OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Risk-Informed Construction Delivery for Resilient Public Infrastructure Under Geotechnical and Environmental Uncertainty

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DOI: https://doi.org/10.36348/sjet.2026.v11i08.002 | **Received:** 13.06.2026 | **Accepted:** 06.08.2026 | **Published:** 08.08.2026

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Abstract

Public infrastructure projects frequently experience schedule delays, cost escalation, rework, coordination failures, and performance uncertainty caused by fragmented construction planning, changing environmental conditions, and incomplete geotechnical information. This study proposes a risk-informed construction delivery model that integrates construction risk prediction, lifecycle performance governance, environmental exposure assessment, and subsurface uncertainty evaluation to improve the resilience of public infrastructure projects. The framework organizes project risk into four connected dimensions: construction execution risk, lifecycle infrastructure performance risk, environmental and drainage-related exposure risk, and geotechnical reliability risk. A weighted decision matrix evaluates project vulnerability using measurable indicators, including delay probability, coordination complexity, design revision frequency, soil variability, and environmental exposure. The study also introduces a Project Resilience Index to evaluate infrastructure delivery performance under changing environmental and geotechnical conditions during planning, design, and construction. The framework is suitable for conceptual, analytical, and simulation-based evaluation without requiring proprietary project datasets. Scenario-based evaluation indicates that increasing environmental exposure and subsurface uncertainty increase project vulnerability while reducing resilience throughout construction delivery. The proposed framework provides a unified project delivery approach connecting BIM-oriented coordination, engineering management, urban environmental systems, and foundation reliability for resilient public infrastructure management.

Keywords: Risk-informed construction delivery, public infrastructure resilience, Geotechnical reliability, Environmental exposure, Project vulnerability assessment, Lifecycle governance.

I. INTRODUCTION

The development of public infrastructure facilities helps with transport, drainage, utilities, and urban development. The success of these public infrastructures is reliant on proper construction management, geotechnical investigation, environmental planning, and project governance. The rapid pace of urbanization, changing climate, and increased complexity of the underground environment have brought more uncertainties into the development of infrastructure projects. Existing systems of construction delivery often treat the above-mentioned factors separately. As a result, there are risks in the risk assessment process that need to be analyzed together. Therefore, the need for an integrated approach exists in order to analyze these uncertainties.

Objective of the Study:

This study develops a risk-informed construction delivery framework that integrates construction execution, environmental exposure, geotechnical reliability, and lifecycle governance to evaluate project vulnerability and resilience through analytical and simulation-based assessment.

A. Background and Motivation

Construction projects have become more difficult to manage because environmental conditions, subsurface characteristics, and project coordination change throughout the construction lifecycle. Schedule delays, cost escalation, design revisions, and communication conflicts continue to affect the delivery of transportation systems, drainage facilities, and other public infrastructure. Digital engineering tools and geotechnical assessment methods have improved individual project activities; however, these approaches generally operate as separate processes. Consequently, engineering decisions often rely on fragmented information collected from multiple disciplines. This situation reduces the ability to identify project vulnerability during the early stages of construction. An integrated construction delivery framework therefore provides an opportunity to evaluate uncertainty across engineering, environmental, and management domains within one analytical structure.

B. Problem Statement

Current construction delivery practices provide limited capability for evaluating interactions among construction execution, environmental exposure, geotechnical uncertainty, and lifecycle governance. Conventional engineering methods commonly apply deterministic design assumptions and historical environmental conditions, although construction sites experience continuous changes throughout project execution. BIM-based coordination improves communication and information exchange but rarely incorporates geotechnical reliability and environmental assessment within the same analytical process. Consequently, project managers encounter difficulties when identifying dominant risk factors and selecting suitable mitigation strategies before project performance declines. This limitation represents an important research gap in resilient public infrastructure management and motivates the development of a unified risk-informed construction delivery framework.

