Smart City Insights

www.sci.reapress.com

Research Expansion Alliance

Smart City Ins. Vol. 3, No. 1 (2026) 1–15.

Paper Type: Original Article

An AI-IoT Conceptual Framework for Predictive Risk Management in Smart City Subsurface Infrastructure: Insights from Tehran

Seyed Ali Seyedian[1,*], Sara Motevalli[2]

[1] Department of Architecture, University of Mazandaran Babolsar, Mazandaran, Iran; a_seyedian@umz.ac.ir

[2] Department of Architecture, University of Tehran, Tehran, Iran; motevallisara@ut.ac.i

Citation:

Received: ----- *Revised:* ----- *Accepted:*---	Seyedian, S. A., & Motevalli, S. (2026). An AI-IoT conceptual framework for predictive risk management in smart city subsurface infrastructure: insights from Tehran. *Smart City Insights*, *3*(1), 1-15.

Abstract

Rapid urbanization and the increasing complexity of underground infrastructure systems in megacities such as Tehran have intensified geotechnical and structural risks, necessitating a transition from reactive monitoring toward predictive and intelligent risk governance. Although recent advances in Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin technologies have transformed smart infrastructure management, significant gaps remain regarding the integration of these technologies within developing urban governance systems. This study proposes a conceptual AI-IoT framework for predictive risk management in smart city subsurface infrastructure using a documentary and descriptive-analytical research approach. The proposed framework consists of three interrelated layers: 1) an IoT-enabled sensing layer for continuous geotechnical and structural monitoring, 2) an intelligent analytics layer employing AI-driven predictive models and Digital Twin simulations for anomaly detection and risk forecasting, and 3) a decision-support layer facilitating adaptive governance and predictive maintenance. Focusing on Tehran as a representative developing megacity, the study analytically examines institutional fragmentation, interoperability limitations, and governance barriers affecting intelligent infrastructure implementation. The findings suggest that integrated AI-IoT governance frameworks can significantly enhance urban infrastructure resilience, predictive decision-making, and adaptive risk management in subsurface smart city systems. The study contributes theoretically to cyber-physical infrastructure governance literature and provides a conceptual foundation for future empirical implementation of predictive smart infrastructure systems in developing urban environments.

Keywords: Artificial intelligence, Internet of thing, Predictive risk management, Smart city infrastructure, Digital twin, Underground infrastructure, Cyber-physical systems, Tehran.

1 | Introduction

The unprecedented pace of urbanization and population growth in megacities has significantly increased the complexity and vulnerability of subsurface infrastructure systems. Underground transportation networks, utility tunnels, water and wastewater pipelines, deep excavations, retaining structures, and metro

Corresponding Author: a_seyedian@umz.ac.ir

developments are now fundamental components of sustainable urban expansion. However, the increasing dependence on underground infrastructure has simultaneously intensified geotechnical, structural, and operational risks associated with urban construction and maintenance activities. In densely populated cities such as Tehran, where rapid urban growth intersects with complex geological conditions, seismic vulnerability, aging infrastructure, and fragmented urban management systems, subsurface infrastructure failures can generate severe economic, environmental, and social consequences. Incidents such as ground settlement, tunnel deformation, soil instability, water leakage, and structural deterioration demonstrate the urgent need for intelligent and predictive risk management systems capable of detecting and mitigating hazards before critical failures occur.

Traditionally, risk management in underground infrastructure projects has relied on periodic inspections, manual monitoring procedures, threshold-based warning systems, and reactive maintenance approaches. Although these conventional methods provide basic operational oversight, they are often insufficient for addressing the dynamic and interconnected nature of modern urban infrastructure systems. Conventional monitoring systems frequently suffer from delayed data processing, limited predictive capability, fragmented information management, and weak integration between sensing technologies and decision-making mechanisms. Consequently, many urban infrastructure organizations remain incapable of transforming raw monitoring data into actionable intelligence for proactive risk mitigation. Recent advancements in Artificial Intelligence (AI), the Internet of Things (IoT), machine learning, cloud computing, and Digital Twin technologies offer transformative opportunities for overcoming these limitations by enabling real-time sensing, predictive analytics, adaptive decision-making, and intelligent infrastructure management.

The integration of IoT-enabled sensing technologies with AI-driven analytics has emerged as one of the central pillars of smart city development. IoT-based monitoring systems enable continuous acquisition of geotechnical and structural data through interconnected sensors embedded within underground infrastructure environments. These sensors can monitor critical parameters such as displacement, pore water pressure, vibration, temperature, strain, groundwater variation, and structural deformation in real time. Simultaneously, AI and machine learning algorithms provide advanced analytical capabilities for detecting hidden patterns, forecasting system failures, and supporting intelligent risk assessment processes. In recent years, Digital Twin technology has further expanded the potential of smart infrastructure management by creating dynamic virtual replicas of physical systems capable of integrating real-time data streams, simulation models, and predictive analytics into a unified operational environment [1]. Through the synergy of AI, IoT, and Digital Twin technologies, urban managers can transition from reactive maintenance toward predictive and adaptive infrastructure governance.

Recent studies have emphasized the growing role of AI-driven predictive analytics in geotechnical monitoring and smart infrastructure management. Cong and Inazumi [2] demonstrated that AI-based predictive models can significantly improve the accuracy of geotechnical risk forecasting in smart city environments by integrating large-scale monitoring datasets with machine learning techniques. Similarly, Adreani et al. [3] argued that Digital Twin frameworks enhance urban resilience by enabling real-time multi-data integration, simulation-based forecasting, and intelligent decision support. Furthermore, emerging research indicates that IoT-integrated Digital Twins can improve maintenance optimization and infrastructure reliability in underground utility systems through continuous environmental monitoring and predictive diagnostics [1]. These developments indicate a major paradigm shift in infrastructure risk management from static and fragmented monitoring systems toward intelligent, data-driven, and adaptive management ecosystems. Despite recent advancements in AI, IoT, and Digital Twin technologies, substantial research gaps remain in both theoretical and practical dimensions of smart subsurface infrastructure management.

