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Original Research Article

An Integrated Quality Assurance, Quality Control, and Geotechnical Compliance Framework for Large-Scale Urban Infrastructure Projects

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Abstract

Large scale urban infrastructure projects such as metro systems, tunnels, highways, and bridges require strict quality management during construction. These projects often involve complex subsurface conditions, dense urban surroundings, and multiple construction activities occurring simultaneously. Quality assurance (QA), quality control (QC), and geotechnical monitoring therefore remain central components of construction supervision. Conventional monitoring practices rely on inspection reports, laboratory testing records, and field instrumentation systems that often operate within separate information platforms. This separation restricts coordinated evaluation of construction quality and ground behavior during project execution. This study presents a Digital Twin enabled Geo-BIM framework for integrated QA, QC, and geotechnical compliance monitoring in urban infrastructure construction. The proposed framework links geotechnical investigation data, monitoring sensors, QA inspection documentation, and QC testing results within a unified digital environment. A Geotechnical Compliance Index (GCI) model is introduced to evaluate construction conditions and identify zones requiring inspection attention. The framework was examined through a simulation scenario representing common urban infrastructure construction activities. Results indicate that the integrated system supports continuous monitoring, automated compliance evaluation, and inspection prioritization based on geotechnical performance. The proposed framework provides a structured digital approach for managing construction quality and subsurface monitoring in complex infrastructure projects.

Keywords: Digital Twin; Geo-BIM; Quality Assurance (QA); Quality Control (QC); Geotechnical Compliance; Urban Infrastructure Construction; Geotechnical Monitoring; Construction Quality Management; Infrastructure Monitoring Systems; Digital Construction Technologies.

I. INTRODUCTION

Large-scale urban infrastructure projects such as metro systems, tunnels, highways, and bridge networks support transportation, economic activity, and urban development. These projects involve complex construction environments, dense built surroundings, underground utilities, and variable subsurface conditions. Quality assurance (QA) and quality control (QC) therefore play an important role in construction management. QA procedures define systematic processes for maintaining construction standards, while QC activities verify material properties, workmanship, and compliance with design specifications. Effective QA/QC practices contribute to construction reliability and long-term infrastructure performance. Urban infrastructure construction often occurs under challenging geotechnical conditions. Subsurface environments may contain multiple soil layers, fluctuating groundwater levels, and spatial variation in geotechnical properties. Excavation, tunneling, and foundation construction introduce additional uncertainties related to ground stability and structural performance. Monitoring of geotechnical behavior during construction therefore remains a key requirement in infrastructure projects. Standard monitoring approaches include field instrumentation, laboratory testing, numerical analysis, and observational

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monitoring methods that evaluate ground response during construction activities [5].

Conventional QA and QC systems rely largely on inspection procedures, laboratory testing programs, and periodic reporting practices. Inspection teams verify construction activities at scheduled intervals, while testing laboratories evaluate material properties and structural components. Geotechnical monitoring systems operate in parallel through instrumentation such as settlement gauges, inclinometers, and pore pressure sensors. These monitoring datasets, inspection records, and testing reports are commonly maintained in separate information systems. This separation limits the ability of project teams to interpret construction quality and geotechnical behavior within a single analytical environment. Recent research has explored the use of digital technologies for construction quality monitoring and data integration. Intelligent compaction systems represent one example of such developments. These systems integrate sensors such as accelerometers and Global Positioning System (GPS) receivers within compaction equipment to measure soil stiffness and compaction performance during earthwork operations. Studies have reported strong relationships between intelligent compaction measurements and traditional field-testing procedures, allowing continuous monitoring of compaction quality across construction areas [1,7]. Intelligent monitoring systems therefore provide additional information regarding construction processes and ground behavior.

Building Information Modeling (BIM) has also gained attention as a platform for organizing and visualizing construction data. BIM models represent infrastructure components in three-dimensional digital form and support data integration throughout the construction lifecycle. Several studies have examined the integration of BIM with Internet of Things (IoT) technologies to connect monitoring sensors with construction models. BIM–IoT frameworks combine compaction measurements, inspection records, and construction data within a digital model environment that supports monitoring and analysis during construction activities [2]. In addition, BIM-based quality management frameworks have been developed for infrastructure construction projects, where digital models store inspection results and construction documentation for quality verification processes [3]. Model-based approaches have also been used for infrastructure planning and quality management. Digital infrastructure models allow engineers to verify compliance with design requirements through structured representations of infrastructure systems. Such methods support systematic evaluation of construction specifications and technical requirements in infrastructure planning and execution [6]. Research has also examined the environmental and economic implications of quality control procedures in construction. Optimized testing protocols for concrete quality control have demonstrated reductions in carbon emissions, material consumption, and operational costs while maintaining compliance with construction standards [4].