C. Proposed Solution

This study proposes a risk-informed construction delivery framework that integrates construction execution risk, lifecycle governance, environmental exposure assessment, and geotechnical reliability within a unified analytical model. Project uncertainty is classified into four interconnected risk dimensions representing the principal sources of construction delivery risk. A weighted Project Vulnerability Score evaluates construction uncertainty using measurable engineering and management indicators, while a Project Resilience Index assesses adaptive infrastructure performance under different project conditions. Scenario-based analytical evaluation demonstrates the application of the proposed methodology without requiring proprietary project datasets. The framework supports planning, design, construction, and governance decisions throughout the infrastructure lifecycle using a consistent analytical approach.

D. Contributions

This research provides four primary contributions. First, it presents an integrated analytical framework connecting construction execution, environmental exposure, geotechnical reliability, and lifecycle governance. Second, it develops a weighted Project Vulnerability Score for systematic ranking of construction uncertainty using measurable project indicators. Third, it introduces a Project Resilience Index for evaluating adaptive infrastructure performance under changing construction conditions. Finally, the study presents a conceptual and simulation-based methodology suitable for public infrastructure research without relying on proprietary field observations. These contributions provide a unified analytical basis for project vulnerability assessment, resilience evaluation, and lifecycle governance throughout infrastructure delivery.

E. Paper Organization

The remainder of this paper is organized into five sections. Section II reviews previous studies related to construction risk management, geotechnical uncertainty, environmental exposure, BIM-based coordination, and lifecycle governance while identifying the remaining research gap. Section III presents the proposed methodology, including the Project Vulnerability Score, Project Resilience Index, lifecycle governance model, and validation strategy. Section IV discusses the analytical results obtained from representative construction scenarios. Section V concludes the paper with the principal findings, study limitations, and future research directions. The overall structure follows a logical progression from problem definition to analytical evaluation and research conclusions.

II. RELATED WORK

Recent studies have investigated construction risk management, climate-resilient infrastructure, geotechnical uncertainty, digital project coordination, and lifecycle governance from different perspectives. Existing research has improved understanding of individual domains such as geotechnical reliability, BIM-based coordination, environmental resilience, and infrastructure performance management. However, these studies generally address these topics independently rather than through an integrated construction delivery framework. The following review summarizes the major contributions of previous studies while identifying the remaining research gap addressed in this study.

Geotechnical Uncertainty and Climate-Resilient Infrastructure

Climate change has introduced new challenges for geotechnical engineering because conventional design approaches often rely on historical loading conditions and deterministic safety factors. Vitale and Liu [1] discussed uncertainty management during geotechnical design and emphasized that changing environmental conditions require adaptive assessment rather than static assumptions. Schmidt *et al.,*[2] reviewed U.S. geotechnical codes and reported limited explicit guidance for incorporating future climatic hazards into engineering practice. Belokas *et al.,*[3] extended infrastructure resilience from individual geotechnical assets to transportation networks. Nevertheless, these studies mainly focus on engineering reliability and provide limited discussion regarding construction delivery decisions, project coordination, and execution risk under evolving subsurface uncertainty.

Construction Risk Management and BIM-Based Project Coordination

Construction management research has increasingly adopted digital technologies to reduce project delays, coordination failures, and unnecessary design revisions. Shoag [6] demonstrated that lean construction principles combined with digital coordination improve façade project efficiency and communication. Al Morshed [13] proposed BIM-based coordination methods that reduce construction rework through improved information exchange among project participants. Islam [9] investigated project management approaches for reducing cost overruns in public infrastructure projects. Although these studies improve construction management practices, they generally evaluate coordination, scheduling, or project control independently without integrating geotechnical reliability, environmental exposure, and lifecycle governance into comprehensive construction risk prediction models.

Environmental Exposure and Infrastructure Resilience

Environmental conditions increasingly influence infrastructure performance throughout planning, construction, and operational stages. Akter [5] proposed green project management strategies supporting environmentally responsible infrastructure development, while Ria [4] discussed sustainable construction materials for resilient rural infrastructure. Abid [10] presented intelligent approaches for improving urban transportation performance, whereas Sultana [11] investigated climate-resilient structural design for flood-prone environments. These studies demonstrate the importance of environmental adaptation within infrastructure systems. However, they primarily evaluate environmental sustainability or structural resilience independently rather than integrating environmental exposure with construction execution risk, geotechnical uncertainty, and infrastructure governance during project delivery.