The proposed framework consists of three interrelated layers that collectively establish an intelligent predictive risk management ecosystem for subsurface urban infrastructure. The first layer is the sensing layer, which utilizes IoT-enabled geotechnical instrumentation and sensor networks for continuous real-time data acquisition. This layer forms the foundation of the framework by enabling high-frequency monitoring of environmental and structural parameters within underground infrastructure systems. The second layer is the intelligent analytics layer, where AI-driven predictive models and Digital Twin simulations transform raw monitoring data into actionable insights. Machine learning algorithms analyze temporal and spatial data patterns to predict potential structural failures, geotechnical instability, or operational anomalies before they escalate into critical risks. Simultaneously, Digital Twin simulations create virtual representations of subsurface systems capable of scenario analysis, behavioral forecasting, and adaptive risk assessment. The third layer is the decision-support layer, which facilitates automated risk forecasting, adaptive management strategies, and intelligent decision-making processes for urban infrastructure authorities and governmental organizations.

From a theoretical perspective, this study contributes to the emerging literature on smart city infrastructure management by developing an integrated conceptual framework that combines AI, IoT, Digital Twin technologies, and predictive risk analytics within a unified model for subsurface infrastructure governance. The study also extends cyber-physical systems theory into the domain of geotechnical and underground infrastructure management by demonstrating how real-time data integration and intelligent analytics can support adaptive urban resilience strategies in developing megacities.

From a practical perspective, the proposed framework offers substantial managerial implications for governmental organizations and urban infrastructure agencies in Iran, including Tehran Municipality, Tehran Metro Company, urban utility authorities, and crisis management organizations. By enabling real-time monitoring, predictive maintenance, and intelligent risk forecasting, the framework can support more effective infrastructure governance, reduce maintenance costs, minimize operational disruptions, and enhance urban safety and resilience. Furthermore, the framework provides a practical roadmap for digital transformation in Iranian public-sector infrastructure organizations by addressing institutional barriers to smart technology implementation and promoting data-driven decision-making practices.

Accordingly, the present study seeks to answer the following research questions:

I. How can the integration of AI, IoT technologies, and Digital Twin simulations support predictive risk management in Tehran's subsurface infrastructure systems?

II. To what extent can the proposed AI-IoT framework overcome the limitations of conventional underground infrastructure monitoring and risk management systems?

III. What technological, organizational, and institutional factors influence the successful implementation of intelligent predictive risk management systems within Iranian governmental infrastructure organizations?

Based on these questions, the primary objective of this study is to develop an intelligent AI-IoT framework for predictive risk management in smart city subsurface infrastructure, with a specific focus on Tehran as a representative megacity case study. The secondary objectives include: 1) identifying the critical components of IoT-based geotechnical monitoring systems, 2) analyzing the role of machine learning algorithms in predictive infrastructure analytics, 3) evaluating the function of Digital Twin simulations in adaptive urban risk management, and 4) proposing localized implementation strategies suitable for Iranian governmental and urban management structures.

Overall, this study attempts to bridge the gap between emerging intelligent technologies and practical urban infrastructure governance by proposing a localized and theoretically integrated AI-IoT framework tailored to the unique environmental, institutional, and infrastructural conditions of Tehran. This study develops a conceptual framework for predictive risk management in smart city subsurface infrastructure by synthesizing insights from the literature on AI, IoT, digital twin systems, and urban governance, with Tehran as an interpretive contextual reference rather than an empirically tested case study. The findings are expected to provide both academic contributions and practical guidance for the development of resilient, data-driven, and sustainable subsurface infrastructure systems in smart cities, particularly within developing urban contexts.

2 | Literature Review

The findings of the literature review, drawn from a systematic survey of prior work in this field, are organized into six overarching categories that collectively characterize the existing research landscape.

2.1 | Smart Cities and the Transformation of Urban Infrastructure Management

The rapid expansion of urban populations and the increasing complexity of urban infrastructure systems have accelerated the global transition toward smart city paradigms. Smart cities are generally conceptualized as data-driven urban ecosystems that integrate digital technologies, intelligent infrastructure, and real-time analytics to enhance sustainability, resilience, operational efficiency, and quality of life [4]. Within this paradigm, underground and subsurface infrastructure systems—including metro tunnels, utility corridors, sewage networks, transportation tunnels, and deep foundations—have emerged as critical components of urban resilience and sustainable development.

Recent studies have emphasized that conventional infrastructure management systems are no longer capable of addressing the multidimensional risks associated with dense urban environments. Batty et al. argued that urban systems are increasingly characterized by interconnected risks, requiring adaptive and intelligent governance models rather than isolated engineering solutions [5]. Similarly, Bibri and Krogstie highlighted that smart cities depend heavily on integrated sensing, analytics, and predictive decision-making capabilities to manage urban complexity effectively [6].

However, despite the growing body of literature on smart cities, underground infrastructure has received comparatively less attention than above-ground urban systems. Existing smart city frameworks often prioritize transportation optimization, energy efficiency, or environmental monitoring, while geotechnical and subsurface risk management remain underdeveloped domains [7]. This imbalance becomes particularly problematic in megacities such as Tehran, where underground infrastructure expansion intersects with seismic vulnerability, heterogeneous soil conditions, aging utilities, and fragmented institutional governance.

Several recent studies have attempted to address this issue by integrating digital technologies into underground infrastructure management. Shen [1] demonstrated that IoT-enabled Digital Twin systems can significantly improve intelligent management of underground pipe galleries through continuous monitoring and predictive diagnostics. Likewise, Cong and Inazumi [2] showed that AI-enhanced geotechnical analytics can improve predictive risk assessment in smart infrastructure systems. Nevertheless, these studies largely focus on technologically advanced urban environments and provide limited discussion regarding institutional constraints and implementation barriers in developing countries.