Despite these developments, current studies often address individual aspects of construction monitoring rather than integrated monitoring systems. Intelligent compaction technologies focus primarily on earthwork operations, while BIM-based systems concentrate on construction data management and visualization. Geotechnical monitoring data, inspection documentation, and testing results frequently remain isolated within separate digital platforms. Urban infrastructure projects generate multiple datasets that include geotechnical investigation results, monitoring sensor measurements, inspection records, and material testing reports. Integration of these heterogeneous information sources remains limited in many construction monitoring systems. Ontology-based models have been proposed to support quality compliance verification in urban construction management, yet practical integration of geotechnical monitoring information with construction quality systems remains incomplete [8]. Digital Twin technology offers a possible solution to this integration challenge. Digital Twin environments represent dynamic digital models that update continuously as monitoring data arrive from the physical construction environment. When combined with Geo-BIM models that incorporate subsurface geotechnical information, such systems provide spatial representation of structural components and ground conditions within the same digital model. Monitoring sensors supply real-time measurements that can be evaluated within the digital environment to assess geotechnical performance and construction quality indicators.

This study proposes a Digital Twin enabled Geo-BIM framework for integrated quality assurance, quality control, and geotechnical compliance monitoring in urban infrastructure construction. The framework connects geotechnical investigation data, monitoring sensors, QA inspection documentation, and QC testing results within a unified digital system. Monitoring data are processed within the digital twin environment to generate compliance indicators and analytical outputs related to construction quality and geotechnical performance. The framework also supports risk-oriented evaluation of construction conditions during active project execution.

The objectives of this research are summarized as follows:

1. To develop an integrated framework for quality assurance, quality control, and geotechnical compliance monitoring in urban infrastructure construction projects.
2. To design a Digital Twin enabled Geo-BIM model for managing construction quality and

monitoring geotechnical conditions during project execution.
3. To evaluate real-time geotechnical compliance using integrated monitoring data obtained from sensors, inspections, and testing systems.
4. To propose key performance indicators for assessing construction quality and geotechnical compliance in infrastructure projects.
5. To simulate and validate the proposed framework through representative infrastructure construction scenarios.
6. To provide recommendations for future adoption of digital QA/QC monitoring systems in large-scale urban infrastructure projects.

II. Related Work

Related work on integrated quality assurance (QA), quality control (QC), and geotechnical compliance frameworks for large-scale urban infrastructure projects can be organized into four subsections: digital and intelligent compaction methods, BIM-based integration frameworks, sustainability and optimization in QC processes, and geotechnical safety and compliance techniques.

A. Digital and Intelligent Compaction Methods

Recent advances focus on intelligent compaction (IC) technologies that support real-time monitoring and automated optimization of earthwork compaction operations. These systems address several challenges such as accurate detection of compaction quality, coordination among multiple machines, and process standardization during construction. Modern IC rollers incorporate accelerometers and Global Positioning System (GPS) sensors that measure soil stiffness and compaction performance during operation. Studies have demonstrated strong correlations between IC measurements and traditional field-testing methods, allowing continuous monitoring of compaction quality across construction segments and improving operational efficiency [1,7,2].

B. BIM-Based Integration Frameworks

Building Information Modeling (BIM) has increasingly been applied to integrate construction information for QA and QC processes in infrastructure projects. BIM platforms support structured data management, visualization, and analysis throughout the construction lifecycle. Recent frameworks integrate BIM with Internet of Things (IoT) technologies to develop digital environments capable of monitoring compaction and construction quality in real time. These BIM–IoT systems combine monitoring sensors, inspection records, and testing results within a unified digital model, improving data accessibility and supporting engineering decision-making during project execution [3,2,6].

C. Sustainability and Optimization in QC Processes

Quality control procedures can also influence the environmental and economic performance of infrastructure projects. Recent research has explored optimized QC testing protocols that reduce environmental impacts and operational costs while maintaining compliance with construction standards. For example, rationalized concrete sampling strategies have demonstrated reductions in carbon dioxide emissions, material waste, and testing costs without compromising quality assurance requirements. These approaches provide practical frameworks for integrating sustainability considerations into QC systems for large-scale infrastructure construction projects [4].

