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Practical Applications of Digital-Twin-enabled Risk Management in Infrastructure Projects

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ABSTRACT

Infrastructure risk management in China still mainly relies on manual inspections and empirical judgment, which is characterized by incomplete monitoring coverage and insufficient risk forecasting capability, and is no longer able to meet the requirements of refined safety control for modern engineering. The industry is beginning to use digital twins to transform traditional risk control models and optimize the effectiveness of engineering safety management. This paper takes transportation, water conservancy and municipal engineering as the main research domains, and analyzes typical projects including Beixi of Jiulong River, City-wide Underground Pipeline Network of Chongqing, and the Yangtze-to-Han River Water Diversion Project as research samples. This paper explores five core dimensions, including risk identification, assessment, risk response, emergency coordination, and full-lifecycle operation and maintenance. Based on multiple practical engineering projects, this paper summarizes the on-site application patterns of digital twins. According to the publicly available engineering data from the Ministry of Water Resources and the Ministry of Housing and Urban Rural Development, the short-term flood forecasting accuracy for the watershed stands at 90% after the application of this technology, and the timely repair rate of municipal pipeline networks exceeds 98%. This technology reduces missed hazard identification, shortens emergency response time and lowers losses resulting from safety incidents. Practical experience from field applications can provide valuable guidance for similar infrastructure projects.

KEYWORDS

Digital twin technology; Infrastructure; Project risk management; Full-lifecycle; Engineering application

1. INTRODUCTION

Infrastructure is a key carrier for ensuring the stable operation of the socio-economic system. Large-scale water conservancy, transportation and municipal projects feature long construction cycles, large capital investment and complex on-site working conditions. Geological hazards, structural defects and extreme weather exist throughout project construction and operation. The domestic infrastructure industry has always relied on manual inspections and paper-based records for risk control. This model has limited monitoring scope and insufficient risk forecasting capability, making it difficult to meet the current requirements for refined management. This management model also leaves potential risks, which impairs the overall operational stability of engineering projects.

The competent departments of the water conservancy and transportation industries are promoting the implementation and application of digital twins, leveraging the Internet of Things, 3D modeling and big data technologies to build a multi-dimensional integrated monitoring system [1]. In 2025, numerous digital twin demonstration projects emerged across China. These projects cover various infrastructure scenarios such as watersheds, transportation corridors, and urban pipelines. Beixi of

Jiulong River is a pilot project in the field of water conservancy. Chongqing's city-wide underground pipeline network system is the first provincial-level pipeline management platform in China. The Yangtze-to-Han River Water Diversion Project is an important part of the South-to-North Water Diversion Project. Shandong's expressway network is also equipped with over 3,000 sets of sensing devices, with relevant technologies fully deployed and applied on site.

Practical experience gained from these pilot projects provides valuable insights for the industry's digital transformation. This paper draws on multiple practical engineering cases to summarize the on-site application modes of digital twins. Based on public data, this paper analyzes the operational logic and application effects of digital twins, and provides practical insights for the intelligent risk control of similar projects.

The pace of digital transformation varies among different infrastructure projects. The supporting facilities for large-scale water conservancy and transportation projects are complete, and the implementation of digital systems is relatively smooth; most small and medium-sized municipal projects are upgraded step by step according to their actual conditions. Nowadays, digital twins are no longer confined to pilot projects and have gradually been integrated into all aspects of daily on-site management.

2. REAL-TIME PERCEPTION OF ALL FACTORS: RELYING ON DIGITAL TWINS TO ACHIEVE PRECISE RISK IDENTIFICATION

Infrastructure is often exposed to latent and sudden risks, and for a long time, infrastructure safety inspections have largely relied on manual operations. Due to limitations in inspection frequency, work visibility, and complex on-site conditions, traditional inspections cannot achieve all-weather and comprehensive coverage, and many hazards are difficult to detect in a timely manner [2]. Digital twins leverage wide-area sensing networks and multi-source data fusion to overcome the limitations of manual inspections. This shifts risk management to early risk warning and underpins on-site intelligent risk control. This sensing network can automatically adjust its monitoring frequency according to external factors such as weather, traffic flow and hydrological conditions, while focusing on high-risk areas. The dynamic monitoring mode further improves hazard detection capability, allowing risk identification to fully adapt to real-time on-site working conditions.