A critical comparison of the literature reveals that while smart city research increasingly emphasizes technological sophistication, it often neglects governance integration and localized implementation realities. In developed economies, smart infrastructure systems typically operate within mature digital ecosystems characterized by standardized data-sharing frameworks, interoperable platforms, and integrated urban governance structures. In contrast, urban management systems in developing countries—including Iran—frequently suffer from fragmented organizational structures, isolated databases, weak interoperability standards, and limited digital coordination among governmental agencies [8]. Therefore, the applicability of existing smart infrastructure models to Tehran's subsurface infrastructure context remains theoretically and practically uncertain.

2.2 | Internet of Things in Geotechnical and Underground Infrastructure Monitoring

The IoT has become one of the foundational technologies for smart infrastructure management due to its ability to facilitate real-time data acquisition through interconnected sensing networks. IoT-based monitoring systems employ embedded sensors, wireless communication protocols, cloud platforms, and edge computing technologies to continuously monitor structural and environmental conditions [9].

Despite these advantages, the literature also identifies several technical and organizational limitations. Many IoT-based systems face challenges related to sensor reliability, data heterogeneity, cybersecurity vulnerabilities, and scalability in dense urban environments [10]. Moreover, the majority of existing frameworks focus primarily on data acquisition rather than intelligent data interpretation or adaptive risk forecasting.

A significant contradiction within the literature concerns the assumption that data abundance automatically leads to better decision-making. While some studies argue that IoT expansion improves infrastructure resilience through enhanced visibility [11], others caution that excessive data generation without advanced analytical capabilities can increase operational complexity and reduce managerial efficiency [12]. This contradiction highlights the necessity of integrating IoT systems with AI-driven analytics capable of transforming raw sensor data into actionable knowledge.

Furthermore, few studies have examined the implementation of IoT systems within public-sector organizations in developing countries. In Iran, institutional barriers such as fragmented data governance, limited interoperability standards, and budgetary constraints continue to impede large-scale deployment of intelligent sensing infrastructures [13]. Consequently, there remains a substantial gap in understanding how IoT technologies can be operationalized effectively within Tehran's governmental infrastructure management ecosystem.

2.3 | Artificial Intelligence and Predictive Risk Analytics in Smart Infrastructure

Recent literature demonstrates that AI-based predictive models significantly outperform traditional threshold-based monitoring systems in terms of forecasting accuracy and early hazard detection. Cong and Inazumi [2] found that machine learning-enhanced geotechnical analytics improve predictive reliability in smart city infrastructure systems by identifying hidden correlations among environmental and structural variables.

Nevertheless, important theoretical and methodological debates remain unresolved. Some scholars argue that AI models function as "black-box" systems with limited interpretability, thereby reducing trust and transparency in critical infrastructure decision-making [14]. Others contend that explainable Artificial Intelligence (XAI) frameworks can mitigate these limitations by improving interpretability and accountability within intelligent infrastructure systems [15].

Another important limitation concerns the fragmentation of AI applications in existing studies. Most prior research focuses on isolated predictive tasks—such as tunnel deformation prediction or fault detection—rather than integrated infrastructure management ecosystems. Consequently, existing AI studies often fail to address how predictive analytics can interact with real-time sensing systems, organizational governance structures, and adaptive decision-support mechanisms.

Additionally, AI adoption in developing countries faces unique institutional and infrastructural barriers that remain underexplored in the literature. Iranian governmental organizations frequently encounter challenges related to insufficient digital maturity, limited AI expertise, regulatory ambiguity, and resistance to technological transformation [8]. Therefore, although AI-based predictive analytics offer substantial potential for subsurface infrastructure management, current literature lacks context-sensitive frameworks tailored to the operational realities of developing urban systems.

2.4 | Digital Twin Technology and Cyber-Physical Infrastructure Systems

Digital Twin technology has emerged as a transformative paradigm for intelligent infrastructure management. A Digital Twin is commonly defined as a dynamic virtual representation of a physical system that continuously integrates real-time operational data, simulation models, and predictive analytics [16]. In urban infrastructure systems, Digital Twins facilitate scenario simulation, predictive maintenance, operational optimization, and risk forecasting.

Recent studies indicate that Digital Twins significantly enhance urban resilience by enabling real-time integration between physical infrastructure systems and digital analytical environments [17]. Adreani et al. [3]

proposed a Digital Twin framework capable of integrating multiple urban data streams into a unified predictive management platform. Their study emphasized the role of Digital Twins in improving adaptive urban governance and infrastructure resilience.

Within the domain of underground infrastructure, Digital Twins have been increasingly utilized for tunnel monitoring, utility management, and predictive maintenance. Shen [1] demonstrated that Digital Twin integration with IoT sensor networks improves intelligent management of underground pipe galleries by enabling dynamic simulation and real-time anomaly detection. Similarly, Kaewunruen et al. [18] argued that Digital Twins can enhance railway and tunnel infrastructure resilience through lifecycle-based predictive management.

The Iranian context illustrates this limitation clearly. Although several recent studies have explored Digital Twin applications in Tehran's urban planning systems [19], there remains little research on Digital Twin integration for subsurface infrastructure risk management within governmental operational environments. Consequently, current literature lacks localized frameworks capable of integrating Digital Twin technologies with AI-driven predictive analytics and IoT-based sensing infrastructures in Tehran's underground infrastructure systems.

2.5 | Integrated AI-IoT Frameworks for Predictive Risk Management

The convergence of AI, IoT, and Digital Twin technologies has given rise to integrated cyber-physical systems capable of enabling intelligent predictive infrastructure management. Integrated AI-IoT frameworks combine continuous sensing, intelligent analytics, and adaptive decision-making into unified operational ecosystems [20].

Recent literature suggests that integrated frameworks outperform isolated technological solutions because they facilitate continuous interaction between data acquisition, prediction, simulation, and managerial response [21]. AI-IoT integration enables predictive maintenance strategies, automated anomaly detection, and adaptive risk forecasting in complex infrastructure systems.

Most importantly, there is a significant absence of localized predictive risk management frameworks specifically designed for Tehran's subsurface infrastructure environment. Existing research rarely considers the interaction between technological complexity, organizational fragmentation, and urban governance structures within Iranian public-sector institutions.