D. Geotechnical Safety and Compliance Techniques

Urban geotechnical construction requires specialized safety and compliance monitoring techniques. Existing approaches include numerical simulations such as finite element modeling, in-situ load testing, observational monitoring methods, and peer review procedures. Advanced foundation solutions, including Combined Pile Raft Foundations, are frequently applied in dense urban environments where new construction occurs near existing structures. In addition, ontology-based information models have been proposed to support automated quality compliance verification by integrating heterogeneous information systems used in urban construction management [5,8]. Overall, these research directions demonstrate increasing interest in integrated digital frameworks that combine intelligent sensing technologies, BIM-based information systems, sustainability-oriented QC procedures, and geotechnical safety monitoring techniques to improve QA/QC compliance in large-scale urban infrastructure projects [1,8].

III. METHODOLOGY

This study presents a Digital Twin enabled Geo-BIM framework designed to integrate Quality Assurance (QA), Quality Control (QC), and geotechnical compliance monitoring during urban infrastructure construction. Conventional construction management systems operate with separate workflows for QA inspection activities, QC testing procedures, and geotechnical monitoring programs. This separation limits the interaction between inspection results, material testing data, and subsurface performance measurements. As a result, construction teams often receive delayed information regarding potential geotechnical deviations or quality issues. The methodology presented in this study introduces an integrated digital environment that connects geotechnical investigation records, monitoring sensors, inspection documentation, and testing results within a unified analytical system. The methodological approach follows a structured sequence that includes research design, framework formulation, Geo-BIM integration, digital twin architecture development, compliance modeling, and simulation-based validation. The objective of this methodology is the development of a system capable of processing multiple construction data streams and generating quantitative indicators related to geotechnical compliance and construction quality performance.

A. Research Design

The research applies a design science approach commonly used in engineering studies that involve the creation of new technological frameworks. The process begins with a review of recent literature related to construction quality management, geotechnical monitoring technologies, building information modeling, and digital twin systems. Previous studies indicate that QA procedures usually focus on inspection protocols and documentation processes, while QC systems concentrate on laboratory testing and material verification. Geotechnical monitoring systems function through instrumentation such as settlement gauges, inclinometers, and piezometers, but interaction with QA and QC inspection records rarely occurs. Most BIM-related research focuses on design coordination, clash detection, and structural visualization. Construction-phase quality compliance receives limited attention in these studies. The separation between subsurface monitoring data and construction quality documentation restricts the ability of project teams to evaluate the combined performance of structural and geotechnical systems during construction. The present study addresses this limitation through the development of an integrated framework that connects geotechnical investigation data, construction inspection records, laboratory testing results, and sensor monitoring outputs. A simulation-based scenario represents typical construction conditions encountered in urban infrastructure projects such as deep foundations, excavation systems, and underground transportation facilities. The simulation allows evaluation of the framework in situations where industrial datasets are unavailable.

B. Framework Development

The proposed framework links several information sources involved in construction quality management. Geotechnical investigation data include borehole logs, soil classification parameters, groundwater levels, and laboratory testing reports. These datasets provide the subsurface information required for the construction of a geotechnical information model. A Geo-BIM environment integrates this geotechnical model with the three-dimensional infrastructure model that represents structural elements such as foundations, retaining systems, and excavation zones. This integration allows visualization of the relationship between infrastructure components and surrounding soil layers. The framework also incorporates a digital twin platform that connects real-time data streams from monitoring sensors and inspection workflows. QA inspection reports and QC laboratory test results enter the digital environment through a structured data interface. Monitoring sensors located at the construction site transmit measurements describing ground settlement, pore pressure changes, and structural displacement.

Analytical modules process the incoming datasets and calculate compliance indicators related to geotechnical performance and construction quality. These indicators provide numerical values that represent the level of compliance with design specifications and safety limits. Construction managers receive this information through a decision support interface that displays alerts and monitoring results. The interaction between these components forms a closed information loop in which monitoring data, inspection records, and quality testing results contribute to continuous evaluation of construction conditions.

