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MINI REVIEW

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Harnessing digital twin technology for earthquake resilience: A case study of disaster management innovation in Japan

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ABSTRACT

Japan's frequent seismic activity has driven continuous innovation in disaster preparedness. This case study investigates the application of Digital Twin (DT) technology to enhance earthquake resilience in Sendai City, a region with significant seismic risk. The study presents a hybrid system combining real-time seismic sensor data, urban infrastructure models, and predictive simulation tools to replicate city-scale responses. The DT model was tested using historical earthquake scenarios and evaluated for response accuracy, early warning capability, and emergency route optimization. Results demonstrate improved situational awareness and decision-making efficiency compared to traditional systems. The integration of IoT and cloud-based analytics further strengthens the model's real-time responsiveness. This research highlights the potential for Digital Twin systems to revolutionize urban disaster management in seismic zones. The findings support broader implementation across earthquake-prone regions and contribute to Japan's national strategy for smart, resilient cities.

KEYWORDS

Digital twin; Earthquake resilience; Disaster management; Smart infrastructure; Japan

ARTICLE HISTORY

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Introduction

Japan is located in the Pacific Ring of Fire, where four tectonic plates converge, making it one of the most earthquake-prone nations in the world. Repeated large-scale seismic events, including the 2011 Great East Japan Earthquake, have highlighted the limitations of conventional disaster response systems [1]. Despite significant investments in infrastructure and early warning mechanisms, the complexity of urban environments and increasing population density demand more adaptive and predictive approaches.

In recent years, digital transformation has emerged as a strategic national goal in Japan, particularly in areas such as smart city development and disaster resilience. Among emerging technologies, Digital Twin (DT) systems offer a novel solution by creating real-time virtual replicas of physical assets and environments. These systems integrate data from IoT sensors, geospatial networks, and simulation platforms to support decision-making before, during, and after a disaster [2].

This study explores the implementation of Digital Twin technology for earthquake preparedness in Sendai City, a region with high seismic exposure and advanced urban planning initiatives. The research aims to evaluate how DT systems can improve situational awareness, optimize emergency responses, and support resilient urban infrastructure. The article is structured as a case study with analysis, results, and policy implications for nationwide application.

Literature Review

Digital Twin (DT) technology has seen increased application in urban safety and disaster response across various regions. In Europe, DTs have been implemented for flood simulation and dynamic evacuation planning, demonstrating their capacity to improve real-time coordination [3]. In North America, the focus has shifted to infrastructure stress modeling under earthquake scenarios, emphasizing the potential of DTs in predictive diagnostics and rapid response systems.

In the Japanese context, initial DT applications have been tested in transport infrastructure and smart city planning. Urban rail networks and public safety systems have experimented with DT integration for simulating earthquake conditions and optimizing evacuation flows [4]. However, these efforts have largely remained confined to controlled environments or pilot studies, without full-scale implementation at the city level.

As shown in Table 1, a significant research gap exists in operational, city-wide DT systems designed specifically for seismic resilience. Moreover, the integration of DTs into existing national disaster management frameworks is still underdeveloped, limiting the technology's real-world applicability in Japan [5].

Table 1. Summary of key studies on digital twin use in disaster management.

Region	Focus Area	Identified Gap
Europe	Flood simulation and evacuation	Lack of seismic-specific applications
North America	Infrastructure stress modeling	Limited real-time operational feedback
Japan	Earthquake simulations in transit	No city-scale implementation
Japan	Smart evacuation systems	Weak integration with public policy

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Methodology

This study adopts a case study design to evaluate the implementation of a Digital Twin (DT) model for seismic disaster response in Sendai City. The methodology focuses on developing a virtual replica of the city's critical infrastructure, integrating real-time sensor data, and simulating earthquake scenarios to support proactive decision-making.

The DT system architecture is composed of three core components: data acquisition, digital modeling, and real-time simulation. Seismic input data were sourced from the Japan Meteorological Agency (JMA), including historical earthquake records and near real-time ground motion alerts [6]. Supplementary environmental data were gathered from IoT-based sensors installed in selected public buildings, roadways, and bridges. These sensors continuously transmitted structural data (e.g., vibration levels, displacement, tilt) to a centralized analytics hub [7].

Digital modeling was performed using Unity3D and MATLAB Simulink, allowing for visual simulation of seismic events and real-time monitoring. A scenario-based simulation was conducted, replicating a magnitude 7.2 earthquake affecting the central district of Sendai [8-9]. Evaluation criteria included system response latency (under two seconds), accuracy of deformation prediction, and efficiency of evacuation route optimization.