2.6 | Research Gap and Positioning of the Present Study

The review of recent literature demonstrates substantial advancements in IoT-enabled monitoring systems, AI-based predictive analytics, and Digital Twin technologies for smart infrastructure management. However, several critical research gaps remain unresolved.

First, existing studies predominantly focus on technologically advanced urban environments and fail to address the institutional, infrastructural, and governance-related realities of developing countries such as Iran. There is limited understanding of how intelligent infrastructure systems can be implemented effectively within fragmented governmental organizations characterized by isolated databases, weak interoperability, and limited digital integration.

Second, prior research often examines AI, IoT, and Digital Twin technologies independently rather than developing integrated frameworks capable of connecting sensing, analytics, simulation, and adaptive decision-making mechanisms. Consequently, current literature lacks comprehensive cyber-physical models specifically designed for predictive risk management in subsurface urban infrastructure systems.

Third, many previous studies remain reactive in orientation and emphasize monitoring or post-event analysis rather than predictive and adaptive risk governance. In dense urban environments such as Tehran, where underground infrastructure failures can rapidly escalate into urban crises, proactive and predictive management approaches are critically necessary.

Fourth, there is a substantial theoretical gap regarding the integration of cyber-physical systems theory, predictive analytics, and urban resilience frameworks within underground infrastructure governance research. Existing theories insufficiently explain how intelligent technologies collectively contribute to adaptive infrastructure resilience in developing urban contexts.

Accordingly, the present study seeks to address these gaps by proposing an integrated AI-IoT framework for predictive risk management in Tehran's subsurface infrastructure systems. Unlike previous studies, this research combines IoT-enabled sensing, AI-driven predictive analytics, Digital Twin simulations, and adaptive decision-support mechanisms within a unified cyber-physical framework specifically localized for the institutional and infrastructural realities of Iranian governmental organizations.

Table 1. Summary of literature review findings and thematic categories.

Thematic Category	Core Focus in Literature	Key Technologies/Concepts
Smart cities and the transformation of urban infrastructure management	Transformation of traditional urban infrastructure toward intelligent, data-driven, and resilient smart city governance systems	Smart cities, urban resilience, digital governance, sustainable infrastructure, cyber-physical urban systems
IoT in geotechnical and underground infrastructure monitoring	Application of IoT-enabled sensing systems for continuous underground infrastructure and geotechnical monitoring	IoT sensors, wireless sensor networks, real-time monitoring, structural health monitoring, underground infrastructure sensing
AI and predictive risk analytics in smart infrastructure	Use of AI and machine learning algorithms for predictive risk analysis and intelligent infrastructure management	Machine learning, predictive analytics, anomaly detection, forecasting algorithms, intelligent risk assessment
Digital twin technology and cyber-physical infrastructure systems	Integration of Digital Twin technologies with cyber-physical infrastructure environments for simulation and adaptive management	Digital Twin, cyber-physical systems, simulation modeling, real-time synchronization, infrastructure virtualization
Integrated AI-IoT frameworks for predictive risk management	Development of integrated frameworks combining sensing, analytics, simulation, and adaptive governance for predictive infrastructure management	AI-IoT integration, predictive risk management, intelligent infrastructure governance, adaptive decision-support systems
Research gap and positioning of the present study	Identification of unresolved theoretical, technological, and governance gaps in predictive smart infrastructure management	Institutional fragmentation, interoperability barriers, developing-country smart governance, localized AI-IoT frameworks

3 | Research Methodology

This study adopts a qualitative conceptual research design grounded in documentary review and descriptive–analytical reasoning to develop an intelligent AI-IoT framework for predictive risk management in smart city subsurface infrastructure. Unlike empirical engineering studies that rely on simulation modeling, pilot implementation, or experimental validation, the present research is positioned as a theory-building and framework-development study aimed at synthesizing interdisciplinary knowledge and proposing a context-sensitive conceptual model for Tehran's underground infrastructure systems.

The methodological orientation of the study is based on the assumption that the complexity of subsurface infrastructure governance in megacities cannot be adequately understood through isolated technical analyses alone. Instead, an integrative analytical approach is required to examine how AI, the IoT, Digital Twin technologies, and predictive risk management interact within the institutional and infrastructural realities of developing urban environments such as Tehran. Accordingly, the study employs a structured documentary analysis process to critically evaluate scholarly literature published between 2015 and 2025, with particular emphasis on recent publications from 2022–2025.

Documentary analysis constitutes the primary methodological foundation of this research. The method is widely recognized as an appropriate qualitative approach for conceptual investigations involving emerging technological paradigms, interdisciplinary synthesis, and policy-oriented infrastructure studies [22]. It enables systematic examination of scientific knowledge, identification of conceptual patterns, and development of integrated explanatory frameworks. The documentary review process involved the collection, classification, and analytical interpretation of academic sources related to smart city infrastructure management, IoT-enabled monitoring systems, AI and machine learning applications, Digital Twin technologies, cyber-physical systems, predictive risk management, urban resilience, and intelligent governance systems.

To ensure academic rigor, only peer-reviewed journal articles, conference proceedings, indexed scientific publications, and reputable institutional reports were included in the review process. The primary databases consulted included Scopus, ScienceDirect, IEEE Xplore, SpringerLink, Emerald Insight, Google Scholar, MDPI, and DOAJ-indexed journals. More than 50% of the reviewed sources were published between 2022 and 2025 to maintain technological and methodological relevance, while earlier foundational studies were selectively incorporated to establish theoretical grounding for concepts such as cyber-physical systems and smart infrastructure governance.

The documentary data collection process employed a structured keyword-based search strategy using combinations such as "AI-IoT infrastructure management," "predictive risk management," "smart city underground infrastructure," "Digital Twin and geotechnical monitoring," "IoT-based structural health monitoring," and "cyber-physical systems in urban infrastructure." The inclusion criteria required that selected studies be directly related to AI, IoT, predictive analytics, Digital Twin technologies, or underground infrastructure systems and be indexed in reputable scientific databases. Priority was given to recent publications and studies addressing developing-country contexts, urban governance challenges, or smart city implementation in Iran.

