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Research Article

Seismic Risk Assessment for Critical Infrastructure Using BIM: A Component-Level Approach

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Abstract

Building Information Modeling (BIM) has become a key technology in engineering projects, encompassing structures such as buildings, bridges, pipelines, and road networks. Despite its widespread adoption, its application in seismic risk assessment for infrastructure systems remains underexplored. This study proposes a BIM-based framework designed to evaluate seismic risk by utilizing detailed digital representations of both structural and non-structural elements. By integrating fragility curves, the framework enables component-level vulnerability analysis, where each element is assigned specific fragility parameters, including median capacity and standard deviation across various damage states. The model facilitates the simulation of different seismic scenarios, allowing for the rapid evaluation of infrastructure performance and the identification of the most at-risk components. This methodology provides engineers and decision-makers with a robust tool for quantifying seismic risk and developing strategies to enhance resilience. Preliminary results indicate that BIM significantly improves the efficiency of seismic risk assessment through structured data management and enhanced visualization capabilities, ultimately aiding in better-informed resilience planning.

Keywords: Building information modeling (BIM); Seismic risk assessment; Infrastructure; Fragility curves; Vulnerability

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Highlights

- A BIM-based framework was developed for precise seismic risk assessment at the infrastructure component level.
- The methodology effectively identifies the most vulnerable components, enabling targeted retrofitting and proactive maintenance.
- A 3D visualization clearly communicates seismic vulnerabilities to stakeholders, facilitating informed decision-making.

1 Introduction

In the last decades, modern societies have become dependent on critical infrastructure (CI) to maintain essential services. CI, including transportation networks, water and wastewater systems, power grids, communication networks, and emergency services, forms the backbone of contemporary society (Urlainis, Shohet, Levy, Ornai, & Vilnay, 2014). The continuous operation of these systems is vital for public health, economic stability, and overall societal well-being. Consequently, a disruption to CI can lead to severe cascading and ripple effects (Buffarini et al., 2022; Lifshitz Sherzer, Urlainis, Moyal, & Shohet, 2024; Pescaroli & Alexander, 2016; Zimmerman & Restrepo, 2009).

Seismic hazards are a serious threat to the integrity and operation of CI, resulting in severe economic losses and human casualties that can extend beyond the damage to the physical structures (Espinoza et al., 2020; Girgin, 2011; Rencoret, Stoddard, Haver, Taylor, & Harvey, 2010; Urlainis, Ornai, Levy, Vilnay, & Shohet, 2022). It was highlighted in the recent seismic event, such as the 2017 Mexico City earthquake, the 2023 Turkey and Syria earthquakes, the 2024 Noto, Japan earthquake, and the 2025 Myanmar earthquake (Cinar, Abbara, & Yilmaz, 2023; Tena-Colunga, Godínez-Domínguez, & Hernández-Ramírez, 2022). These events emphasized the vulnerabilities in the design, the operation, and the maintenance practices of the infrastructure, highlighting the importance for practical frameworks to seismic risks assessment and management.

Given the inherent complexity of critical infrastructure (CI), which consists of interconnected and interdependent components, seismic risk assessment remains a significant challenge. Traditional approaches typically focus on overall structural evaluations and often overlook the nuanced vulnerabilities of individual components within infrastructure systems. Each component, whether structural or non-structural, such as pumps, HVAC systems, electrical panels, and sensors, can exhibit distinct seismic response vulnerabilities. The failure of a single component can compromise the functionality of the entire infrastructure system, intensify damage, and prolong recovery efforts (Gehl, Desramaut, Réveillère, & Modaressi, 2014; Urlainis & Shohet, 2022b, 2022a).

Building Information Modeling (BIM) has been widely adopted in the architecture, engineering, and construction (AEC) industry (Gurevich & Sacks, 2020; Mitelman & Gurevich, 2021; Urlainis & Mitelman, 2025). BIM enables the digital representation of physical and functional characteristics of structures and infrastructure systems, fostering enhanced collaboration, design optimization, construction coordination, and lifecycle management (Fernández García et al., 2020; Nguyen, Lou, & Nguyen, 2024; Shah, Kathiriya, Suthar, Pandya, & Soni, 2023). Widely adopted across various engineering disciplines, BIM provides a comprehensive database encompassing geometry, materials, connections, and performance characteristics at the component level. Despite BIM's proven benefits and widespread adoption, its potential for risk management, specifically seismic vulnerability assessment, remains significantly underutilized.

