accuracy by incorporating plug formation	Limited to specific soil profiles	Refines cyclic-tension performance prediction in suction foundations

Results and Discussion

The reviewed literature presents significant progress in the development and application of advanced techniques for deep foundation design and performance monitoring. Innovations in computational modelling, machine learning, and hybrid structural systems have emerged as transformative tools, while the integration of field instrumentation and digital sensing technologies has enhanced the ability to validate and optimize foundation behaviour under complex loading scenarios. This section synthesizes findings across the selected studies, categorizing them into design approaches, performance monitoring methods, and their degree of integration.

Innovative Design Approaches

Fifteen of the reviewed articles focused on novel design methodologies aimed at enhancing prediction accuracy, reducing material consumption, and improving safety margins. Among these, the application of high-fidelity numerical simulations was the most frequently adopted approach. (Byrne et al., 2019)demonstrated the advantages of the PISA framework, which uses site-calibrated p–y curves derived from large-scale testing to reduce steel usage in monopile design by up to 30%, compared to conventional API-based methods.

Advanced constitutive models and finite element analyses (FEA) have also been employed to simulate soil-structure interaction with greater precision. For example, (Li et al., 2024)implemented a GPU-accelerated Distinct Lattice Spring Model (DLSM) coupled with a modified Cam-Clay law to simulate deep retaining wall behaviour efficiently, while Zhang B.-N. (2024) applied a finite-discrete element method (FDEM) to model fracture propagation in rock-socketed piles, revealing failure mechanisms not captured by standard FEA.

Machine learning (ML) models have gained prominence for their ability to predict load capacity, settlement, and damage progression with high computational efficiency. (Rabiei & Choobbasti, 2020)developed a multilayer perceptron (MLP) model for estimating piled raft settlements, achieving a coefficient of determination (R^2) of 0.93 compared to field measurements. Similarly, (Du et al., 2021)proposed a closed-form equation derived from a large FEM database using evolutionary polynomial regression (EPR), significantly improving the accuracy of base-enlarged pile capacity predictions.

Hybrid pile designs were also explored. (Trojnar, 2021)introduced a composite monopile system with a granular annulus that reduced lateral displacement by over 70%. This structural modification alters the pile-soil interaction mechanism, offering new design opportunities for offshore wind foundations. Collectively, these studies reflect a trend toward performance-based, site-specific, and computationally optimized deep foundation design frameworks.

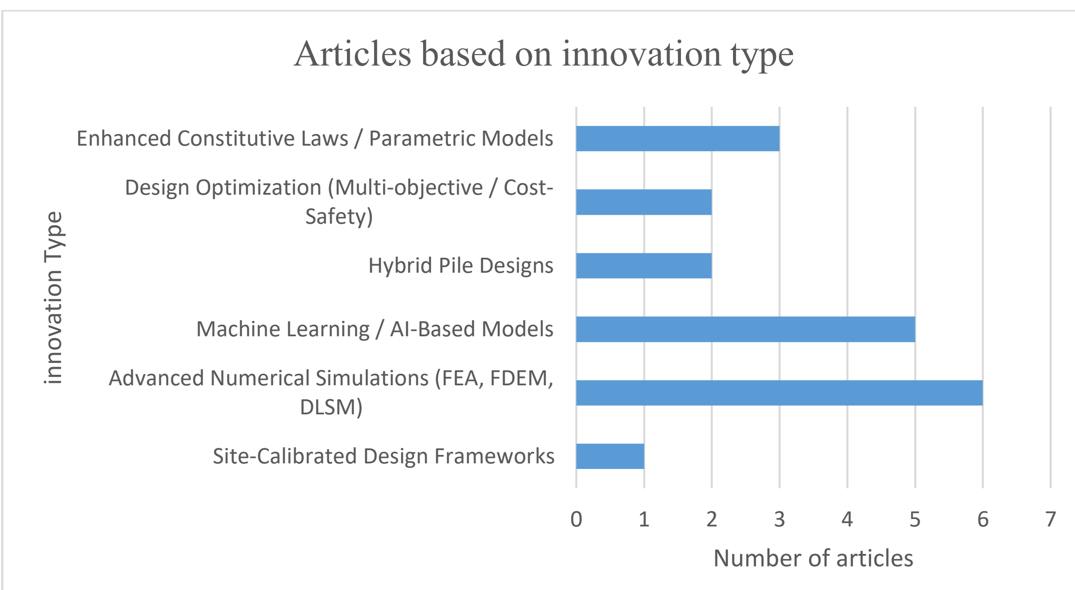

Fig.4. Articles based on innovation type

Advances in Performance Monitoring

Nine studies emphasized performance monitoring innovations, which ranged from embedded instrumentation to large-scale cyclic load testing. (Jin et al., 2021) deployed fiber-optic sensors in energy piles to monitor thermo-mechanical behaviour during heating and cooling cycles. Their data revealed dynamic changes in shaft resistance, supporting refined design assumptions under thermal loading conditions.