Lifecycle Governance and Integrated Infrastructure Performance

Recent studies have expanded infrastructure management beyond construction completion by emphasizing lifecycle performance and long-term resilience. Jasem [7] introduced predictive infrastructure monitoring through intelligent system health assessment, while Hossain [15] proposed a multilayer governance framework for sustainable built environments. Khan *et al.,*[8] examined performance-based ground improvement methods, Avi [12] evaluated construction quality control, and Uddin [14] explored intelligent maintenance prioritization for public infrastructure. Despite these advances, previous research rarely combines lifecycle governance, environmental uncertainty, geotechnical reliability, and BIM-oriented construction coordination into a unified, risk-informed project delivery framework that supports resilient public infrastructure under changing environmental conditions.

III. METHODOLOGY

This study adopts a conceptual, analytical, and simulation-based methodology to develop a unified framework for risk-informed construction delivery under geotechnical and environmental uncertainty. The framework combines construction management, lifecycle governance, geotechnical reliability, environmental exposure assessment, and BIM-based coordination within a single decision-support structure. The study does not depend on proprietary project data. Instead, it defines measurable indicators, analytical relationships, and governance mechanisms suitable for scenario-based simulation and comparative evaluation across representative public infrastructure projects.

Research Framework and Methodological Architecture

Figure 1 presents the overall risk-informed construction delivery framework. The workflow begins with project inputs and uncertainty identification, followed by four interconnected risk dimensions, BIM-based coordination, weighted vulnerability assessment, Project Resilience.

The research framework provides a systematic structure for integrating construction management, environmental assessment, and geotechnical reliability throughout public infrastructure delivery. The process starts with identifying uncertainty associated with construction activities, environmental conditions, and subsurface characteristics. These uncertainty sources are converted into measurable indicators and grouped into four interconnected dimensions: construction execution risk, lifecycle infrastructure performance risk, environmental exposure risk, and geotechnical reliability risk. BIM-based coordination serves as the information exchange platform throughout planning, design, and construction. The framework then performs weighted risk evaluation, lifecycle governance assessment, and Project Resilience Index (PRI) estimation. The resulting information supports construction decisions intended to reduce delays, limit design rework, improve coordination, and maintain project performance throughout the infrastructure lifecycle. Index evaluation, lifecycle governance, adaptive construction decisions, and resilient public infrastructure delivery.