This research addresses this gap by proposing a comprehensive BIM-integrated framework designed specifically for seismic risk assessment of critical infrastructure at the component level. The proposed methodology integrates detailed BIM-based component-level data with seismic fragility curves and location-specific seismic hazard curves. By combining these data, the framework facilitates a evaluation of seismic vulnerability for each component. The primary goal of this research is to develop a decision-support tool tailored for engineers and decision-makers. The component-level analysis enables engineers to identify vulnerabilities within complex infrastructure systems effectively. Evaluating each component's seismic vulnerability allows for targeted risk mitigation strategies, informed maintenance planning, and more resilient infrastructure design. Consequently, resources can be allocated strategically to enhance retrofitting measures, streamline maintenance efforts, and improve emergency preparedness.

2 Concepts and Frameworks

2.1 Key Concepts

Critical Infrastructure (CI) refers to assets, systems, and networks, whether physical or virtual, that are vital for the continuous functioning of societies and economies(Moteff, Copeland, & Fischer, 2003; Rinaldi, Peerenboom, & Kelly, 2001). The U.S. Department of Homeland Security (DHS) and European Commission emphasize CI's critical role in maintaining public safety, national security, economic vitality, and societal resilience (EuropeanCommission, 2015; US DHS, 2015).

Building Information Modeling (BIM) is defined as a digital representation of physical and functional characteristics of structures or infrastructure systems, intended to enhance decision-making processes throughout an asset's lifecycle (International Organization for Standardization, 2018; Sacks, Eastman, Lee, & Teicholz, 2018). The adoption of BIM offers several advantages including 3D visualization, improved collaboration, reduce design error, increase productivity and efficiency, clash detection, easy quantity take-offs, improved cost estimation, efficient construction planning and management, Monitor and track progress during construction, and more (Al-Ashmori et al., 2020; Bensalah, Elouadi, & Mharzi, 2019; Salleh, Ahmad, Abdul-Samad, Alaloul, & Ismail, 2023).

Probabilistic Seismic Hazard Analysis (PSHA) is a systematic approach used to estimate the likelihood of different levels of earthquake-induced ground shaking occurring at a specific location over a defined time. This methodology integrates data on regional seismic sources, earthquake recurrence rates, and ground motion models to assess potential seismic hazards. The outcomes are typically represented as hazard curves, which depict the annual probabilities of exceeding various ground motion intensities (Figure 1). These hazard assessments are crucial for informing engineering decisions related to building design, infrastructure development, and emergency planning in areas susceptible to seismic activity (J. Baker, Bradley, & Stafford, 2021; J. W. Baker, 2013; Mulargia, Stark, & Geller, 2017) .

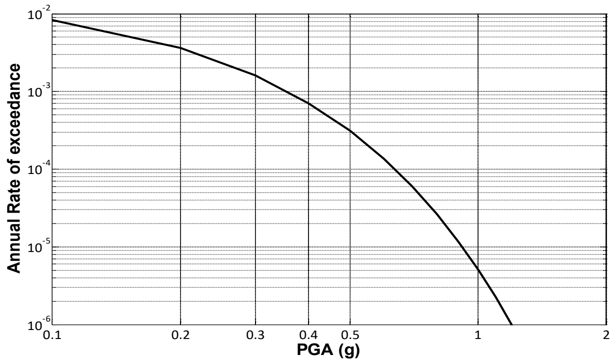

Figure 1 - Example of a seismic hazard curve illustrating the relationship between PGA and its annual probability of exceedance, typically derived from Probabilistic Seismic Hazard Analysis (PSHA).

A fragility curve is a graphical method to express the probability of a component or system exceeding a certain damage state (DS) as a result of an earthquake's intensity measure (IM) parameter. (Alliance American Lifelines (ALA), 2001; Porter, 2020; Urlainis & Shohet, 2022a). The fragility curves for a structure, system, or components are represented as a lognormal cumulative distribution function

(CDF). The function is defined by two parameters: the median capacity of the component to resist damage state (θ_{ds}) and the standard deviation of the capacity (β_{ds}). In the case of multiple and sequential damage states, the damage states are ordered by damage severity, and the fragility function defines the probability of being in a specified damage state (Eq. 1). Figure 2 presents an example of possible fragility curves for components.

$$P(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 1 \leq i \leq n-1 \\ P(DS \geq ds_i|IM) & i = n \end{cases} \quad (1)$$