Real-time structural health monitoring was demonstrated by (John et al., 2025), who instrumented railway overhead line foundation piles with synchronized strain gauges and accelerometers. These sensors captured wind-induced and train-induced dynamic responses, providing data that contradicted conservative load assumptions in current codes.

(Abadie et al., 2023)conducted laboratory-based pseudo-random fatigue testing on offshore monopiles, identifying a 12% reduction in axial capacity after 10^7 loading cycles. This insight fills a critical gap in fatigue life assessment, which is often underrepresented in offshore foundation design standards. Likewise, (Coleman et al., 2021)showcased the value of Statnamic and rapid load testing in minimizing intrusive inspections, reducing construction schedules by up to 20%.

However, a notable limitation across many of these studies is the lack of long-term monitoring and feedback into design recalibration. While data acquisition technologies have advanced, integration into design codes and predictive models remains limited.

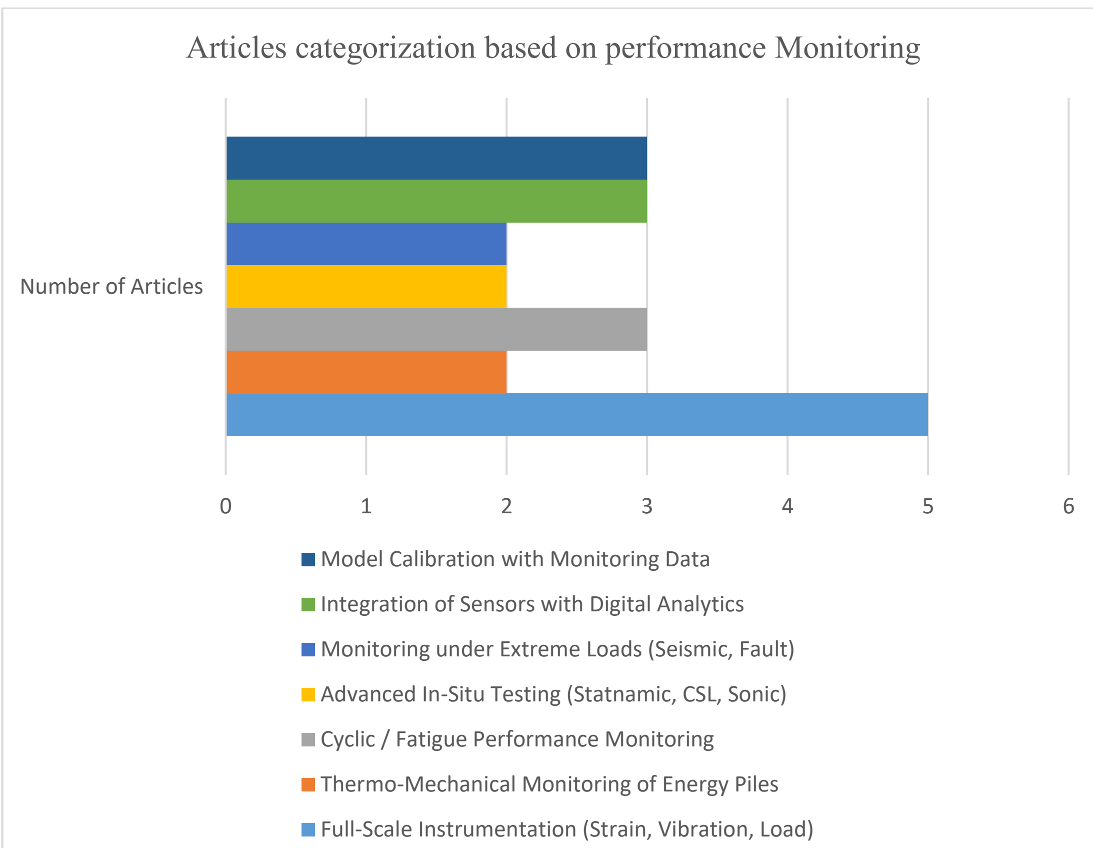

Fig.5. Articles categorization based on performance Monitoring

Design–Monitoring Integration

Only six of the thirty articles demonstrated a deliberate feedback loop between performance data and design updates. (Hong et al., 2024)developed a digital twin framework that combined neural networks with genetic algorithms to continuously update excavation support models based on observed deformations. (Amlashi, 2023)applied reliability-based calibration methods, showing that updated resistance factors based on field observations shifted safety indices by up to 0.2.
These examples underscore the potential of closing the design–monitor–update (DMU) loop but also highlight the scarcity of practical implementations. The majority of AI-driven models are developed using static datasets without real-time calibration, while monitoring campaigns are often isolated case studies with limited cross-project applicability(Al-Atroush et al., 2024).

Cross-Cutting Themes and Identified Gaps

Three major benefits of design and monitoring innovations emerged from the synthesis:

- **Material Efficiency**: Reductions in steel or concrete usage of 20–30% were reported in hybrid or optimized pile designs.
- **Predictive Accuracy**: AI-based models and advanced simulations showed improved alignment with field data, reducing predictive uncertainty.
- **Project Delivery**: Rapid testing and real-time monitoring enabled faster construction timelines and enhanced risk management.