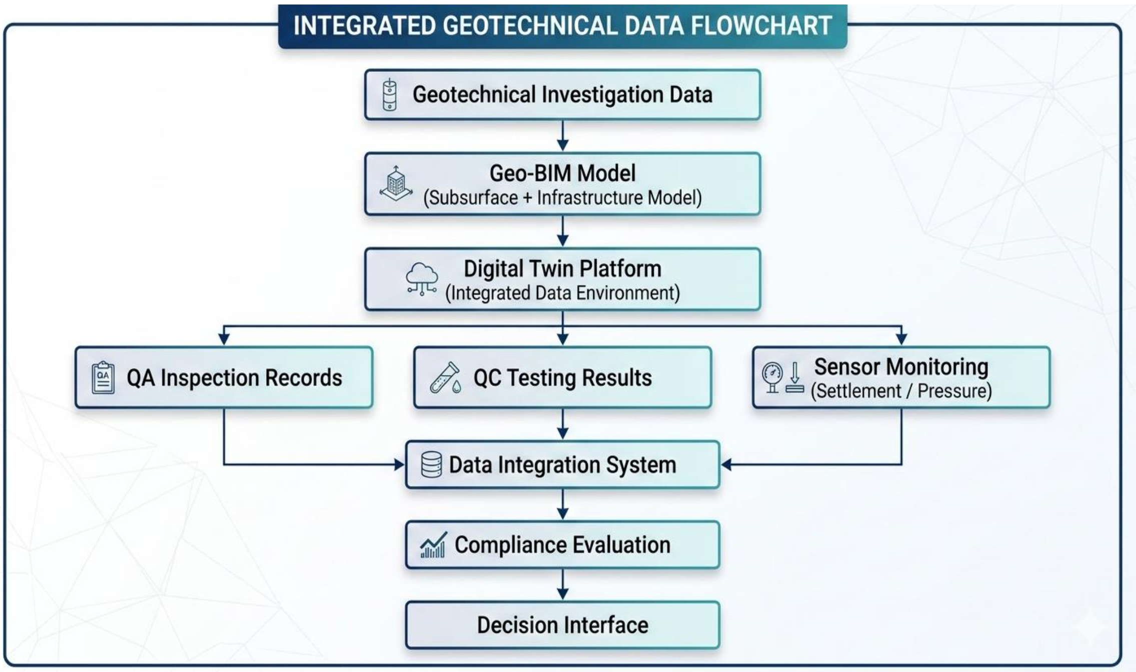

Figure 1: Conceptual architecture of the integrated QA–QC–Geotechnical Digital Twin framework

Figure 1 presents the conceptual architecture of the framework. Geotechnical data, monitoring measurements, and quality inspection information converge within the digital twin platform where compliance analysis occurs.

C. Geo-BIM and Data Integration

Geo-BIM functions as the central information model within the proposed framework. This model integrates subsurface geotechnical information with the structural representation of the infrastructure system. Conventional BIM models contain structural and architectural elements but often omit detailed subsurface conditions. Geo-BIM expands the modeling environment to include soil layers, groundwater conditions, and geotechnical parameters. The integration process begins with the digital conversion of geotechnical investigation reports. Borehole coordinates, soil classification data, and laboratory test results are entered into a geotechnical database. Each borehole location corresponds to spatial coordinates within the project environment. The infrastructure BIM model represents structural elements such as piles, foundations, retaining structures, and excavation boundaries. A connection between the geotechnical database and the infrastructure model creates a unified Geo-BIM environment. This model provides a spatial representation of both structural and subsurface systems. Monitoring sensors installed at the construction site generate real-time measurements. Each sensor location corresponds to a specific element within the Geo-BIM model. Inspection reports from QA teams and testing results from QC procedures also link to relevant structural components within the model. The Geo-BIM platform therefore functions as the primary repository for all construction related information.

D. Digital Twin Architecture

The digital twin component represents a dynamic virtual model of the construction system. Continuous updates occur as new data arrive from monitoring sensors, inspection documentation, and testing databases. The architecture includes several functional layers responsible for data collection, processing, analysis, and visualization. The data acquisition layer gathers information from field instrumentation, inspection records, and testing systems. The processing layer evaluates the incoming datasets and identifies inconsistencies or measurement errors. Processed data move to the analytical layer where geotechnical performance indicators and compliance values are calculated. The analytical layer evaluates construction performance against predefined design thresholds. When monitoring results exceed allowable limits, the system generates warnings that indicate potential geotechnical issues. Engineers and project managers view these results through a digital dashboard that presents monitoring trends, inspection outcomes, and compliance indicators.