Where,

DS	Uncertain damage state of a particular component $\{0,1,\ldots N_n\}$
ds	A particular value of DS
N_{DS}	Number of possible damage states
IM	Uncertain excitation, the ground motion intensity measure (i.e., PGA, PGD, or PGV)
x	A particular value of IM
Φ	Standard cumulative normal distribution function.
θ_{ds}	The median capacity of the component to resist a damage state ds measured in terms of IM
β_{ds}	The logarithmic standard deviation of the uncertain capacity of the component to resist a damage state ds

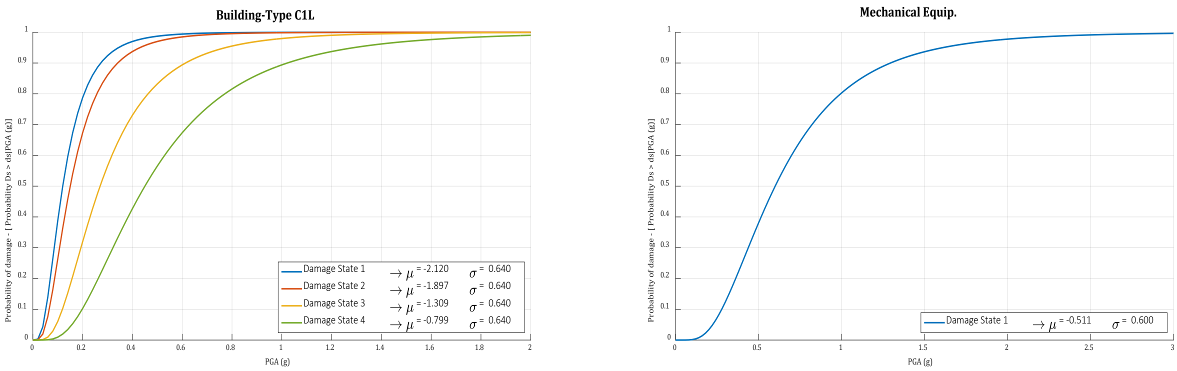

Figure 2 - Example of fragility curves for different types of possible infrastructure components

2.2 Existing Theories and Frameworks

Probabilistic Seismic Hazard Analysis (PSHA) is a systematic approach used to evaluate the probability of various levels of earthquake-induced ground motions occurring at specific locations over defined periods. PSHA integrates seismic source characterization, seismicity rates, and ground motion attenuation relationships to quantify uncertainties and probabilistically assess seismic hazards. However, PSHA typically emphasizes regional hazard estimations, producing hazard curves that represent the likelihood of exceeding specific ground motion intensities.

Urlainis et al. (2022) propose a methodology for developing exclusive fragility curves tailored specifically for infrastructure components. This approach involves decomposing complex infrastructure systems into subcomponents and performing detailed analyses of failure mechanisms. Implementing this methodology demands comprehensive data collection and precise component-level information, typically available within datasets provided by the BIM model. Therefore, integrating BIM data can enhance the applicability of fragility curves in evaluating seismic vulnerabilities.

FEMA's Hazus methodology provides an established framework, that is a geographic information system-based tool, for estimating potential losses from earthquakes by integrating hazard characterization, inventory classification, and fragility functions (FEMA, 2012). However, it mostly applies generic typologies rather than component-specific vulnerabilities. This highlights the potential

2.3 Knowledge Gaps and Research Opportunities

Different methodologies for seismic risk assessment are presented in existing literature. However, the traditional seismic risk assessment approaches often focus on the overall structure rather than individual components. On the other hand, the component level approaches, require detailed and precise component-level data, which is often difficult to collect and manage effectively with traditional approaches. This affects their practical applicability in infrastructure resilience planning.

BIM inherently provides detailed component-level data, including precise geometric information, functional characteristics, and material properties. These elements are essential for conducting robust seismic vulnerability assessments. Despite BIM's widespread adoption within the AEC industry, its full potential remains underutilized in current seismic risk assessment frameworks. Consequently, there exists a missed opportunity to enhance the precision of risk analyses, improve informed decision-making processes, and develop targeted vulnerability mitigation strategies.