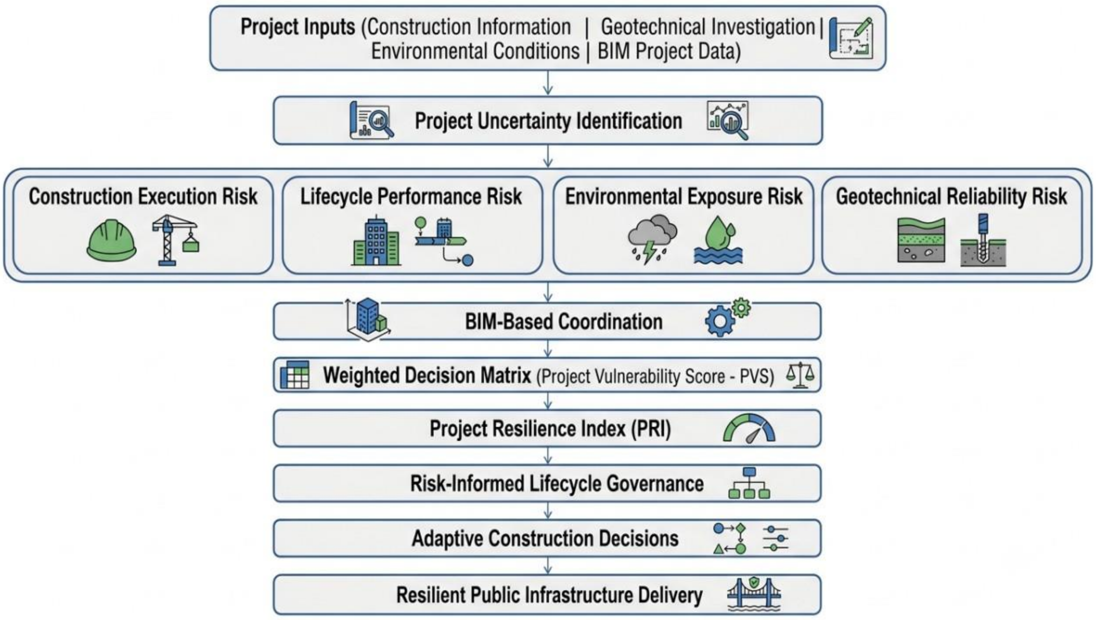

Figure 1: Overall Risk-Informed Construction Delivery Framework

Table 1: Methodological Components of the Proposed Framework

Methodological Component	Primary Function	Expected Output
Construction Risk Assessment	Evaluate execution uncertainty	Delay and rework prediction
Environmental Exposure Assessment	Measure climate and drainage effects	Environmental risk score
Geotechnical Reliability Assessment	Evaluate soil and foundation uncertainty	Reliability level
BIM-Based Coordination	Support multidisciplinary information exchange	Lower coordination conflicts
Lifecycle Governance	Monitor project performance	Governance score
Weighted Decision Matrix	Rank project vulnerability	Project risk priority
Project Resilience Index	Measure resilience performance	Resilience score

Identification of Construction Risk Dimensions

The proposed framework classifies project uncertainty into four connected dimensions representing the principal sources of construction delivery risk. Construction execution risk includes schedule delays, contractor coordination, resource conflicts, and design revisions. Lifecycle infrastructure performance risk examines operational continuity, maintenance readiness, and governance effectiveness after project completion. Environmental exposure risk includes rainfall intensity, flood potential, drainage limitations, and climate-related disturbances that influence construction activities. Geotechnical reliability risk considers soil variability, groundwater fluctuation, settlement potential, and foundation behavior. These dimensions are evaluated collectively because construction performance depends on continuous interactions among engineering management, environmental conditions, and subsurface characteristics instead of isolated technical factors.

Development of the Weighted Project Vulnerability Matrix

The methodology introduces a weighted project vulnerability matrix to quantify construction delivery risk using measurable project indicators. Delay probability, coordination complexity, design revision frequency, soil variability, groundwater uncertainty, environmental exposure, and drainage sensitivity form the assessment criteria. Each indicator receives a normalized weight according to its contribution to overall project vulnerability. The matrix allows comparison of alternative construction scenarios and identifies the dominant sources of uncertainty before project execution. This evaluation combines engineering, environmental, geotechnical, and management perspectives within one analytical structure. The resulting vulnerability score provides a consistent basis for project prioritization while remaining applicable to different infrastructure sectors and environmental conditions.

The overall Project Vulnerability Score (PVS) is expressed as

$$PVS = \sum_{i=1}^{n} w_i R_i$$

Where

w_i represents the normalized weight assigned to risk indicator *i*;

R_i denotes the normalized value of risk indicator *i*;

n is the total number of selected indicators.

Project Resilience Index (PRI) Development

The Project Resilience Index (PRI) measures the capacity of a public infrastructure project to maintain acceptable construction performance under geotechnical uncertainty, environmental disturbances, and execution-related risks. Conventional performance indicators mainly emphasize schedule, cost, or quality outcomes. In contrast, the proposed PRI evaluates the adaptive capability of the entire construction delivery system throughout planning, design, and construction. The index combines four resilience characteristics: resistance, recovery, resource management, and redundancy. These characteristics represent the project's response to uncertainty, design modifications, coordination conflicts, and environmental changes. The resulting PRI serves as a lifecycle performance indicator that supports construction governance and assists project teams in selecting appropriate management actions under changing site conditions.