This architecture allows continuous observation of construction conditions and interaction between geotechnical monitoring data and construction quality documentation.

E. Geotechnical Compliance Index Model

A quantitative indicator called the Geotechnical Compliance Index (GCI) evaluates the relationship between measured geotechnical parameters and their corresponding design limits. The index combines several monitored variables into a single value representing the overall compliance status of the construction system.

The Geotechnical Compliance Index is defined as

$$GCI = \sum_{i=1}^{n} w_i C_i$$

Where GCI represents the overall geotechnical compliance index, w_i represents the weighting factor assigned to parameter i , C_i represents the compliance score for parameter iii, and nnn represents the total number of monitored parameters.

The compliance score for each parameter is calculated using

$$C_i = 1 - \frac{|M_i - D_i|}{T_i}$$

In this equation, M_i represents the measured value obtained from monitoring sensors, D_i represents the design target value, and T_i represents the allowable tolerance range defined in the design specifications.

A geotechnical risk score is also introduced to represent the potential impact of parameter deviations during construction.

$$R = \sum_{i=1}^{n} P_i I_i$$

In this expression, R represents the geotechnical risk score, P_i represents the probability of deviation associated with parameter i , and L_i represents the impact factor corresponding to that deviation. The combined interpretation of the compliance index and the risk score provides quantitative information related to construction safety and geotechnical performance.

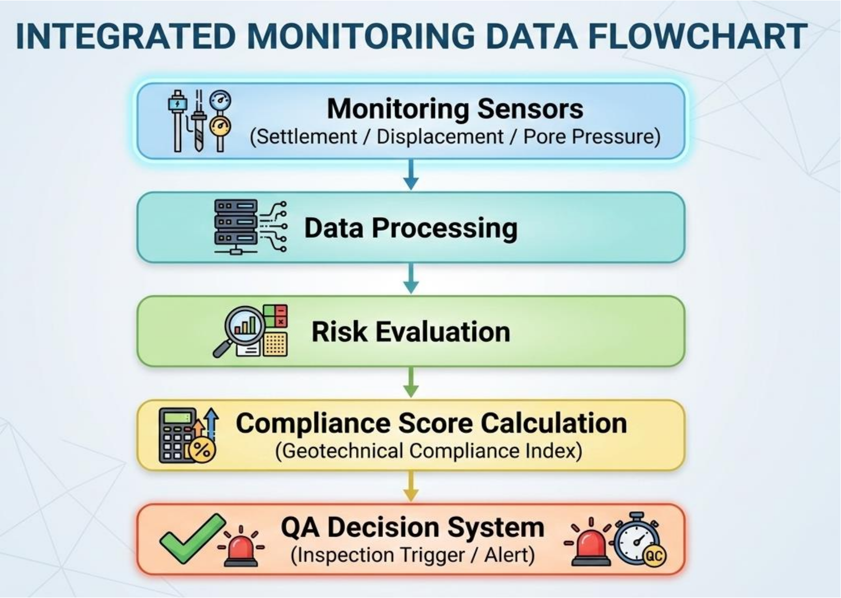

Figure 2: Operational workflow of real-time geotechnical compliance monitoring

Figure 2 illustrates the operational sequence of geotechnical monitoring within the digital framework. Sensor measurements move through data processing and risk evaluation stages before the calculation of compliance indicators.

Table 1: Components of the proposed Digital Twin Geo-BIM framework

Data Source	System Component	Function	Output
Geotechnical investigation reports	Geo-BIM database	Representation of subsurface soil conditions	Digital geotechnical model
Monitoring sensors	Digital twin monitoring system	Collection of field measurements	Settlement and pore pressure data
QA inspection documentation	QA management module	Recording inspection results	Inspection records
Laboratory and field tests	QC testing module	Evaluation of material and construction quality	Testing reports
Integrated analytical system	Compliance evaluation module	Calculation of compliance and risk indicators	Compliance values
Visualization interface	Decision-support dashboard	Presentation of monitoring results and alerts	Project management information

F. Validation Strategy

The proposed framework undergoes evaluation through a simulation scenario representing construction conditions in urban infrastructure projects. The scenario includes activities such as foundation installation, excavation processes, and ground monitoring operations. Simulated datasets represent typical measurements obtained from settlement gauges, pore pressure sensors, and displacement monitoring instruments. The digital twin platform processes these datasets through the compliance evaluation model described earlier. Calculated compliance indices and risk scores represent the response of the framework to changes in geotechnical conditions during construction. The simulation demonstrates the interaction between monitoring systems, inspection documentation, and compliance analysis within the digital framework. The results illustrate how the proposed system supports continuous monitoring and quality evaluation during construction operations.