At present, the three core infrastructure fields of transportation, water conservancy, and municipal engineering in China have completed the layout and technical implementation of large-scale sensing equipment. Multiple highways in Jiangxi Province have deployed intelligent sensing devices in bridge and slope-prone areas, collecting real-time parameters such as structural deformation, stress and vibration and regularly monitoring risks such as overloading and landslides. This solution has been implemented in 17 high-risk highway locations within the province. The national water conservancy industry relies on 136,000 ground hydrological flood reporting stations to continuously collect basic hydrological data of the basin. The digital twin basin of the Yangtze River relies on this sensing system to achieve dynamic control of the entire water situation, and the short-term hydrological forecasting accuracy of key sections stands at 90%. At the same time, Yuzhong District in Chongqing has set up Internet of Things (IoT) monitoring terminals for urban underground pipelines, covering 275 gas lines and 273 drainage pipelines in the jurisdiction, accurately capturing municipal hazards such as pipeline leakage and soil settlement [3].

Standardizing various monitoring data formats can effectively improve the accuracy of hazard identification. There are significant differences in data formats and statistical standards across various monitoring devices, which can easily lead to data silos. A dedicated data platform has been built for the Beixi Digital Twin Watershed of Jiulong River, integrating hydrological, geological and sluice facilities monitoring data from 135 local sites, and effectively improving data analysis efficiency via data normalization. The utility tunnel in Xiong'an New Area relies on data fusion technology to integrate multiple types of pipeline monitoring information, compressing the traditional 2-hour fault location duration to 90 seconds.

Standardized monitoring data is fed into the intelligent model to rapidly identify anomalies and classify risk levels. Once put into operation, this approach effectively eliminates hazards, replaces inefficient manual inspections and remedies the defects of traditional management, while delivering real-time data for all types of risk response activities.

3. DYNAMIC SIMULATION AND PREDICTION: IMPROVING THE SCIENTIFIC VALIDITY OF RISK ASSESSMENT

In the full-lifecycle risk management system of infrastructure, risk assessment links the two major tasks of hazard identification and on-site risk response. Traditional evaluation mainly relies on historical static data and staff's empirical judgment, which can only conduct simple analysis for a single scenario and cannot reflect how risks evolve with changing environments and over time. The evaluation may also introduce subjective biases. By adopting high-fidelity 3D models for dynamic simulation, digital twins accurately reproduce risk evolution under complex working conditions and turn risk assessment into a data-driven, 3D visualized approach.

Building a realistic 3D digital model is necessary to complete high-precision simulation analysis work. Large and medium-sized water conservancy and transportation projects in China generally combine Building Information Modeling (BIM) and Geographic Information System (GIS) technology to build digital models, fully replicating the main body of the project, supporting facilities, and surrounding natural landforms [4]. The Yangtze-to-Han River Water Diversion Project constructs a refined model around an ultra-long tunnel, which clearly presents the surrounding rock structure, support system, and construction equipment, and can simulate the structural stress characteristics of different construction stages. The Baihetan Hydropower Station models core facilities such as dams, generator sets and power houses individually, laying a digital foundation for risk assessment under extreme conditions such as floods and water level fluctuations.

During operation, real-time on-site monitoring data is imported to update and optimize model parameters. This narrows the gap between simulation results and actual working conditions, and improves the reference value of risk assessment outcomes.

After the model is built, the industry combines multidisciplinary simulation algorithms to predict risk evolution trends. In the field of water conservancy, fluid mechanics and structural mechanics models are often combined to analyze the impacts of flood forces and water level fluctuations on dam bodies and river channels; in the field of transportation, meteorological-structural coupling models are adopted to study the stress changes of bridges and road surfaces under strong winds, heavy rainfall and other extreme weather conditions. The Kuitun River Water Conservancy Project integrates multiple simulation modules to synchronously simulate the water flow state and the operation of hydraulic structures, providing dynamic support for flood control assessment in the basin.

Based on the complete data generated by simulation, the industry can establish a hierarchical evaluation system to achieve quantitative determination of risk levels [5]. The evaluation framework is constructed by selecting core indicators such as water level, flow velocity, and gate load in the Beixi River Basin of Jiulong River. The system updates the risk index based on real-time data to facilitate management personnel to grasp the on-site risk situation. Compared with traditional manual judgment methods, digital twin simulation not only has faster analysis speed, but also reduces human error, and the analysis results match actual field conditions, helping staff formulate targeted risk response plans.