The Project Resilience Index is calculated as
4
$PRI = \sum a\ C$

Where
j=1
j j

Cj represents the normalized resilience characteristic;
a denotes the weighting factor assigned to characteristic$j$
j

$\sum a = 1$
j

The resilience characteristics are defined as follows:
Resistance (RS): Capacity of construction activities to continue under disturbances.
Recovery (RC): Ability to restore planned project performance after disruptions.
Resource Management (RM): Efficiency of allocating engineering, financial, and construction resources.
Redundancy (RD): Availability of alternative construction procedures, materials, or scheduling options.

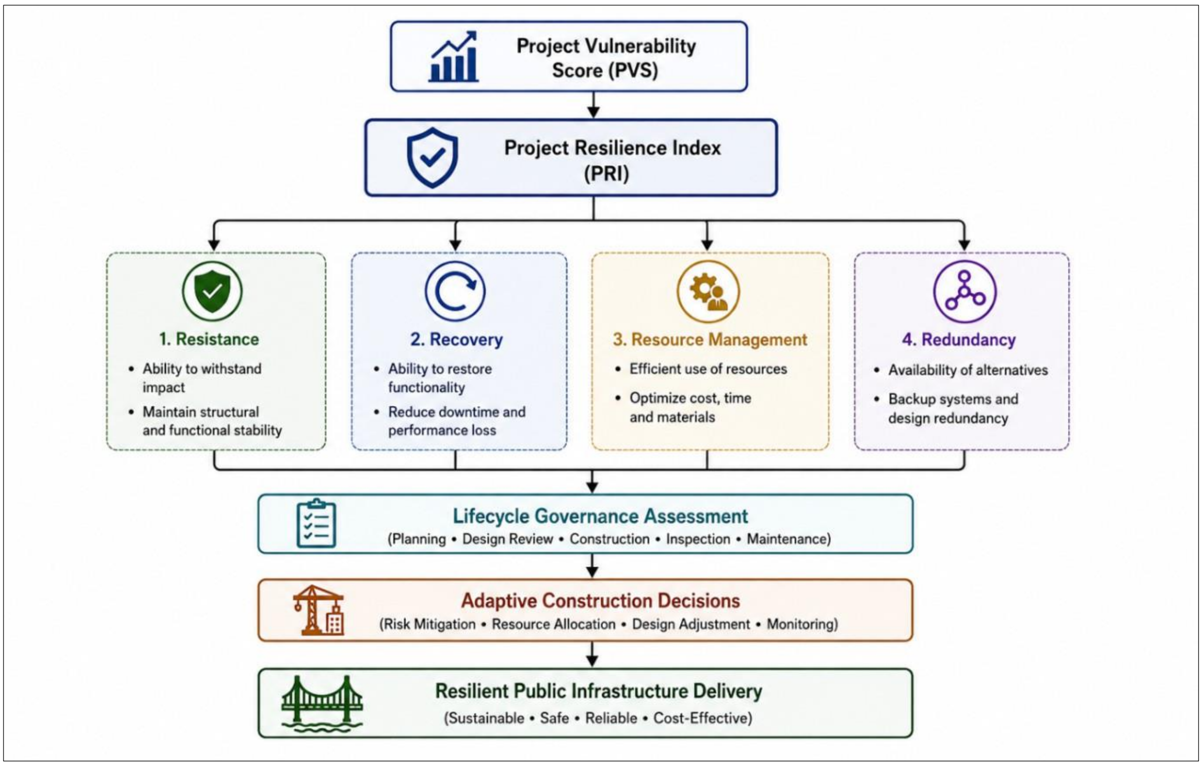

Figure 2: Project Resilience Assessment Framework

Figure 2 illustrates the Project Resilience Assessment Framework. The Project Vulnerability Score supports Project Resilience Index evaluation through four resilience characteristics: resistance, recovery, resource management, and redundancy. These outputs guide lifecycle governance and adaptive construction decisions for resilient infrastructure delivery.

A larger PRI value indicates stronger project resilience and lower sensitivity to construction uncertainty.