The analytical phase of the research employed a descriptive–analytical synthesis approach grounded in thematic interpretation and logical reasoning. Rather than conducting statistical meta-analysis or quantitative content analysis, the study utilized comparative conceptual analysis to identify recurring themes, theoretical convergences, technological relationships, and unresolved gaps within the literature. The analytical procedure consisted of four stages: Thematic classification, comparative interpretation, conceptual integration, and contextual localization.

First, the reviewed studies were categorized into thematic clusters corresponding to the core dimensions of the proposed framework, including IoT-enabled sensing systems, AI-based predictive analytics, Digital Twin integration, intelligent decision-support systems, and urban governance challenges. Second, comparative interpretation was conducted to identify similarities, differences, and methodological limitations in previous studies, particularly regarding reactive versus predictive risk management approaches, interoperability assumptions, and organizational barriers affecting implementation in developing urban environments.

Table 2. Research methodological stages and analytical procedures applied in the study.

Research Stage	Methodological Activity
Research design	Adoption of a qualitative conceptual and documentary research approach combined with descriptive–analytical reasoning
Documentary review	Systematic collection and review of scientific literature from indexed academic databases
Source selection and screening	Application of inclusion and exclusion criteria for selecting reliable and relevant academic sources

Table 2. Continued.

Research Stage	Methodological Activity
Thematic classification	Categorization of reviewed studies into major thematic domains
Comparative and critical analysis	Comparative interpretation of previous studies and identification of conceptual convergences and limitations
Conceptual integration	Integration of fragmented findings into a unified conceptual structure
Framework development	Development of a three-layer architecture including sensing, intelligent analytics, and decision-support layers
Contextual localization for Tehran	Adaptation of the conceptual framework to Tehran's institutional and infrastructural conditions
Theoretical interpretation	Interpretation of findings based on cyber-physical systems theory, smart city governance theory, and predictive risk management theory

Third, the fragmented findings of previous studies were synthesized into a unified conceptual structure consisting of three interrelated layers: 1) a sensing layer based on IoT-enabled geotechnical and structural monitoring systems for continuous real-time data acquisition, 2) an intelligent analytics layer employing AI-driven predictive models, machine learning algorithms, anomaly detection, and Digital Twin simulations for infrastructure forecasting, and 3) a decision-support layer facilitating adaptive governance, predictive maintenance, automated risk assessment, and resilience-oriented infrastructure management.

Finally, the conceptual framework was localized for Tehran's subsurface infrastructure environment by considering contextual factors such as geological vulnerability, rapid underground urban expansion, fragmented institutional structures, limited interoperability among governmental databases, and digital transformation challenges within Iranian public organizations. Rather than claiming universal applicability, the framework was intentionally adapted to reflect the organizational and infrastructural realities of Tehran as a representative developing megacity.

The methodological approach of this study is theoretically informed by cyber-physical systems theory, smart city governance theory, and predictive risk management theory [6], [23], [24]. Together, these perspectives provide the conceptual basis for integrating sensing technologies, intelligent analytics, and adaptive governance mechanisms within urban infrastructure systems.

Despite its theoretical contributions, the study has several limitations. First, it does not involve empirical data collection, simulation modeling, field experiments, or pilot implementation; therefore, the proposed framework remains conceptual and requires future operational validation. Second, documentary analysis depends on the availability and quality of existing literature, which may limit analytical depth in rapidly evolving technological domains. Nevertheless, the selected methodology is appropriate for the objectives of the present study because the primary purpose is conceptual development, theoretical integration, and analytical interpretation rather than technological experimentation.

4 | Discussion

4.1 | Summary of Key Findings

The present study proposed a conceptual AI-IoT framework for predictive risk management in smart city subsurface infrastructure, with Tehran serving as the contextual case study. The findings derived from the documentary and analytical review indicate four major insights. First, the study demonstrates that the integration of IoT sensing systems, AI-driven predictive analytics, and Digital Twin simulations creates a more adaptive and intelligent infrastructure governance model compared with conventional reactive monitoring approaches. The proposed three-layer architecture—comprising sensing, intelligent analytics, and decision-support layers—provides a coherent cyber-physical structure for continuous monitoring and predictive risk assessment.

Second, the analysis revealed that existing underground infrastructure management systems in Tehran suffer from fragmented institutional structures, limited interoperability, and insufficient real-time data integration, which significantly reduce predictive decision-making capacity. Third, the study identified that AI-based predictive analytics can potentially transform subsurface risk governance by enabling early detection of geotechnical instability, infrastructure degradation, and operational anomalies before catastrophic failures occur. Fourth, the findings suggest that Digital Twin technologies can function as strategic decision-support mechanisms by integrating simulation-based forecasting with real-time infrastructure monitoring.

Overall, the study highlights that intelligent AI-IoT integration is not merely a technological enhancement but represents a paradigm shift toward resilient, data-driven, and anticipatory urban infrastructure governance in developing megacities such as Tehran.

4.2 | Comparison with Previous Research

The findings of this study are generally consistent with recent smart infrastructure and Digital Twin research emphasizing the transformative role of intelligent technologies in urban resilience and infrastructure governance. For instance, Shen [1] argued that integrating IoT systems with Digital Twin environments improves the intelligent management of underground utility corridors through continuous monitoring and predictive diagnostics. The present study extends this perspective by demonstrating that such integration is particularly critical in complex urban contexts characterized by institutional fragmentation and high geotechnical risk, such as Tehran.

Similarly, Cong and Inazumi [2] emphasized the effectiveness of AI-driven predictive analytics in geotechnical investigations and smart infrastructure systems. The current research supports these findings by highlighting the capability of machine learning models to improve predictive risk governance in subsurface infrastructure environments. However, unlike prior studies that primarily focused on technical prediction accuracy, the present study incorporates organizational and governance dimensions into the analytical framework. This broader perspective suggests that predictive intelligence alone is insufficient unless supported by institutional interoperability and adaptive decision-making mechanisms.

