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How AI And Machine Learning Are Transforming The Geotechnical Lifecycle

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A DISCIPLINE BUILT ON UNCERTAINTY

Geotechnical engineering has always been defined by uncertainty. Subsurface conditions are variable, data is limited, and decisions made early in a project can influence performance, risk, and cost for decades. At the same time, infrastructure projects face growing complexity driven by urbanization, aging assets, climate-related hazards, and increasing expectations for safety, resilience, and cost certainty.

In practice, most of the traditional geotechnical industry still depends heavily on manual, document-driven workflows to manage an inherently uncertain highly variable subsurface. Field logs, laboratory results, design calculations, and monitoring records are scattered across logs, reports, spreadsheets, and PDFs, often requiring engineers to re-enter data, repeat calculations, and reinterpret the same information at multiple stages. This fragmentation limits traceability between project phases, reduces reuse of valuable data, and makes it difficult to explicitly quantify, track, and reduce uncertainty as a project progresses.

This is where modern data-driven approaches are transforming geotechnical practice. Advances in data management, advanced data analytics, artificial intelligence (AI), machine learning, and remote sensing technologies are creating an opportunity to connect these phases into a continuous lifecycle. Robust data management provides the foundation, ensuring subsurface information is structured, traceable, and reusable, while advanced analytics and AI convert that data into insight.

PLANNING AND SITE INVESTIGATION

Setting the Foundation for Better Decisions

The geotechnical lifecycle begins long before the first boring is drilled. Early planning decisions shape the level of uncertainty that must be managed later in design and construction.

Remote sensing technologies such as Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR), and historical aerial images allow engineers to step back and view site conditions at a regional scale. When combined with historical geotechnical investigation data, these tools help to identify ground deformation, slope movement, and historical settlement trends early, helping teams focus detailed investigations where risk is highest rather than relying on uniform sampling strategies.

As intrusive investigations begin, advanced data management strategies support fully digital data capture directly in the field, enabling onsite development of draft deliverables and automation of laboratory testing workflows and reporting. By eliminating repetitive manual data entry, these systems reduce transcription errors, improve data traceability, and significantly accelerate the overall investigation-to-deliverable timeline.

Building on this digital foundation, modern data management and visualization platforms integrated with machine learning enables more effective integration of geophysical and geotechnical data. Information from borings, Cone Penetration Tests (CPT), seismic surveys, resistivity testing, and ground-penetrating radar, as well as past geotechnical data can be combined into more spatially continuous subsurface models, reducing blind spots between investigation points.

For large and high-frequency datasets, such as measurement-while-drilling records, CPT profiles, and instrumented testing, AI plays a critical role in automated data screening and analysis. Machine learning algorithms can identify anomalies, outliers, and critical trends that warrant engineering attention. AI further supports a shift away from single-value soil parameters toward probabilistic characterization, including two-and three-dimensional modelling of stratigraphy and spatial variability.

By deriving soil properties from multiple data sources and explicitly quantifying uncertainty in 2D as well as 3D, engineers gain a clearer understanding of the confidence and limitations of their assumptions. These quantified uncertainty measures provide direct inputs into reliability and performance-based design frameworks, allowing risk to be evaluated explicitly rather than absorbed implicitly through conservative assumptions. In emerging applications, this uncertainty awareness feeds back into adaptive site investigation planning, where additional exploration is targeted specifically to reduce the most critical unknowns.

DESIGN AND ENGINEERING

Moving Beyond Deterministic Assumptions

Design is where uncertainty is traditionally absorbed, often through conservative assumptions and safety factors. While effective, this approach can mask risk and lead to inefficiencies. Machine learning as well as advanced data analytics offers a way to refine, rather than abandon, traditional geotechnical methods. Empirical correlations can be recalibrated using project-specific and historical data, improving accuracy while maintaining physical relevance. Physics-informed machine learning builds on this by embedding soil mechanics and constitutive behavior directly into machine learning models. These surrogate models can approximate complex numerical analyses with greater speed while remaining interpretable and grounded in engineering principles.