Risk-Informed Lifecycle Governance Model

The lifecycle governance model links project risk assessment with construction decision-making throughout infrastructure delivery. Information generated from the Project Vulnerability Score and the Project Resilience Index forms the basis of governance evaluation during planning, design, and construction. Environmental exposure, geotechnical reliability, construction execution status, and BIM coordination are reviewed together instead of separate technical assessments. The governance model identifies situations requiring corrective action when vulnerability exceeds predefined limits or resilience decreases below acceptable levels. Project managers can then revise construction sequencing, coordination procedures, inspection priorities, or resource allocation. This process maintains consistent project performance while reducing delay risk, design revisions, and uncertainty associated with changing environmental and subsurface conditions.

Method Validation Strategy

The proposed methodology follows a conceptual and analytical validation approach supported through scenario-based simulation. No proprietary project database is required because the framework evaluates relationships among measurable indicators rather than project-specific observations. Representative scenarios describe different combinations of soil variability, groundwater conditions, rainfall intensity, coordination complexity, and construction execution risk. Sensitivity analysis examines the influence of indicator weights on the Project Vulnerability Score and the Project Resilience Index. Comparative evaluation then measures changes in project performance under low-, medium-, and high-risk conditions. The validation process demonstrates the internal consistency of the proposed framework and confirms its applicability for future implementation across different categories of public infrastructure projects.

IV. RESULTS AND DISCUSSION

The proposed analytical framework was evaluated using three representative construction scenarios that reflect low, moderate, and high levels of project uncertainty. The assessment considered the interaction among construction execution, environmental exposure, geotechnical reliability, and lifecycle governance using the indicators defined in the methodology. The results explain how changes in these indicators influence project vulnerability and resilience while demonstrating the practical application of the proposed decision-support framework for public infrastructure delivery.

