Theory and Practice of Science and Technology
2025, VOL. 6, NO. 9, 175-178
DOI: 10.47297/taposatWSP2633-456934.20250609

Research on the Construction of a Safety Management System for Bridge Engineering

Zhitai Yu

Jiaxing Nanhu University, Jiaxing, Zhejiang, 314033, China

ABSTRACT
With the rapid development of China's transportation infrastructure construction, bridge engineering is evolving towards long spans, high piers, and complex structural forms. Inherent links in the construction process, such as aerial work, heavy lifting, and structural system transformations, are making safety risks increasingly prominent, posing severe challenges to traditional safety management models. This paper systematically analyzes the multi-dimensional risks faced by modern bridge engineering throughout its entire life cycle, including structural safety, construction dynamics, and organizational management. It points out the limitations of traditional management models in terms of systemic risk perception, information transmission efficiency, and the depth of safety culture. The study proposes the construction of a modern safety management system for bridge engineering, guided by the concept of "resilience defense," supported by "digital twin" technology, and encompassing whole-process dynamic risk control and the cultivation of a deep-seated safety culture. This system aims to achieve a fundamental shift from post-incident response to pre-event prediction and control, and from passive compliance to active immunity, providing a theoretical framework and practical path for enhancing the intrinsic safety level of bridge engineering.

KEYWORDS
Bridge engineering; Safety management; System construction; Resilience defense; Digital twin; Risk pre-control

1 Introduction

Bridge engineering, as the hub and throat of transportation networks, directly affects the safety of people's lives and property and the smooth operation of the economy and society. In recent years, although bridge construction technology has made significant progress, accidents such as structural collapses and casualties during the construction phase, as well as structural diseases and insufficient load-bearing capacity during the operation phase, still occur from time to time, profoundly revealing the extreme importance and complexity of bridge safety management. The construction process of modern bridge engineering, especially long-span cable-stayed bridges, suspension bridges, and high-pier bridges, is full of dynamic changes and uncertainties. From deep-water foundation construction, the climbing of high piers using hydraulic climbing formwork, to the cantilever assembly or incremental launching of large girder segments, and until the system transformation during the bridge completion process, each link is a severe test of technical and management capabilities. The traditional safety management model, which mainly relies on regulatory constraints and post-event experience summarization, increasingly shows its limitations in terms of slow response and one-sided perception when facing such a highly complex and dynamically changing giant engineering system. Therefore, there is an urgent need to reconstruct the paradigm of safety management in bridge engineering from a systematic and forward-looking perspective, and to build a modern safety management system that can adapt to the characteristics of modern bridge engineering, integrate advanced concepts and technologies, and cover all personnel and the entire process. This study is based on this aim, intending to deeply analyze the internal mechanism of safety risks in bridge engineering and systematically propose a construction plan for a future-oriented safety management system.

2 Core challenges in bridge engineering safety management

The challenges of safety management in bridge engineering are rooted in the complexity of its technical processes and the particularity of the site operation environment.

2.1 Concentration and high risk of technical hazards are its significant characteristics

During the construction of high piers, the climbing and stability of the formwork system, and the quality control of concrete pumping and pouring are all accompanied by extremely high risks; any negligence may lead to disastrous consequences. The construction of long-span main girders, whether using the cantilever casting, assembly method, or incremental launching method, belongs to a typical dynamic construction process. The internal forces and alignment of the structure change with the construction progress, requiring extremely high precision in construction control. The interaction between temporary construction structures and permanent structures brings great safety uncertainty. In addition, the lifting operation of large prefabricated components, such as the hoisting and positioning of large girder segments and bridge decks, not only places strict requirements on the performance of lifting equipment and the skills of operators, but its safety status is also more susceptible to interference from on-site sudden gusts and other environmental factors. These key technical activities are all in a critical state of mechanics and operation, constituting a high-incidence area for safety risks.

2.2 Complexity of Organizational Management and Information

Silos constitute the core challenge at the management level. The construction of a large bridge usually involves dozens or even hundreds of units, including general contractors, subcontractors, supervision, monitoring, and material suppliers, forming a huge, multi-level project organization network. In such a complex collaborative system, how to clearly define and effectively implement safety responsibilities among various participants, and how to achieve efficient and lossless transmission and feedback of safety information (such as design changes, monitoring data, hidden danger reports) between design, construction, and management layers, are long-standing management problems. Quality fluctuations in any part of the supply chain, such as minor defects in a batch of prestressed anchors or early cracks in a precast girder, may be transmitted through the structure, posing a potential threat to the overall safety, while vertical and horizontal management barriers may delay or even cover up the exposure of these threats.