IV. DISCUSSION AND RESULTS

This section presents the outcomes of the simulation-based evaluation of the proposed Digital Twin enabled Geo-BIM framework for integrated Quality Assurance (QA), Quality Control (QC), and geotechnical compliance monitoring. The analysis examines system behavior within a simulated urban infrastructure construction environment. The discussion focuses on the interaction between geotechnical monitoring systems, QA/QC inspection documentation, and the Geo-BIM digital twin platform. The results illustrate how the integrated system processes construction monitoring data, inspection records, and testing results within a unified digital model. Particular attention is given to the calculation of geotechnical compliance indicators and their role in construction decision processes. The discussion also considers practical implications for large-scale urban infrastructure projects where monitoring and inspection activities occur simultaneously.

A. Overview of Simulation Results

The simulation scenario represents typical activities in large urban infrastructure projects. The modeled construction sequence includes foundation installation, excavation operations, and structural element placement. Monitoring sensors record parameters such as ground settlement, lateral displacement, and pore pressure variation. QA inspection reports and QC laboratory testing results enter the digital system to represent routine construction quality documentation. Integration of these datasets within the Geo-BIM digital twin platform allows continuous evaluation of geotechnical performance and construction quality indicators. The analytical module processes monitoring measurements together with inspection records to generate compliance values for multiple construction zones. The simulation indicates that the digital twin environment maintains synchronized updates between monitoring sensors, inspection documentation, and the Geo-BIM model. When new measurements enter the system, the Geotechnical Compliance Index (GCI) values update automatically within the monitoring dashboard. Construction managers therefore receive immediate information regarding variations in subsurface conditions across the project site. A comparison with conventional inspection workflows highlights the operational difference of the integrated framework. Traditional systems require separate interpretation of monitoring reports and inspection documentation. The proposed system presents these datasets within a single environment. Engineers can evaluate structural and geotechnical performance simultaneously rather than reviewing independent reports.

B. Integration Performance and Data Flow

Evaluation of integration performance focuses on the interaction between four principal system elements: the Geo-BIM model, monitoring sensors, QA inspection records, and QC testing datasets. Within the Geo-BIM environment, each structural element and monitoring location possesses spatial coordinates. Monitoring sensors transmit measurements at predefined intervals. These measurements appear within the model at their corresponding spatial locations. Inspection reports and testing outcomes connect to specific structural elements such as piles, retaining walls, and excavation sections. The digital twin platform functions as the central processing environment. Sensor measurements pass through validation and processing routines before entering the compliance evaluation module. Inspection records and laboratory testing results enter the same analytical structure. This process forms a continuous information cycle. Monitoring measurements update compliance values. Inspection teams access the updated information through the digital dashboard. Conventional construction management systems typically store monitoring reports and inspection records in separate documentation repositories. The integrated framework presented in this study allows direct interaction between these datasets. The simulation demonstrates a coordinated monitoring environment where subsurface measurements and construction quality documentation exist within a common digital model. This configuration supports a structured interpretation of construction conditions during active operations.

C. Geotechnical Compliance Evaluation

The proposed framework evaluates geotechnical performance using the Geotechnical Compliance Index (GCI). This indicator combines several monitoring parameters into a single value representing the overall compliance condition of a construction zone.

The compliance index is calculated as

$$GCI = \sum_{i=1}^{n} w_i C_i$$

In this expression, GCI represents the geotechnical compliance index. The parameter w_i represents the weighting factor assigned to monitored parameter i The variable C_i represents the compliance score associated with that parameter. The total number of monitored parameters is represented as nnn.

To incorporate geotechnical risk conditions, a risk-adjusted compliance indicator is also defined:

$$GCI_r = GCI(1 - R)$$

The variable GCI_r represents the adjusted compliance score, while R represents the geotechnical risk factor associated with parameter deviations. The simulation indicates variation in compliance values across construction zones. Areas with stable settlement conditions and minimal pore pressure variation maintain high compliance scores. Zones with larger deviations from design limits display lower compliance values. These areas generate inspection alerts within the digital monitoring dashboard.