Project Vulnerability Assessment Under Multi-Dimensional Risk

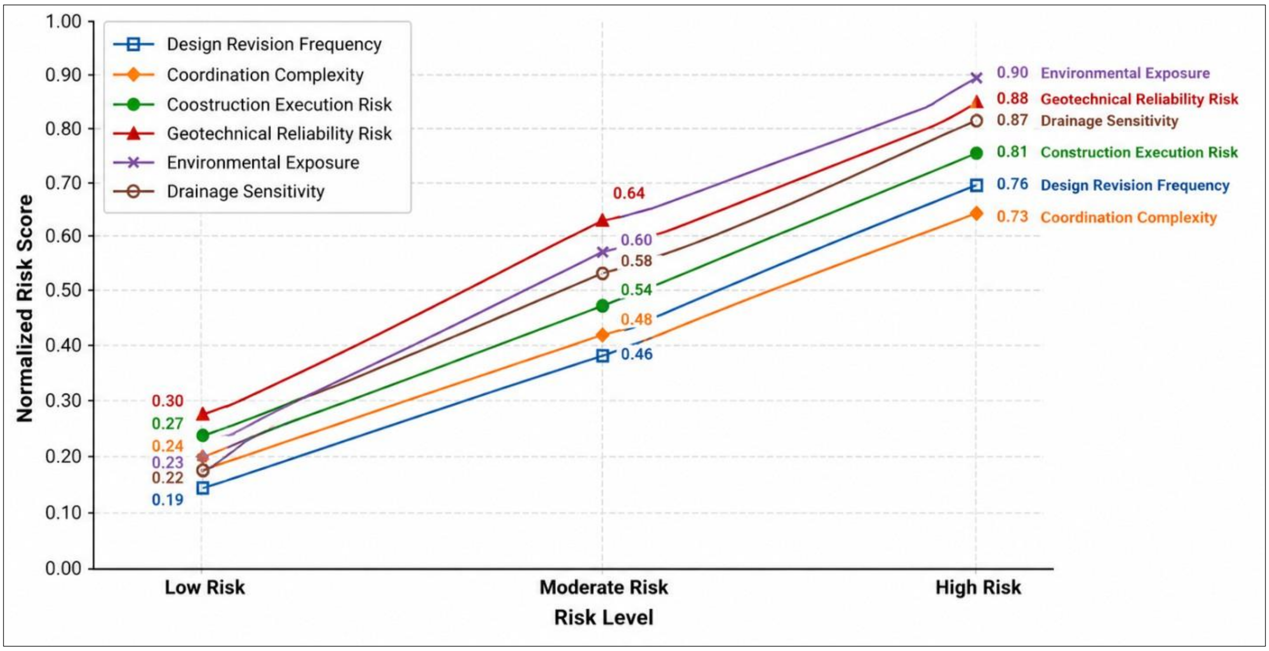

Figure 3: Comparative Contribution of Risk Indicators to Project Vulnerability

Figure 3 compares normalized risk indicator values across representative construction scenarios. Environmental exposure and geotechnical reliability exhibit the greatest increase under higher uncertainty, while construction execution, coordination complexity, and design revision frequency also increase progressively.

The Project Vulnerability Score (PVS) was calculated for three representative construction scenarios using the weighted decision matrix presented in Section III. The analytical evaluation indicates a gradual increase in project vulnerability as construction uncertainty becomes more significant. Under the low-risk scenario, stable soil conditions, limited environmental disturbance, and efficient project coordination produced the lowest vulnerability score. Moderate uncertainty introduced additional design revisions, localized groundwater variation, and increased coordination activities, resulting in a noticeable increase in vulnerability. The high-risk scenario combined severe environmental exposure, substantial soil variability, drainage limitations, and frequent construction modifications. Consequently, the Project Vulnerability Score reached its highest value, indicating greater difficulty in maintaining planned construction performance under changing project conditions.

Table 2: Analytical Results of Project Vulnerability Assessment

Performance Indicator	Low Risk	Moderate Risk	High Risk
Construction Execution Risk	0.27	0.54	0.81
Environmental Exposure	0.23	0.60	0.90
Geotechnical Reliability Risk	0.30	0.64	0.88
Coordination Complexity	0.24	0.48	0.73
Design Revision Frequency	0.19	0.46	0.76
Drainage Sensitivity	0.22	0.58	0.87
Project Vulnerability Score (PVS)	**0.29**	**0.56**	**0.84**

Construction Resilience Evaluation Using the Project Resilience Index

The Project Resilience Index (PRI) was evaluated after calculating the Project Vulnerability Score to examine the adaptive capability of construction delivery under different uncertainty conditions. The analytical results indicate an inverse relationship between project vulnerability and resilience. The low-risk scenario produced the highest resilience because construction activities experienced limited environmental disturbance, stable subsurface conditions, and fewer coordination issues. The moderate-risk scenario recorded a lower resilience level following increases in soil variability, drainage uncertainty, and design revisions. The high-risk scenario generated the lowest resilience because multiple uncertainty sources affected construction activities concurrently. The results indicate that maintaining satisfactory project performance requires continuous assessment of construction execution, environmental exposure, geotechnical reliability, and lifecycle governance throughout infrastructure delivery.

Lifecycle Governance Performance Under Dynamic Construction Conditions

The lifecycle governance assessment examined the response of construction management under changing project conditions. Governance performance remained satisfactory during the low-risk scenario because construction activities followed the planned schedule with limited design modifications and stable subsurface conditions. The moderate-risk scenario required additional engineering reviews due to increasing coordination conflicts, groundwater variation, and drainage related issues. Under high-risk conditions, project teams implemented more frequent construction inspections, schedule adjustments, and design updates because environmental exposure and geotechnical variability affected several construction activities simultaneously. The analytical evaluation indicates that governance decisions should respond to changing project conditions continuously throughout construction. This approach improves communication among project participants and supports timely management actions before uncertainty affects overall project performance.