This study aims to address these gaps by proposing a detailed and integrated BIM-based framework designed explicitly for component-level seismic risk evaluation in critical infrastructure systems

2.4 Proposed Conceptual Model

The proposed conceptual model integrates BIM digital model with seismic risk assessment tools. The model consists of three main interrelated components:

- BIM Model: Detailed representation of infrastructure system geometry, materials, and functionality.
- Fragility Curve: Probabilistic models representing the likelihood of exceeding defined damage states under varying seismic intensities.
- Seismic Hazard Curve: Site-specific seismic intensity probabilities derived through seismic hazard analyses.

These components interact sequentially, beginning with the creation of a detailed BIM model, followed by assigning fragility curves to each BIM model component based on literature data. Subsequently, the seismic hazard curves provide the seismic occurrence probability against which component vulnerabilities are evaluated. Finally, the results are visualized in a three-dimensional BIM environment, offering intuitive, actionable insights.

3 Methodology

The proposed BIM-based seismic risk assessment framework consists of five steps, as illustrated in Figure 3.

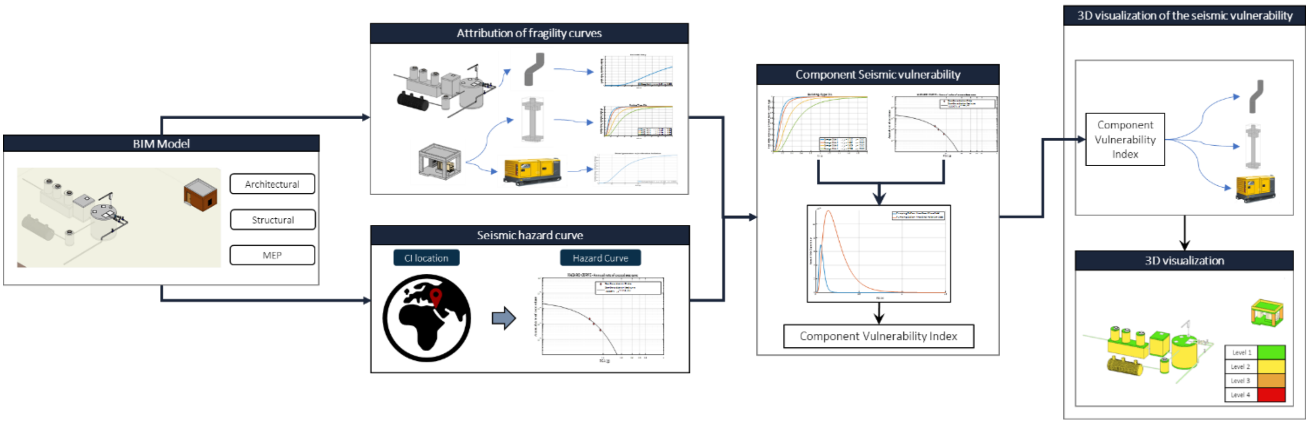

Figure 3- Methodology Framework

1. **Structure or infrastructure BIM model**: development of a BIM model containing data on the structural and non-structural elements of the infrastructure system. This model forms the basis for subsequent seismic risk analysis. In this study, Autodesk Revit software.
2. **Attribution of fragility curves**: Attributing fragility curves to each component in the BIM. Each component is assigned the median and standard deviation capacity for the defined damage state. The data of fragility parameters for structure and system infrastructure and for individual components can be found in the literature (Alliance American Lifelines (ALA), 2001; Gehl et al., 2014; NIBS, 2004; Rossetto, D'Ayala, Ioannou, & Meslem, 2014). Each component in the BIM model is attributed with fragility parameters: the median θ_{ds} and standard deviation β_{ds} for each damage state.
3. **Seismic hazard curve**: Deriving a seismic hazard curve for the infrastructure system's location. The hazard curve represents the relationship between the probability of exceedance of a given ground motion level and the corresponding return period. This curve is typically obtained based on regional seismic hazard studies or by PSHA.
4. **Seismic vulnerability**: The seismic vulnerability of each component is determined by integrating component fragility curves with the hazard curve. The probability of exceeding the damage states is computed for each component. The outcome is a vulnerability index representing the likelihood of the component experiencing degrees of damage during seismic events.
5. **3D visualization**: The seismic vulnerability is visualized through the BIM model. This offers 3D visualization that assists in identifying the most critical components in the system.

4 Results - Key Findings

A conceptual case study of a sewage pumping station was conducted to demonstrate the proposed methodology. Sewage pumping stations are facilities within wastewater management systems designed to transport wastewater from lower to higher elevations, enabling gravity-fed or pressurized flow towards treatment facilities. Due to their crucial role, continuous operation during and after seismic events is imperative, underscoring the importance of accurately assessing their seismic vulnerabilities.