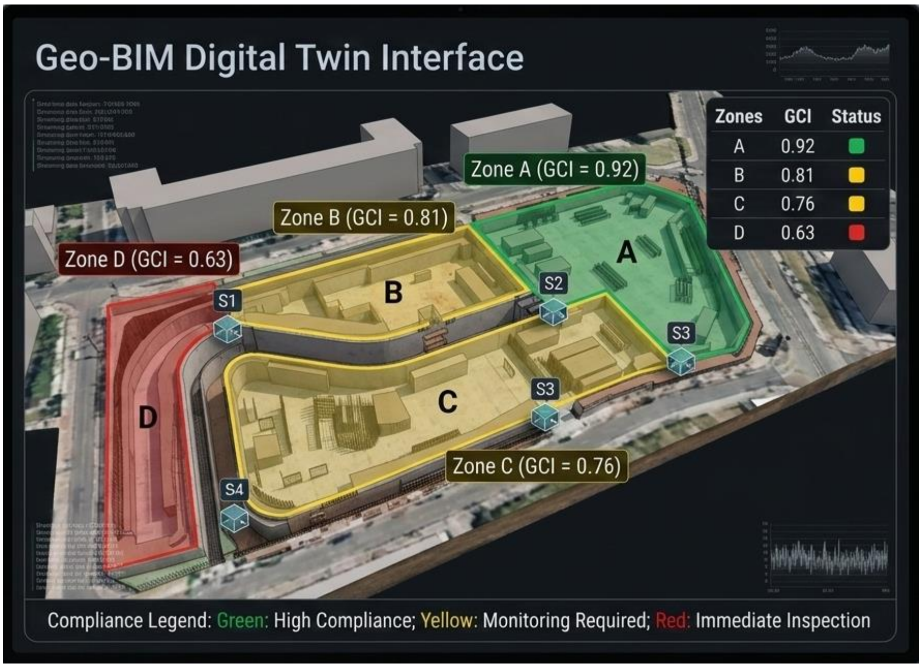

Figure 3: Geo-BIM digital twin dashboard showing spatial distribution of Geotechnical

Figure 3. Geo-BIM digital twin interface showing spatial distribution of the Geotechnical Compliance Index (GCI) across construction zones. Monitoring sensors provide real-time data that are processed within the digital twin platform to classify zones according to compliance levels and inspection priority.

D. Real-Time Decision Support Insights

The integrated framework connects monitoring measurements with QA inspection workflows. Sensor measurements update the compliance model in real time. A decrease in compliance values triggers inspection notifications within the digital system. The simulation illustrates how this feedback process functions during construction monitoring. When settlement measurements exceed predefined limits, the system recalculates the compliance score for the affected construction zone. The updated compliance value appears within the digital dashboard. QA teams receive inspection alerts related to the affected structural elements. Field inspections focus on these locations. QC testing procedures then verify construction materials and workmanship associated with those elements. This inspection mechanism introduces a risk-prioritized inspection strategy. Conventional inspection programs often follow fixed schedules. The integrated framework directs inspection attention toward areas where monitoring data indicate potential deviations from design limits. The digital twin environment therefore connects geotechnical monitoring with inspection activities in a coordinated monitoring cycle.