As shown in Table 2, the DT system integrates multiple data sources, modeling tools, and performance metrics. The system's functionality was validated through simulations and feedback from disaster management professionals, ensuring both technical feasibility and operational relevance [10].

Table 2. Core components of the digital twin system.

Component	Description
Data Sources	JMA seismic data, IoT sensor input from infrastructure
Modeling Tools	Unity3D, MATLAB Simulink
Evaluation Metrics	Latency, simulation accuracy, and evacuation effectiveness

Case study: Implementation in Sendai City

Sendai City, the capital of Miyagi Prefecture, was selected for this case study due to its high seismic risk profile and proactive smart city initiatives. The city experienced significant damage during the 2011 Great East Japan Earthquake, making it an appropriate location for testing advanced digital disaster response technologies [11].

The Digital Twin (DT) system was implemented in the Aoba Ward, which includes a mix of residential, commercial, and public infrastructure [12]. IoT sensors were strategically installed on key assets, including bridges, emergency shelters, and public buildings. These sensors continuously transmitted structural performance data, such as vibrations, tilt, and cracks, into the DT platform [13].

The virtual model of Aoba Ward was created using GIS data combined with real-time sensor feeds. Unity3D was used for 3D visualization, while seismic simulation inputs were modeled using parameters from a hypothetical magnitude 7.2 inland earthquake [14]. The system allowed disaster managers to simulate various emergency response scenarios, such as real-time evacuation flows, structural vulnerabilities, and route blockage predictions.

The DT interface provided city officials with a live dashboard showing building stability, predicted collapse zones, and suggested evacuation corridors. In one scenario, the model accurately predicted that two bridges would become impassable within 90 seconds of the seismic event, prompting automated route reallocation for ambulances and emergency responders [15].

This implementation demonstrated not only the technical feasibility of Digital Twin integration in Sendai's urban context but also its operational value in enhancing situational awareness and emergency coordination [16]. Feedback from local disaster response teams suggested that the system could significantly reduce response time and improve safety outcomes during actual seismic events.

Results and Discussion

The implementation of the Digital Twin (DT) system in Sendai yielded several significant outcomes related to real-time disaster response and predictive accuracy. Simulation tests showed that the DT system successfully processed seismic input and structural data with a latency of approximately 1.6 seconds, meeting the operational threshold required for emergency responsiveness [10].

The system's simulation engine accurately predicted structural vulnerabilities with over 90% precision when compared to historical earthquake damage records from the 2011 event. In particular, the DT correctly identified key bottlenecks in transportation routes and suggested alternative evacuation paths, which reduced simulated evacuation time by approximately 18% compared to standard static plans [17].

The interactive dashboard enabled city officials to visualize cascading failures, such as bridge collapses or blocked intersections, and take preemptive measures. Local disaster response personnel highlighted the value of the DT's real-time scenario adjustment capability, which helped coordinate ambulance deployment and shelter capacity management more efficiently [5].

Despite these promising results, several limitations were identified. The system's performance relies heavily on uninterrupted data flow from IoT sensors, which may be compromised during large-scale events [18]. Additionally, full integration with city-wide emergency operation centers and cloud-based backups is still under development.

These findings suggest that while the current DT prototype offers substantial improvements in urban earthquake response, its scalability and robustness must be further validated across diverse infrastructure conditions and administrative environments [4].

Policy and Practical Implications

The Sendai case study highlights the critical role of Digital Twin (DT) technology in enhancing urban earthquake resilience

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[19]. For policymakers, the integration of DT systems into municipal disaster protocols offers an opportunity to modernize emergency response infrastructure. Urban planners can leverage real-time modeling to optimize evacuation routes and shelter placement. From a technical perspective, expanding DT deployment across other high-risk cities in Japan requires national-level coordination, investment in sensor networks, and standardized data governance. Ultimately, institutionalizing DT within Japan's disaster management framework can improve readiness, reduce response time, and enhance public safety during future seismic events [10,20].

Conclusions

This case study demonstrates the practical effectiveness of Digital Twin (DT) technology in enhancing earthquake resilience within urban infrastructure. The implementation in Sendai City revealed that DT systems can provide accurate real-time simulation, enable efficient emergency coordination, and support data-driven decision-making. The system's ability to predict structural vulnerabilities and optimize evacuation strategies highlights its potential as a critical tool in municipal disaster response. Overall, the study confirms that Digital Twin integration can significantly contribute to Japan's broader efforts toward digital transformation in disaster management.

Disclosure statement

The authors declare that they have no competing interests.

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