



Recent Developments in Foundation Engineering: A Review

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Abstract: Foundation engineering has experienced rapid, multidisciplinary advancement over the past five years. Progress spans high-fidelity numerical methods and multi-physics coupling, large-scale experimental facilities (including advanced centrifuge testing), integration of physics-informed machine learning with classical constitutive models, and sustainability-driven innovations in materials and ground improvement (e.g., geopolymers and low-carbon binders). At the same time, seismic soil–structure interaction (SSI) modeling and performance-based design approaches continue to mature, supported by improved boundary treatments and large-scale validation datasets. Remaining gaps include standardization of SSI practice, long-term durability data for novel binders and ground improvement, and deployment of data-driven tools in routine design. This review synthesizes recent (2020–2025) advances, highlights key trends, and suggests priority research directions to move innovations from laboratory and pilot projects into mainstream practice.

Keywords: Foundation, Soil-structure, Geopolymers, Liquefaction, PIML

I. INTRODUCTION

Foundations form the critical interface between structures and the ground. The last half decade has witnessed intensified research motivated by higher performance demands (seismic resilience, serviceability under cyclic loads, rapid construction), carbon-reduction targets, and the availability of large datasets and computational power. This review examines major developments in numerical modelling, experimental validation, data-driven/physics-informed methods, materials and ground improvement, seismic SSI, and practice/standardization (circa 2020–2025). It aims to help researchers and practitioners understand where the field is moving and what is needed to translate advances into safe, cost-effective designs.

II. REVIEW METHODOLOGY

This paper synthesizes peer-reviewed reviews, recent journal articles, conference proceedings, and large-scale experimental reports published primarily between 2020 and mid-2025. Searches targeted topics: soil–structure interaction, foundation numerical modelling, centrifuge and full-scale testing, physics-informed machine learning (PIML) in geotechnics, low-carbon binders/deep mixing, and sustainability of foundation solutions. Representative, high-impact works and specialist review articles were prioritized to identify core trends and evidence-backed conclusions.

III. ADVANCES IN NUMERICAL AND COMPUTATIONAL MODELLING

3.1 Coupled multiphysics and multi-scale approaches

Recent work has focused on bridging scales (from lab specimens to field systems) and coupling physical processes (mechanics, pore-fluid flow, thermal effects). Coupled FE–DEM frameworks and domain decomposition techniques enable simulation of large systems while capturing soil nonlinearity, interface slip, and particle rearrangement where needed. These approaches make it feasible to model phenomena such as foundation rocking, soil yielding, and pile group interactions with improved fidelity.

3.2 Improved boundary treatments and radiation damping

For dynamic SSI, improved absorbing boundary conditions, domain reduction methods, and enhanced radiation damping formulations have reduced artificial reflections and allowed more realistic simulation of wave propagation and energy dissipation in large-footprint foundations and embedded structures. These advances are crucial for accurate seismic response prediction of bridges, tall buildings, and offshore foundations.

3.3 Constitutive laws & cyclic behavior

Constitutive models that capture cyclic degradation, stiffness-reduction, and accumulation of permanent displacements are increasingly incorporated into foundation analyses—particularly for piles and shallow foundations under repeated or seismic



loading. Improved soil–pile interface models and hysteretic behavior formulations enable better prediction of settlement, bending moments, and lateral load capacity under service and extreme loads.

IV. EXPERIMENTAL METHODS & VALIDATION

4.1 Centrifuge testing and large-scale facilities

High-acceleration centrifuge modelling remains a cornerstone for validating SSI models under controlled scaled conditions. New large-scale (higher-g and larger model space) centrifuge campaigns and facility upgrades (including multidirectional loading capabilities) have enhanced our understanding of complex behavior, such as rocking, soil improvement effects, and liquefaction mitigation performance. Recent large facility tests have also combined advanced instrumentation (DAS fiber optics, dense geophone arrays) to capture dynamic responses at high resolution.

4.2 Full-scale and instrumented field tests

Full-scale pile and mat load tests, instrumented during construction and over service life, are increasingly used to validate numerical predictions and to calibrate constitutive models for site-specific conditions. Real-time monitoring (including remote sensing and fiber optics) supports long-term performance studies for settlements, lateral deflections, and cyclic degradation. These datasets are essential for benchmarking numerical tools and for building open experimental repositories.

V. DATA-DRIVEN METHODS AND PHYSICS-INFORMED MACHINE LEARNING (PIML)

5.1 Supervised learning for geotechnical screening

Conventional supervised ML algorithms (random forests, gradient boosting, SVMs, deep neural networks) are widely employed for rapid estimation tasks: soil classification from geotechnical logs, preliminary bearing capacity and settlement estimates, and screening of foundation configurations. These methods accelerate early design stages but often lack robustness when extrapolated beyond training data.