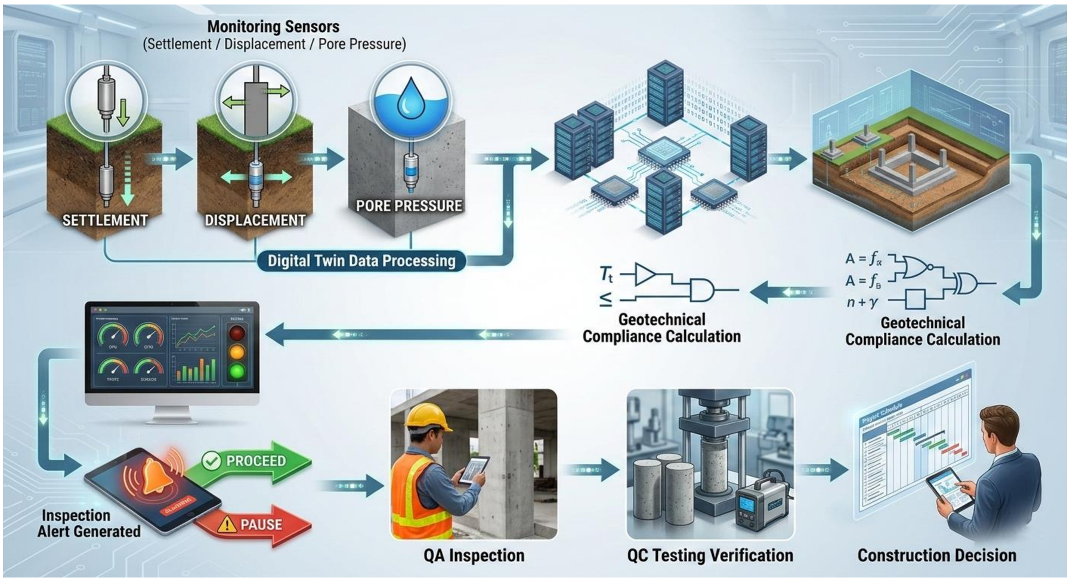

Figure 4: Real-time QA/QC decision feedback workflow during construction monitoring

Figure 4 illustrates the operational workflow linking monitoring measurements with inspection decisions. Monitoring data enter the digital twin platform, compliance values are calculated, and inspection teams receive alerts when deviations occur.

Table 2: Summary of key evaluation outcomes

Performance Indicator	**Conventional Monitoring Approach**	**Digital Twin Geo-BIM Framework**
Monitoring data integration	Independent monitoring databases	Integrated Geo-BIM data environment
Inspection scheduling	Periodic inspection intervals	Compliance-triggered inspection alerts
Compliance evaluation	Manual review of monitoring reports	Automated compliance score calculation
Data accessibility	Distributed documentation repositories	Unified digital dashboard
Interaction between QA and geotechnical monitoring	Limited coordination	Direct interaction within digital twin platform

The results summarized in Table 2 indicate that the integrated framework provides a coordinated monitoring structure for construction quality and geotechnical performance evaluation. Monitoring data and inspection documentation appear within the same digital model, which simplifies interpretation during construction operations.

E. Limitations of the Study

The proposed framework represents a conceptual integration of Geo-BIM modeling, digital twin systems, and construction quality management processes. Implementation of such a framework in large infrastructure projects requires standardized data structures across multiple information systems. Construction organizations frequently operate with different data management platforms and documentation formats. These differences may influence the practical integration of monitoring databases, inspection records, and geotechnical information models. The analytical compliance indicators presented in this study follow generalized formulations that apply to a range of infrastructure construction scenarios. Actual project conditions often involve site-specific geotechnical parameters, monitoring instrumentation configurations, and construction methods. Future studies may examine how the framework operates within different project environments such as tunnels, bridge foundations, and urban excavation systems. Additional research may also evaluate integration with automated monitoring technologies and advanced analytical models used in construction monitoring systems.

V. CONCLUSION

This study presented a Digital Twin enabled Geo-BIM framework for integrated quality assurance (QA), quality control (QC), and geotechnical compliance monitoring in urban infrastructure construction. The framework connects geotechnical investigation data, monitoring sensors, QA inspection documentation, and QC testing results within a unified digital environment. Integration of these datasets within the Geo-BIM digital twin model allows continuous evaluation of construction activities and ground performance during project execution. A Geotechnical Compliance Index (GCI) was introduced to represent compliance levels across construction zones and to support inspection prioritization during construction operations. Simulation results illustrated the interaction between monitoring measurements, inspection records, and testing information within the digital model environment. Compliance indicators generated through the system provided clear representation of geotechnical conditions and construction quality status across the monitored areas. The results indicate that integrated monitoring platforms support coordinated interpretation of construction performance and subsurface behavior in complex infrastructure projects.

Future research may examine implementation of the proposed framework in active infrastructure construction projects such as metro systems, bridge foundations, or underground transport tunnels. Field deployment of monitoring instrumentation together with integration of construction inspection records would provide additional information regarding operational performance of digital twin monitoring systems. Further investigation may also consider analytical models that process monitoring datasets and support prediction of geotechnical deviations during construction activities. Expansion of monitoring datasets, integration with project information systems, and application of advanced analytical tools may support broader development of digital monitoring frameworks for infrastructure construction management.

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