Together, these tools support a more explicit reliability- and performance-based design process. Instead of relying on implicit conservatism, engineers can directly link soil uncertainty, model uncertainty, and performance criteria, making risk more transparent to owners and stakeholders. AI-driven automation further enhances the design workflow by assisting with soil and rock parameter estimation, improving consistency, accuracy, and efficiency. AI-assisted retrieval-augmented generation (RAG) as well as agentic AI enable efficient extraction and application of information from design standards and guidelines significantly improving efficiency, consistency, and productivity. By automating information retrieval and cross-referencing, these tools allow engineers to focus on judgment rather than manual information searches and consistency checking. These capabilities also support automated geotechnical report review and the development of initial draft reports. Repetitive, rule-based tasks are well suited for automation, allowing engineers to focus on complex technical challenges, professional judgment, and higher-value engineering decisions.

CONSTRUCTION

Turning Monitoring into Active Risk Management

Construction is the stage at which designs are implemented at actual ground conditions and design assumptions are tested against actual ground conditions. Traditionally, geotechnical monitoring and quality control during construction have been largely reactive, with data reviewed after issues have already emerged.

Real-time geotechnical monitoring enabled by installed instrumentation shifts this paradigm toward proactive risk management. Continuous measurements of ground and structural response provide immediate feedback on performance, enabling earlier intervention and reducing the risk for failure for critical infrastructure. Machine learning enhances this process by distinguishing true ground movement from temperature effects and ambient noise, an area where manual interpretation often proves challenging and by supporting short- and medium-term forecasting of movement under changing site conditions.

Machine learning further strengthens construction quality control by automatically screening large volume of construction data, including compaction data, piling records, grouting logs, and instrumentation outputs. Anomalies and patterns that might be overlooked in manual reviews can be identified and flagged in near real time, improving consistency and responsiveness and supporting a more systematic quality control process.

These capabilities enable an automated observational method, where monitoring data is directly linked to predefined response actions and can be used to back-calculate and refine design parameters. When conditions deviate from expectations, adjustments can be made quickly and systematically closing the loop between design and construction.

Emerging vision-based monitoring using drones and site cameras complements these approaches, providing additional context for progress, condition, and safety.

OPERATIONS AND ASSET MANAGEMENT

Extending Insight Beyond Construction

Geotechnical performance does not end at project completion. Settlement, deformation, and degradation can continue for years or decades, yet long-term data is often underutilized.

Digital twins provide a framework for carrying geotechnical knowledge forward. By integrating investigation data, design models, construction records, and monitoring results, these living models support ongoing performance assessment. Monitoring data collected during construction establishes the initial state of the geotechnical digital twin, which is then continuously updated throughout the operational life of the asset.

Long-term LiDAR and InSAR monitoring enable continuous tracking of deformation trends across large areas, supporting proactive maintenance rather than reactive response.

When combined with predictive degradation and service-life models, owners can better anticipate future performance and plan interventions before problems escalate. Early warning systems further support this shift by linking risk thresholds to predefined mitigation strategies.

CROSS-CUTTING FOUNDATIONS

Making AI Practical and Trustworthy

Across all phases of the lifecycle, success depends on strong foundations. Consistent data standards and interoperability ensure that information flows seamlessly from planning through operations.

Knowledge and asset management systems allow firms to systematically reuse historical data and lessons learned, turning past projects into assets for future decision-making. This traceability also supports auditability of assumptions, decisions, and uncertainty management across the lifecycle.

Equally important is governance. AI models must be transparent, validated, and traceable to maintain engineering accountability and regulatory confidence. Trust is built when AI enhances clarity rather than obscuring how decisions are made.

A CONNECTED LIFECYCLE FOR A CHANGING INDUSTRY

By linking planning, design, construction, and operations into a continuous lifecycle, AI helps engineers manage uncertainty more explicitly, respond to risk more proactively, and deliver more resilient infrastructure.

Rather than replacing the engineer, these tools augment engineering expertise by automating repetitive, routine tasks and improving efficiency, consistency, and insight. This allows geotechnical engineers to focus on complex technical challenges, sound professional judgment, and higher-value engineering decisions that directly influence project performance and long-term asset value.

The organizations that adopt these tools thoughtfully, grounded in engineering judgment and supported by strong governance, will be best positioned to meet the evolving demands of modern infrastructure.

About the Author

Rakam Tamang, Ph.D., PE, is a senior geotechnical project manager at TRC with more than 13 years of experience delivering routine to complex, large-scale geotechnical projects across the infrastructure, energy, and environmental sectors. Rakam's work bridges advanced analytics and conventional geotechnical engineering practice, integrating machine learning and large language models to enable automated data workflows, knowledge extraction from reports and logs, uncertainty quantification, and anomaly detection for design validation, risk assessment, and construction quality control.

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