Nevertheless, several persistent gaps remain:

- Lack of full-scale, long-term validation across soil types and load conditions;
- Underutilization of monitoring data in updating design models and safety factors;
- Absence of standard performance indicators for comparing foundation performance across projects;
- Minimal open-access data sharing, limiting replication and benchmarking.

Addressing these issues requires coordinated efforts among researchers, practitioners, and standard-setting bodies to develop shared protocols, open databases, and integrated DMU workflows.

Future Research Directions

The findings of this systematic review underscore the transformative potential of combining innovative design methodologies with advanced performance monitoring in deep foundation systems. However, despite significant strides in both domains, their integration remains limited and often isolated to experimental or project-specific applications. Future research must move beyond proof-of-concept models and toward a standardized, data-driven framework that enables performance-based, adaptive foundation design.
A primary direction for future work involves the development of open-access, full-scale foundation performance datasets that include design parameters, installation records, soil profiles, and long-term monitoring data. Such datasets would facilitate benchmarking, improve model training and validation particularly for AI-based surrogates and support probabilistic

reliability calibration. Without this, many machine learning models risk becoming site-specific tools that lack broader applicability across diverse geotechnical settings.

There is also a pressing need for cross-disciplinary digital twin frameworks that connect real-time monitoring data with adaptive design recalibration. These systems should be capable of autonomously updating safety margins, modifying pile configurations, or triggering alerts when performance deviates from predicted behaviour. Although a few studies have demonstrated the technical feasibility of this approach, its scalability and integration into construction practice remain underexplored.

In addition, future research should focus on multi-hazard and multi-load scenario modelling. Deep foundations are increasingly being designed for environments where they are exposed not only to static and dynamic structural loads but also to thermal, seismic, hydrodynamic, and corrosive conditions. Coupled modelling frameworks that incorporate these load effects validated against field data are essential to ensure long-term durability and resilience. For example, energy piles, hybrid monopiles, and suction caissons installed in heterogeneous marine sediments must be evaluated under simultaneous thermal-cyclic loading and corrosion scenarios to better capture service-life performance.

Another emerging research frontier lies in the sustainability assessment of innovative foundation systems. While reductions in material volume have been achieved through optimization, few studies have extended this into comprehensive life-cycle assessments (LCA). Metrics such as embodied carbon, end-of-life recyclability, and environmental impact from installation activities need to be quantified and compared across traditional and novel foundation types. Additionally, integration of bio-based soil improvement techniques, such as microbially induced calcite precipitation (MICP), into deep foundation design warrants further attention for its potential to improve ground conditions while lowering environmental footprint.

Finally, future studies should contribute toward the standardization of performance metrics and validation protocols. Developing industry-accepted indicators such as displacement ratios, energy dissipation indices, fatigue degradation rates, and instrumentation reliability factors will facilitate fair comparison across projects and help bridge the gap between academic research and practical implementation. Collaboration among researchers, industry stakeholders, and code-development agencies is vital to ensure that these innovations translate into updated design codes and best practice guidelines.

By addressing these research needs, the geotechnical community can advance toward a new paradigm of performance-based foundation engineering, one that is intelligent, adaptable, and environmentally responsible.

Conclusions

This systematic review examined thirty peer-reviewed articles published between 2010 and 2025 that explored innovations in the design and performance monitoring of deep foundation systems. The findings highlight a growing convergence between advanced computational models, machine learning-based design tools, and real-time performance monitoring techniques. Collectively, these innovations represent a shift from deterministic, empirically driven foundation engineering to a more adaptive, data-informed, and performance-based practice.

The reviewed literature demonstrates that significant improvements in structural efficiency, safety, and material optimization are achievable through high-fidelity numerical methods, AI surrogates, and hybrid pile designs. For instance, monopile and base-enlarged pile studies reported up to 30% reductions in steel usage, while machine learning algorithms achieved prediction accuracies comparable to conventional FEM tools in a fraction of the computational time. Similarly, field-scale instrumentation and monitoring campaigns using fiber-optic sensors, embedded strain gauges, and rapid load testing have provided valuable insights into in-service foundation behavior under axial, lateral, thermal, and cyclic loads.

Despite these advancements, the review also reveals persistent gaps that must be addressed to fully realize the potential of integrated design–monitor–update(DMU) workflows. Many AI and high-fidelity models lack validation across diverse site conditions, while monitoring data are seldom used to recalibrate design models or update reliability indices. Furthermore, the absence of open-access datasets and standardized performance metrics limits the scalability and replicability of proposed innovations.

To move the field forward, future research must prioritize the development of shared data repositories, long-term monitoring infrastructures, and digital twin systems capable of real-time design adaptation. Additionally, expanding the scope of foundation design to include multi-hazard scenarios and sustainability indicators will better align foundation engineering with contemporary environmental and resilience objectives.

In summary, this review provides a consolidated view of the current state of knowledge on innovations in deep foundation systems and offers a roadmap for bridging the divide between predictive design and empirical performance. By promoting evidence-based practice and fostering collaboration across disciplines, the geotechnical engineering community can advance toward more reliable, efficient, and sustainable foundation solutions.

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