5.2 Physics-informed and hybrid models

A major recent trend is the integration of physical laws with ML (PIML). By embedding governing equations or constitutive constraints into learning architectures, these hybrid models yield better generalization, reduced requirement for labeled data, and physically consistent predictions—addressing one of the main criticisms of purely data-driven approaches. The 2025 direction paper on PIML in geotechnical engineering synthesizes recent applications and argues for broader adoption in foundation design and SSI modelling.

5.3 Uncertainty quantification and reliability

Bayesian ML and probabilistic surrogate models are being used to quantify predictive uncertainty and to integrate data uncertainty directly into reliability-based foundation design. These approaches enable performance-based design under epistemic and aleatory uncertainty and support risk-informed decisions for critical infrastructures.

VI. SEISMIC SOIL–STRUCTURE INTERACTION (SSI)

6.1 Site-specific SSI effects and performance-based design

Recent reviews emphasize that SSI may lengthen or shorten structural periods and change damping characteristics in ways that are highly site and structure dependent. Modern practice increasingly recommends site-specific SSI analyses (rather than blanket simplifications), especially for critical structures such as bridges, hospitals, and tall buildings. Improved nonlinear SSI models under cyclic loading, along with better radiation and kinematic coupling treatments, are enabling more reliable performance assessments.

6.2 Liquefaction and post-liquefaction foundation performance

Predictive models and mitigation strategies for liquefaction (e.g., stone columns, deep soil mixing, geosynthetic reinforcement) have been refined using combined centrifuge and field test datasets. Recent experimental studies show partial ground improvement can drastically reduce post-liquefaction settlements and tilt in structures but highlight the need for more full-scale validation to generalize findings.

VII. FOUNDATION TECHNOLOGIES, MATERIALS, AND SUSTAINABILITY

7.1 Low-carbon binders and geopolymers soil stabilization

Environmental pressure has accelerated research into low-carbon alternatives to ordinary Portland cement (OPC) for deep mixing and soil stabilization. Geopolymers, alkali-activated binders, and blended low-carbon mixes have been tested in multiple pilot



projects and field cases; recent comparative in-situ studies report promising strength gain and reduced embodied CO₂ for several binder formulations. Nevertheless, long-term durability and quality control remain active research subjects.

7.2 Recycled aggregates and geosynthetics

Use of engineered fill with recycled aggregates, and incorporation of geosynthetics for reinforcement and drainage, is rising—backed by laboratory and field performance data. These materials support circular construction strategies and can improve bearing capacity and reduce settlement when used appropriately.

7.3 Constructability: prefabrication & additive manufacturing

Prefabricated foundation elements, driven piles with improved QA/QC, and early experiments in 3D printing of foundation components are being piloted to increase speed and reduce waste. While 3D printing of foundations is still at a demonstration/pilot stage, it promises complex geometries, on-site customization, and potential material efficiency gains when paired with optimized mixes. More research is required on structural reliability and inspection standards for printed foundation elements.

VIII. CODES, STANDARDIZATION, AND PRACTICE GAPS

Despite technical progress, practice lags in several respects:

- **Lack of updated SSI provisions in many national codes** that reflect nonlinear, coupled analyses and data-driven validation. A coordinated effort is needed to translate model- and experiment-driven insights into pragmatic code clauses.
- **Insufficient open experimental repositories and benchmarks**, limiting reproducibility and robust validation of ML and numerical methods. The community has begun to call for curated benchmark problems and shared datasets.
- **Quality control and long-term performance data** for low-carbon binders and novel ground improvement methods are limited, constraining widespread adoption. Field monitoring and standardized acceptance tests are necessary to build practitioner confidence.

IX. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

1. **Scale bridging & multi-physics validation:** Robust multi-scale frameworks that are verified against centrifuge, large-scale, and full-scale tests are critical. Harmonizing lab and field results remains a priority.
2. **Operationalizing PIML:** Translate promising PIML prototypes into validated tools with clear applicability domains, interpretability, and regulatory acceptance. Focused benchmark problems will accelerate this.
3. **Durability & lifecycle studies:** Long-term monitoring of foundations using low-carbon binders and recycled materials to assess creep, chemical degradation, and serviceability over decades.
4. **Standardization & codes:** Develop pragmatic code updates that integrate modern SSI insights (e.g., nonlinear kinematic/inertial coupling guidelines) and provide validated simplified procedures for common practice.
5. **Digital twins & asset management:** Leverage instrumented monitoring, digital twin frameworks, and probabilistic models to manage foundation performance over life cycles and to enable condition-based interventions.

X. CONCLUSION

Foundation engineering is evolving rapidly through the confluence of computational power, advanced experiments, data science, and sustainability drivers. High-fidelity numerical methods, expanded experimental capabilities (centrifuge and full-scale), and the emergence of PIML mark important steps towards more reliable, efficient, and low-carbon foundations. For these advances to become routine, the community must prioritize open benchmark datasets, code revisions grounded in experimental evidence, long-term monitoring of novel materials, and translational research that addresses constructability and cost. With coordinated efforts, foundation engineering can meet modern society's demands for resilient, sustainable, and cost-effective infrastructure.

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