In this case-study, the station in located in a seismically active region composed of a reinforced concrete structure equipped with essential operational components, including two pumps, electrical systems, piping, valves, and various non-structural elements. A detailed digital BIM model was created in Autodesk Revit (Figure 4).

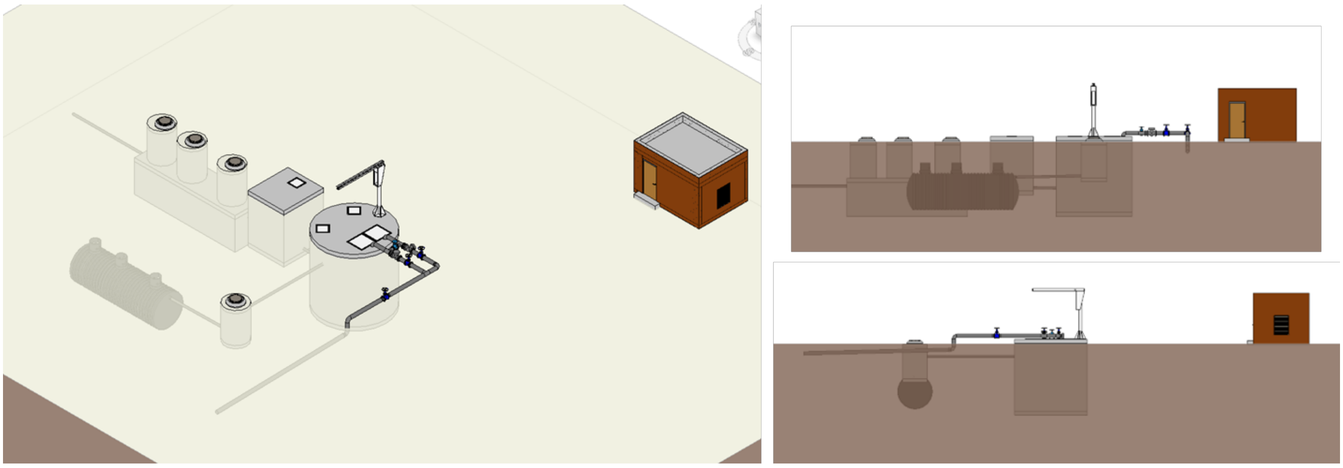

Figure 4 - BIM model of the sewage pumping station illustrating structural and non-structural components

The case study highlighted several key findings:

- Identification of Highly Vulnerable Components: The analysis clearly identified specific elements, most notably electrical systems and valve connections, as highly susceptible to seismic damage. These critical components showed significantly increased probabilities of exceeding defined damage states, pinpointing them as priority targets for focused retrofitting and preventive maintenance.
- Quantitative Risk Assessment: The methodology provided precise, quantifiable measures of vulnerability at the component level, offering clear benchmarks for decision-making. This precision enables effective resource allocation for risk reduction measures.
- 3D visualization for Decision-Making: The 3D visualization enabled rapid comprehension of the station's seismic vulnerabilities, offering stakeholders a practical tool for efficiently communicating risks, planning maintenance schedules, and optimizing retrofitting strategies.

This conceptual case study illustrates the substantial potential of the BIM-based seismic risk assessment framework, demonstrating its capability to accurately and efficiently identify, quantify, and visualize seismic vulnerabilities (Figure 5). Consequently, infrastructure managers and engineers can proactively enhance infrastructure resilience, significantly improving preparedness for future seismic events.

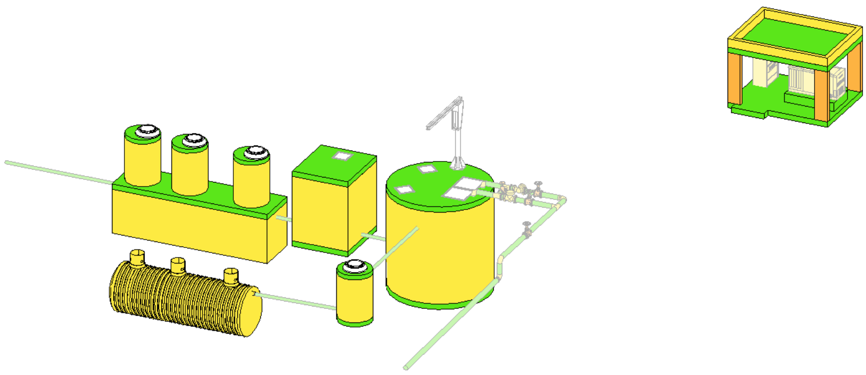

Figure 5 - 3D visualization of the pumping station's seismic vulnerability, highlighting component risk levels