The study also aligns with Adreani et al. [3], who argued that Digital Twin frameworks enhance urban resilience through real-time multi-data integration and simulation-based management. Nevertheless, while previous research often assumes technologically mature urban ecosystems, the present study differs by explicitly addressing the limitations of developing urban governance systems. In Tehran's context, fragmented databases, bureaucratic structures, and limited digital integration create barriers that are frequently overlooked in technologically deterministic smart city literature.

In contrast to many existing studies that focus on isolated technological components such as IoT monitoring or AI algorithms independently, this research proposes a unified conceptual framework integrating sensing, predictive analytics, simulation, and adaptive governance within a single cyber-physical infrastructure ecosystem. Therefore, the study contributes a more context-sensitive and institutionally grounded perspective to the existing body of smart city infrastructure literature.

4.3 | Theoretical Implications

The present study contributes theoretically to the emerging literature on cyber-physical infrastructure systems, predictive risk governance, and smart city resilience. Existing theoretical models of infrastructure risk management have traditionally relied on static probabilistic frameworks, reactive monitoring systems, or isolated engineering analyses. In contrast, the findings of this research support the argument that intelligent infrastructure governance should be conceptualized as a dynamic cyber-physical ecosystem characterized by continuous interaction between sensing technologies, computational analytics, and adaptive decision-making processes.

From a cyber-physical systems perspective, the proposed framework advances theoretical understanding by integrating three interconnected layers: IoT-enabled sensing, AI-driven predictive analytics, and Digital Twin-supported decision systems. This layered structure refines existing smart infrastructure theories by emphasizing that predictive urban resilience emerges not from individual technologies but from the synergistic interaction among data acquisition, intelligent interpretation, and governance adaptation.

The study also contributes to predictive risk management theory by shifting the analytical focus from reactive hazard response toward anticipatory and learning-oriented governance. Unlike conventional infrastructure management paradigms that rely primarily on threshold-based alerts and post-event analysis, the proposed framework conceptualizes risk management as a continuously evolving predictive process capable of identifying weak signals and emerging infrastructure vulnerabilities before operational disruption occurs.

Furthermore, the findings challenge technologically deterministic assumptions frequently observed in smart city literature by demonstrating that institutional readiness, governance coordination, and interoperability significantly influence the effectiveness of intelligent infrastructure systems. Consequently, the study expands existing theoretical discussions by incorporating organizational and governance dimensions into AI-IoT infrastructure resilience models.

4.4 | Practical Implications

The findings of this study provide several important practical implications for urban policymakers, infrastructure authorities, and governmental organizations responsible for underground infrastructure governance. First, the proposed AI-IoT framework offers a strategic roadmap for transitioning from reactive infrastructure maintenance toward predictive and adaptive risk management systems. Municipal authorities, metro operators, utility agencies, and urban crisis management organizations can utilize the framework to enhance real-time monitoring, infrastructure resilience, and preventive maintenance planning.

Second, the study emphasizes the necessity of institutional integration and data interoperability within public-sector infrastructure management systems. For Tehran Municipality and related governmental agencies, establishing unified digital platforms capable of integrating geotechnical, structural, and environmental data streams represents a critical prerequisite for intelligent risk governance.

Third, the framework highlights the practical value of Digital Twin technologies for infrastructure simulation and scenario-based decision support. Policymakers can employ Digital Twin systems to evaluate potential infrastructure failures, optimize maintenance strategies, and improve emergency response planning under different risk conditions.

Finally, the study suggests that successful implementation of intelligent infrastructure systems requires investment not only in technological infrastructure but also in organizational capacity-building, digital governance policies, interdisciplinary collaboration, and workforce training programs. Without institutional adaptation, the technological potential of AI-IoT systems may remain underutilized within urban management environments.

4.5 | Limitations

Despite its theoretical and conceptual contributions, the present study has several limitations. First, the research adopts a documentary and conceptual methodology and therefore does not include empirical data collection, pilot implementation, simulation modeling, or quantitative validation of the proposed framework. Consequently, the operational effectiveness of the AI-IoT framework remains theoretically inferred rather than experimentally verified.

Second, the study focuses specifically on Tehran as a representative developing megacity, which may limit the generalizability of the findings to other urban environments with different institutional, technological, or geological conditions. Third, because the analysis relies on secondary literature sources, the study is dependent on the availability, quality, and methodological diversity of existing research. Finally, the rapidly evolving nature of AI, IoT, and Digital Twin technologies may require continuous refinement of the framework as new technological capabilities and governance models emerge.

4.6 | Future Research Directions

Future research should focus on empirical validation and operational evaluation of the proposed AI-IoT framework within real urban infrastructure environments. Pilot implementations involving metro systems, underground utility networks, or tunnel infrastructures in Tehran could provide valuable evidence regarding the practical feasibility, scalability, and predictive performance of intelligent infrastructure governance systems.

Further studies may also employ quantitative modeling, simulation techniques, or machine learning experimentation to evaluate the effectiveness of predictive analytics under different geotechnical and operational conditions. Comparative cross-city analyses involving other developing megacities could additionally improve understanding of how institutional structures, governance models, and technological maturity influence intelligent infrastructure implementation.

Moreover, future research should investigate ethical, cybersecurity, and data governance challenges associated with AI-driven urban infrastructure systems. Exploring XAI models, digital governance frameworks, and human-centered decision-support mechanisms would contribute to improving transparency, accountability, and institutional trust in predictive smart city infrastructure management.