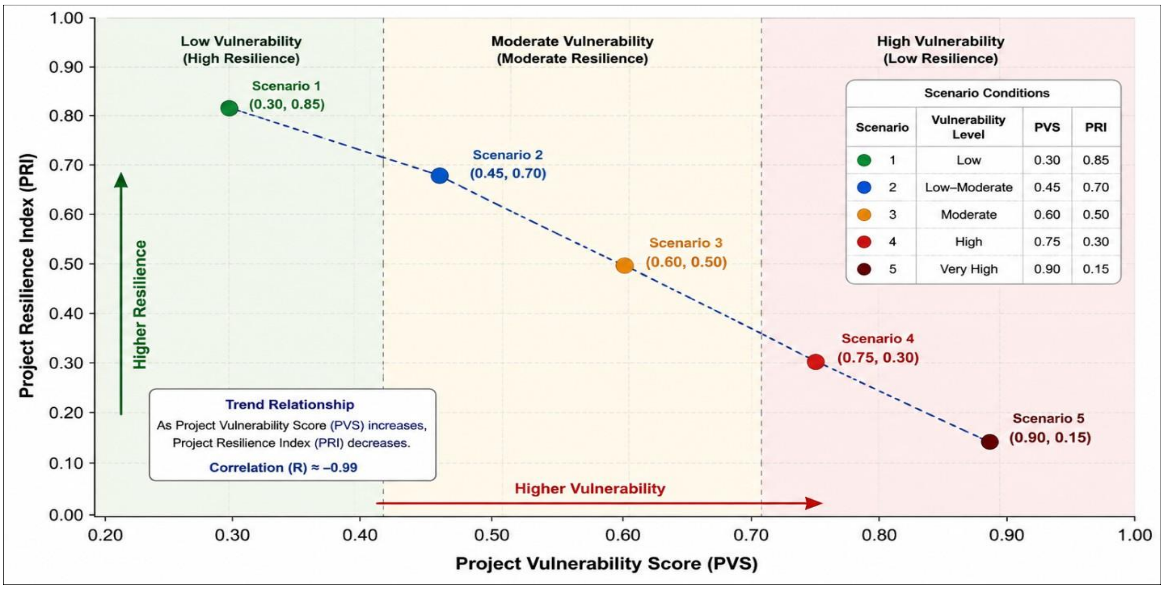

Figure 4: Relationship Between Project Vulnerability Score (PVS) and Project Resilience

Figure 4 shows an inverse relationship between Project Vulnerability Score and Project Resilience Index. Higher project vulnerability corresponds to lower resilience across representative construction scenarios.

DISCUSSION OF ANALYTICAL FINDINGS

The analytical results indicate that project vulnerability increases as construction execution risk, environmental exposure, and geotechnical uncertainty occur simultaneously. Environmental exposure and soil variability contributed the largest changes in the Project Vulnerability Score, while coordination complexity and design revisions also influenced construction performance.

The Project Resilience Index showed an inverse relationship with project vulnerability, indicating that projects with lower vulnerability maintained better operational performance throughout construction. The weighted decision matrix successfully ranked project risk using measurable indicators, while the lifecycle governance model supported adaptive construction decisions under changing site conditions. These findings demonstrate that integrating construction management, environmental assessment, geotechnical reliability, and resilience evaluation provides a practical approach for risk-informed public infrastructure delivery.

Limitations of the Study

This study presents a conceptual and simulation-based framework without validation using real project datasets. Future research may evaluate the proposed methodology using field measurements from different public infrastructure projects.

V. CONCLUSION

This study proposed a risk-informed construction delivery framework for public infrastructure projects exposed to geotechnical and environmental uncertainty. The framework integrated construction execution risk, lifecycle governance, environmental exposure, and geotechnical reliability within a unified analytical structure. Project vulnerability was evaluated through a weighted decision matrix, while the Project Resilience Index measured adaptive infrastructure performance under different uncertainty conditions. Scenario-based assessment demonstrated that increasing environmental exposure and subsurface variability produced higher project vulnerability and lower resilience. The proposed methodology offers a structured approach for evaluating construction risk, supporting project governance, and improving decision-making throughout planning, design, and construction without relying on proprietary project datasets.

Future studies should evaluate the proposed framework using data from completed and ongoing public infrastructure projects. Additional research may incorporate Digital Twin technology, BIM-integrated monitoring, probabilistic geotechnical assessment, climate projection datasets, and real-time sensing systems. Comparative studies across different infrastructure sectors and geographical regions could further examine the applicability and performance of the proposed methodology under diverse construction and environmental conditions.

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