4. CLOSED-LOOP INTELLIGENT CONTROL: USING DIGITAL TWINS TO ENHANCE THE TIMELINESS OF RISK RESPONSE

Timely implementing risk response measures after risk identification and assessment is the key to reducing losses from engineering disasters. The traditional risk response mode has problems such as lagging early warning, low efficiency in plan formulation, and poor cross-departmental collaboration, which may delay hazard response and result in missed optimal handling opportunities [6]. Digital twins have built a closed-loop system of "monitoring-warning-response-feedback". This workflow covers all on-site operations, integrates scattered management nodes to form a complete workflow from hazard detection to on-site handling, and clarifies the duties and authorities of each post.

Graded warning is the fundamental link of closed-loop management. All types of projects adopt industry safety standards and historical risk records to set specific warning thresholds for different hazards. The system compares monitoring data in real time and automatically triggers alerts when thresholds are exceeded. The underground pipeline network digital twin platform in Yuzhong District, Chongqing is divided into multi-level warning standards. When pipeline leakage or road settlement occurs, the platform issues alerts hierarchically. Most initial pipeline hazards can be addressed during the warning phase. Fujian Shuikou Hydropower Station also uses digital twins to build an intelligent warning module. The system can screen for abnormal insulation of electrical equipment and other faults in advance to avoid power outages, equipment damage, and other issues.

After receiving the warning information, staff can follow the system-generated plan to implement risk response measures. The platform integrates historical cases and simulation data to help managers quickly make decisions [7]. The Jiulong River Beixi Sluice Dispatch System calculates the gate opening based on the upstream and downstream water conditions, tidal effects, and other factors. The scheduling plan simultaneously considers the two core needs of flood control safety and regional water supply. The underground utility tunnel system in Xiong'an New Area can formulate corresponding workflows and arrange Operation and Maintenance (O&M) personnel according to fault types, greatly reducing the time required for fault repair.

After risk response measures are completed, staff continue to collect on-site monitoring data. Staff compare the operating status of equipment and pipeline networks before and after risk response to verify the implementation effect of solutions, synchronize and archive data, and accumulate reusable risk response experience. The Shandong Expressway Intelligent Maintenance System uses digital twins to formulate maintenance plans, accurately calculate engineering quantities, and reasonably control resource consumption.

Closed-loop management shifts the traditional post-event handling mode and realizes early intervention in hidden hazard control to mitigate the impact of safety problems on facility operation.

5. CROSS-DOMAIN COLLABORATIVE LINKAGE: RELYING ON DIGITAL TWINS TO IMPROVE OVERALL EMERGENCY MANAGEMENT CAPABILITIES

Major infrastructure safety risks tend to spread and produce cascading effects. Such emergencies cannot be addressed by a single department alone and require joint efforts from municipal, water conservancy, transportation, emergency management and meteorological authorities. The independent business systems of various departments have formed data barriers, which not only delays emergency information transmission, but also impedes the allocation of emergency resources. Building a digital twin-based emergency command platform can break down data and business barriers between departments and enhance the level of major risk management.

The digital twin visualization interface, the core of the platform, aggregates monitoring data and business information from various fields and achieves centralized management of emergency information [8]. At present, relevant applications have been implemented in many parts of China. Chongqing has developed a comprehensive underground pipeline digital system that integrates data from multiple sources such as gas, drainage, transportation, and emergency response. When problems such as pipeline damage and road collapse occur, management personnel can view the on-site situation and the status of surrounding facilities in real time, and organize emergency operations in a unified manner. The digital twin platform built for the Beixi River Basin of Jiulong River links the businesses of water conservancy, meteorology, emergency management and other departments. It has established a collaborative mechanism covering emergency forecasting, early warning, drills and contingency plans, and plays a vital role in flood control and typhoon prevention during flood seasons.

In addition to enabling information interconnection, dynamic allocation of emergency resources is also a core function of the platform in practical application [9]. Supported by 3D models, the system accurately locates accident sites, checks nearby maintenance teams, equipment and material reserves, and plans optimal routes to complete resource scheduling efficiently. In urban flood control scenarios, this method can quickly allocate pump stations, personnel, and flood control materials, speeding up on-site rescue operations. When applied to underground pipeline repair, the system will prioritize matching the nearest maintenance team to effectively shorten response time.

Daily emergency drills can also be conducted in conjunction with this platform. Staff simulate sudden events such as floods, typhoons, and structural collapses in digital scenarios, and organize multiple departments to conduct joint exercises. Regular drills can not only verify the effectiveness of contingency plans, but also enable frontline personnel to continuously accumulate on-site risk response experience. The Yangtze River Water Resources Commission relies on the digital twin system of the basin to regularly organize flood control drills, and continuously improves the scheduling plan based on the problems encountered during the drills.