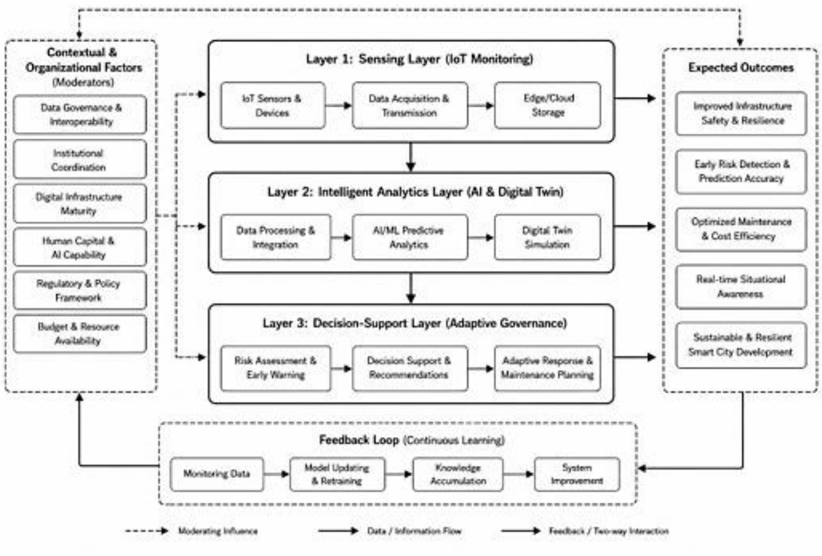

Fig. 1. Analytical integration of sensing, intelligent analytics, and adaptive governance layers in the proposed AI-IoT framework.

5 | Conclusion

The rapid expansion of underground infrastructure systems in megacities has significantly increased the complexity of urban risk management and intensified the need for intelligent, adaptive, and predictive governance mechanisms. In densely populated urban environments such as Tehran, where subsurface infrastructure development intersects with seismic vulnerability, geotechnical instability, aging utility networks, and fragmented institutional structures, conventional monitoring and maintenance approaches are no longer sufficient for ensuring long-term infrastructure resilience and urban safety. In response to these challenges, the present study proposed a conceptual AI-IoT framework for predictive risk management in smart city subsurface infrastructure systems.

The findings of this documentary and analytical study demonstrate that the integration of IoT sensing technologies, AI-driven predictive analytics, and Digital Twin simulations provides a comprehensive cyber-physical infrastructure management architecture capable of supporting intelligent urban resilience. The proposed framework was structured around three interdependent layers: 1) the sensing layer, responsible for continuous real-time geotechnical and structural data acquisition through IoT-enabled monitoring systems; 2) the intelligent analytics layer, which employs machine learning algorithms and Digital Twin simulations for predictive risk analysis, anomaly detection, and infrastructure forecasting, and 3) the decision-support layer, designed to facilitate adaptive governance, predictive maintenance, and intelligent urban risk management.

One of the central conclusions of this study is that predictive infrastructure governance should not be conceptualized merely as a technological upgrade of traditional monitoring systems, but rather as a paradigm shift from reactive management toward anticipatory and data-driven urban resilience. The analytical review of recent literature revealed that most conventional infrastructure management systems remain largely reactive, fragmented, and insufficiently integrated, particularly within developing urban environments. Existing approaches often emphasize isolated monitoring functions without effectively connecting real-time sensing, intelligent analytics, and institutional decision-making processes. Consequently, the study argues that the effectiveness of future smart infrastructure systems depends on the establishment of integrated cyber-physical ecosystems in which sensing, computation, simulation, and governance operate continuously and interactively.

Another important conclusion concerns the contextual significance of institutional and governance factors in the successful implementation of intelligent infrastructure systems. Although recent technological advancements in AI, IoT, and Digital Twin technologies have demonstrated substantial potential for improving predictive infrastructure management [1–3], the study identified that many existing frameworks implicitly assume technologically mature and institutionally integrated urban environments. However, the Tehran case illustrates that technological capability alone is insufficient without organizational interoperability, coordinated data governance, and digital transformation within public-sector infrastructure agencies. Fragmented databases, bureaucratic silos, weak inter-organizational coordination, and limited smart governance capacity remain major obstacles to implementing predictive urban infrastructure systems in developing cities.

The study also contributes theoretically by extending cyber-physical systems and predictive risk management theories into the domain of subsurface urban infrastructure governance. Unlike traditional infrastructure management paradigms that primarily rely on static probabilistic analysis or threshold-based warning systems, the proposed framework conceptualizes risk management as a dynamic, adaptive, and continuously learning process. Through the integration of AI-enabled analytics and Digital Twin simulation environments, urban infrastructure systems can potentially transition toward more resilient and proactive governance models capable of identifying hidden vulnerabilities and emerging risks before infrastructure failures occur.

From a practical perspective, the proposed framework provides a strategic roadmap for governmental organizations, urban policymakers, metro authorities, and infrastructure management agencies in Tehran and similar developing megacities. The implementation of intelligent AI-IoT systems can improve infrastructure safety, optimize maintenance planning, reduce operational disruptions, and enhance urban crisis preparedness. Furthermore, the study emphasizes that successful digital transformation in subsurface infrastructure management requires simultaneous investment in technological infrastructure, institutional integration, workforce development, and regulatory modernization.

Nevertheless, the study acknowledges that the proposed framework remains conceptual and documentary in nature. No empirical testing, pilot implementation, simulation modeling, or quantitative validation was conducted within the scope of this research. Therefore, the operational feasibility and predictive performance of the framework require future empirical investigation through field-based experimentation, machine learning validation studies, and real-world smart infrastructure deployments.

In conclusion, this research argues that the future of subsurface infrastructure governance in smart cities depends increasingly on the integration of intelligent technologies capable of transforming fragmented monitoring systems into predictive and adaptive urban resilience ecosystems. By proposing a localized AI-IoT framework tailored to the institutional and infrastructural realities of Tehran, the study contributes both theoretically and practically to the evolving discourse on smart city infrastructure governance. The framework offers a foundation for future interdisciplinary research and provides a conceptual pathway toward more resilient, sustainable, and data-driven underground infrastructure systems in developing urban environments.