5 Discussion

The proposed BIM-based framework advances the use of BIM for risk management. By integrating the component-level data from a BIM model with fragility curves and seismic hazard analysis, this approach delivers a robust, systematic method for assessing seismic vulnerability of critical infrastructure. Several significant benefits arise from adopting this framework:

1. The utilization of component-specific data available in BIM enhances the accuracy of seismic risk assessments. By attributing detailed fragility parameters directly to individual components, the methodology captures variations in component properties and their specific responses to seismic events. This helps identify the most vulnerable components and enables managers to strategically prioritize retrofitting actions, targeted inspections, and proactive maintenance measures.
2. Seismic risk assessment directly in BIM environment offers substantial advantages for ongoing risk management. As new data becomes available or changes occur in infrastructure conditions, the BIM platform facilitates dynamic updates and continuous tracking of infrastructure vulnerabilities. Consequently, stakeholders can maintain an up-to-date understanding of seismic risk, supporting adaptive risk management practices and enhancing long-term resilience.
3. The BIM 3D visualization capabilities significantly enhance stakeholder engagement and decision-making processes. Complex seismic risk data can be intuitively, simplifying effective communication among engineers, infrastructure managers, and decision-makers. Such clarity assists stakeholders in rapidly comprehending risk profiles, optimizing retrofitting plans, scheduling preventive maintenance activities, and efficiently coordinating emergency response strategies.

5.1. Limitations and Future research

While the proposed BIM-based framework effectively enables component-level seismic risk assessment, it currently operates on static input data and predefined fragility parameters. As such, it does not account for real-time monitoring or adaptive risk updates. A promising direction for future research involves integrating Digital Twin technologies and IoT-based sensor networks with the BIM environment (Alsehaimi et al., 2024; Mitelman, Eilat, & Urlainis, 2024). This would enable real-time condition monitoring, dynamic updating of fragility parameters, and continuous risk assessment. Such integration could significantly enhance the responsiveness and accuracy of infrastructure resilience planning throughout the asset's lifecycle.

In addition, integratiing artificial intelligence (AI) and machine learning (ML) approaches can significantly augment the predictive and analytical capabilities of the framework. Recent studies (e.g.,(Mangalathu, Karthikeyan, Feng, & Jeon, 2022; Mitelman & Urlainis, 2023; Mitelman, Yang, Urlainis, & Elmo, 2023) have demonstrated the value of ML for engineering applications. Specifically, transfer learning techniques were shown to overcome limitations posed by small datasets, while hybrid approaches combining numerical simulation and ML enabled real-time predictive insights. Drawing from these findings, future work could explore the application of ML to enhance seismic fragility model calibration, automate risk classification, and prioritize maintenance interventions based on learned patterns from historical and sensor-based data. Incorporating AI models into the BIM environment will support intelligent decision-making, improve the interpretability of complex risk interactions, and accelerate resilience planning.

6 Conclusions

This paper presented a comprehensive BIM-based framework for seismic risk assessment of critical infrastructure systems. By leveraging component-level data available in BIM models with fragility and seismic hazard curves, this approach provides a systematic and effective method to quantify and visualize infrastructure vulnerabilities. The conceptual case study involving a sewage pumping station demonstrated the framework's substantial benefits, clearly identifying critical components most vulnerable to seismic damage, facilitating targeted retrofitting, and enabling informed, strategic decision-making. The 3D visualization capabilities highlighted vulnerabilities intuitively, significantly improving stakeholder communication and decision-making. As BIM technology becomes increasingly prevalent within engineering and construction industries ((Al-Ashmori et al., 2020; Urlainis & Mitelman, 2025), this framework has the potential to become an essential tool for infrastructure risk management. Continuous refinement, adaptation to complex structures, and incorporation of diverse hazard types represent valuable directions for future research, promising enhanced resilience and safety for critical infrastructure systems worldwide.

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No external datasets were utilized in this research.
Conflicts of Interest
The authors declare no conflict of interest.

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