The integrated command mode changes the decentralized management pattern, reorganizes emergency procedures, and improves the emergency response capability of infrastructure projects against sudden hazards.

6. FULL-LIFECYCLE O&M: DIGITAL TWIN DRIVES LONG-TERM RISK PREVENTION AND CONTROL

Infrastructure management runs through the full-lifecycle stages including planning, construction, operation, renovation and decommissioning, and risk control also needs to run through the full-lifecycle of the project. In the past, infrastructure O&M mostly focused on post-event risk response, with insufficient early risk prevention measures and poor data sharing across different project phases. Over time, the project may develop latent structural hazards. Segmented management not only reduces operational efficiency, but also fails to conduct historical hazard tracing. Digital twin-enabled systems eliminate information silos across different project phases. This facilitates full-lifecycle risk tracking and review, and helps the industry establish unified and standardized long-term management mechanisms [10].

The electronic ledger supported by digital twins has formed a complete full-lifecycle data chain. The O&M requirements of different categories of projects have their own focuses, with water conservancy projects paying more attention to dynamic hydrological changes, while road and bridge projects focus on monitoring structural degradation. Beyond static archiving, electronic ledgers synchronize real-time monitoring data and update content dynamically as operating conditions change, allowing frontline management personnel to access data for comparative analysis at any time. At present, many infrastructure projects feature grouped layout and cross-regional management, and the traditional isolated management model is difficult to balance the operational status of the entire region. Relying on this dynamic data system, district management personnel can synchronously grasp the real-time situation of multiple projects, making daily inspections and periodic maintenance better coordinated, and effectively improving the risk coordination ability at the regional level [11].

The monitoring data and risk response records generated during project operation are continuously retained. These raw data and records not only support daily equipment O&M, but also provide reference for the construction of similar projects. Massive data accumulated over time can be compiled into a professional O&M knowledge base, which summarizes risk response strategies and routine inspection guidelines for various operating conditions. When frontline workers carry out on-site operations, they can refer to the standardized operation guidelines in the knowledge base and gradually unify the O&M standards in different areas. This experience sharing mechanism helps share practical achievements of individual projects and further maximize the value of digital management.

For old facilities that have reached their design service life, digital models can be used to comprehensively analyze the working conditions, and control plans for renovation and decommissioning stages can be developed based on historical data to mitigate potential safety risks at the source. Digital O&M abandons the traditional post-event handling mode and relies on digital ledgers for standardized data management, which can make O&M work more targeted and gradually promote the establishment of a normalized risk control system in the industry.

7. CONCLUSION

The current infrastructure industry is generally promoting digital transformation, and digital twins are gradually being applied to engineering risk management. Combining field engineering practices and following the full-lifecycle risk management process, this paper summarizes five major application modules: risk identification, assessment, risk response, emergency coordination, and full-lifecycle O&M. These modules can be adapted to the risk control work of various types of infrastructure, including transportation, water conservancy, municipal engineering, and energy.

Based on the operational status of projects in various regions and industry research results, the implementation of digital twins has effectively addressed many shortcomings in traditional infrastructure risk management. The front-end perception network lowers the risk of missed hazards, while dynamic simulation technology improves the accuracy of risk assessment. Supported by closed-loop workflows and cross-departmental collaboration mechanisms, the system speeds up emergency response and strengthens multi-party coordination. The long-term retention of data further strengthens the foundation of security management. Typical projects including the Beixi of Jiulong River, the City-wide Underground Pipeline Network of Chongqing, the Yangtze-to-Han River Water Diversion Project, and Shandong Expressway have also fully confirmed that this intelligent management mode can reduce the incidence of safety accidents, minimize economic losses, and ensure the smooth operation of large-scale infrastructure.

In actual on-site application, the promotion of this technology still faces multiple practical challenges. Small and medium-sized infrastructure projects generally have problems such as insufficient deployment of sensing equipment and unstable quality of basic data; the cost of high-precision modeling in complex engineering remains high, and lightweight modeling technologies still need to be improved; some regions have not yet established data sharing channels, and the advantages of inter-departmental collaboration have not been fully exploited.

In response to the above issues, the industry can promote optimization work from multiple dimensions: deploy additional front-end sensing devices and consolidate the foundation of data applications; intensify the R&D of lightweight models, reduce application costs for small and medium-sized projects, and formulate unified data sharing rules. In the future, with the continuous upgrading of technology and the increasing number of application scenarios, digital twins will be fully integrated into the entire process of infrastructure risk control, helping the industry move beyond traditional experience-based management and ensure the safe operation of various types of infrastructure via intelligent technologies.

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