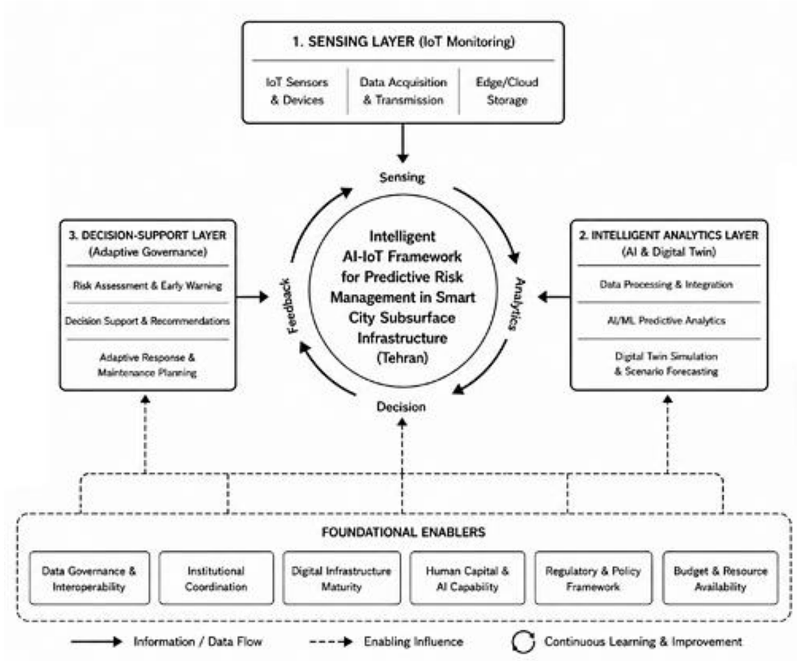

Fig 2. Proposed integrated AI-IoT conceptual framework for predictive risk management in smart city subsurface infrastructure (case of Tehran).

References

[1] Shen, Y. (2025). Integration of IoT and digital twin for intelligent management of urban underground pipe galleries in smart cities. *Informatica*, *49*(15), 179–192. https://doi.org/10.31449/inf.v49i15.7903

[2] Cong, Y., & Inazumi, S. (2024). Integration of smart city technologies with advanced predictive analytics for geotechnical investigations. *Smart Cities*, *7*(3), 1089–1108. https://doi.org/10.3390/smartcities7030046

[3] Adreani, L., Bellini, P., Fanfani, M., Nesi, P., & Pantaleo, G. (2024). Smart city digital twin framework for real-time multi-data integration and wide public distribution. *IEEE Access*, *12*, 76277–76303. https://doi.org/10.1109/ACCESS.2024.3406795

[4] Caragliu, A., Bo, C. Del, & Nijkamp, P. (2009). Smart cities in Europe. *Journal of Urban Technology*, *18*. https://doi.org/10.1080/10630732.2011.601117

[5] Batty, M., Axhausen, K. W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., & Portugali, Y. (2012). Smart cities of the future. *The European Physical Journal Special Topics*, *214*(1), 481–518. https://doi.org/10.1140/epjst/e2012-01703-3%0A%0A

[6] Bibri, S. E. (2018). *Smart Sustainable Cities of The Future*. Springer. https://doi.org/10.1007/978-3-319-73981-6%0A%0A

[7] Masoumi, H., Shirowzhan, S., Eskandarpour, P., & Pettit, C. J. (2023). City digital twins: Their maturity level and differentiation from 3D city models. *Big Earth Data*, *7*(1), 1–36. https://doi.org/10.1080/20964471.2022.2160156

[8] Zali, N., Soltani, A., Najafi, P., Qajari, S. E., & Mehrju, M. (2024). Digital twins for smarter Iranian cities: A future studies perspective. *Computational Urban Science*, *4*(1), 43. https://doi.org/10.1007/s43762-024-00155-9%0A%0A

[9] Da Xu, L., He, W., & Li, S. (2014). Internet of things in industries: A survey. *IEEE Transactions on Industrial Informatics*, *10*(4), 2233–2243. https://doi.org/10.1109/TII.2014.2300753

[10] Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of things for smart cities. *IEEE Internet of Things Journal*, *1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328

[11] Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*, *79*(1), 1–14. https://doi.org/10.1007/s10708-013-9516-8%0A%0A

[12] Hollands, R. (2008). Will the real smart city stand up? *City*, *12*(3), 302–320. https://doi.org/10.1080/13604810802479126

[13] Shariatpour, F., Behzadfar, M., & Zareei, F. (2022). *City information modeling (CIM) and digital twin approach for urban planning, design and management in the smart city age (Case study: Narmak neighborhood of Tehran city, Iran)*. SSRN Electronic Journal (Elsevier). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4231292

[14] Rai, A. (2020). Explainable AI: From black box to glass box. *Journal of the Academy of Marketing Science*, *48*(1), 137–141. https://doi.org/10.1007/s11747-019-00710-5%0A%0A

[15] Gunning, D., & Aha, D. W. (2019). DARPA's explainable artificial intelligence program. *AI Magazine*, *40*(2), 44–58. https://doi.org/10.1609/aimag.v40i2.2850

[16] Grieves, M., & Vickers, J. (2016). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches* (pp. 85–113). Springer. https://doi.org/10.1007/978-3-319-38756-7_4%0A%0A

[17] Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital twins and cyber--physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014

[18] Kaewunruen, S., Peng, S., & Phil Ebosie, O. (2020). Digital twin aided sustainability and vulnerability audit for subway stations. *Sustainability*, *12*(19), 7873. https://doi.org/10.3390/su12197873

[19] Shariatpour, F., Behzadfar, M., & Zareei, F. (2024). Urban 3d modeling as a precursor of city information modeling and digital twin for smart city era: A case study of the narmak neighborhood of tehran city, Iran. *Journal of Urban Planning and Development*, *150*(2), 4024005. https://doi.org/10.1061/JUPDDM.UPENG-4650

[20] Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, *101*, 1–12. https://doi.org/10.1016/j.compind.2018.04.015

[21] Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

[22] Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, *9*(2), 27–40. https://doi.org/10.3316/QRJ0902027

[23] Tao, F., Qi, Q., Liu, A., & Kusiak, A. (2018). Data-driven smart manufacturing. *Journal of Manufacturing Systems*, *48*, 157–169. https://doi.org/10.1016/j.jmsy.2018.01.006

[24] Aven, T. (2012). The risk concept—historical and recent development trends. *Reliability Engineering & System Safety*, *99*, 33–44. https://doi.org/10.1016/j.ress.2011.11.006