2.3 The relevance of environmental and social risks cannot be ignored

Bridge engineering is mostly linearly distributed, often passing through complex geological areas (such as landslide and karst areas), crossing existing traffic lines (such as railways and highways), or sensitive ecological areas. The impact of construction activities on the surrounding environment, and the feedback effect of the external environment on construction safety, constitute a complex interactive system. In the operation phase, as public infrastructure, the service safety of bridges is more directly related to public safety. Factors such as vehicle overload, accidental impact (such as vehicle collision, ship collision), earthquakes, and long-term fatigue effects all place continuous management requirements on the long-term safety monitoring, inspection, and maintenance of bridges that far exceed those during the construction period.

3 Analysis of the limitations of traditional safety management models

When applied to modern large-scale bridge engineering, the inherent limitations of the traditional safety management model originating from conventional construction projects are increasingly prominent.

3.1 Static and localized risk perception

The traditional model often simplifies safety risk management into a static list of hazard sources, lacking a systematic understanding of the evolution, coupling, and transmission paths of risks in the dynamic process of bridge construction. For example, the design party may focus more on the ultimate safety of the completed bridge, while insufficiently assessing the time-varying risks brought by temporary loads and multiple structural system transformations during the construction process; the construction party may focus on the short-term safety of a single process, while lacking in-depth consideration of the potential impact of certain construction measures on the long-term performance of the structure (such as prestress loss, concrete durability). This fragmented perception leads to blind spots in risk management.

3.2 Poor information transmission

Under a huge project management structure, the traditional information flow mode relying on paper forms and meeting reports makes it difficult for hidden dangers found at the frontline, such as support deformation, abnormal cable force, or equipment failure, to be transmitted to the decision-making layer in real-time and accurately. In critical processes with short technical windows, such as the closure of the main girder and system transformation, this slow communication and decision-making feedback mechanism can easily miss the best opportunity for risk intervention, putting the project in danger.

3.3 Generally insufficient specificity and practicality of traditional emergency plans

Although the contingency plan text system seems complete, for low-probability, high-consequence extreme scenarios such as fires on high pier construction platforms, instability of large bridge erection machines, and severe imbalance during cantilever construction, there is often a lack of specific, operable disposal procedures and sufficient full-element practical drills. The "paper-based" nature of the plans makes frontline personnel prone to decision-making confusion and disordered response when facing real emergencies, unable to effectively control the spread of the situation.

3.4 Superficiality of safety culture construction

In the construction mode highly dependent on labor subcontracting, safety concepts, knowledge, and regulations are often difficult to effectively penetrate to the most basic level of operation teams. If the core value pursuit of "life first, safety first" cannot be truly internalized from the strategic slogan of project managers into the common belief, knowledge system, and behavioral habits of every frontline worker, then no matter how advanced the technical solutions and how strict the management system, they will face a sharp decline in effectiveness at the "last mile" of execution.

4 Construction path of a modern safety management system for bridge engineering

To effectively address the above challenges and systematically overcome the limitations of the traditional model, it is necessary to build a modern safety management system that adapts to the characteristics of modern bridge engineering and is forward-looking, self-adaptive, and collaborative.

4.1 Promote the transformation of safety management from "event response" to "system resilience"

The goal of safety management should no longer be merely to avoid accidents, but should be committed to building the "resilience defense" capability of the engineering system - that is, when the system suffers internal disturbances (such as discrete material properties, measurement errors) or external impacts (such as sudden equipment failure, extreme weather), it can rely on its inherent redundant design (such as safety reserves of key load-bearing members), robustness (such as the statically indeterminate characteristics of the structure), and rapid recovery mechanisms to maximize the maintenance of structural stability and the controllability of construction activities. This requires fully considering various unfavorable conditions during the construction process in the design stage and establishing an elastic emergency mechanism in the management system that allows for rapid research, judgment, and 临机 disposal in emergency situations.

4.2 Create a "digital twin" body that grows synchronously with the physical bridge and has a virtual mapping

This virtual model throughout the entire life cycle of planning, design, construction, and operation can simulate and analyze the structural response under various load combinations during the design period; during the construction period, it can integrate real-time sensor data from the Internet of Things (such as stress, deformation, displacement, temperature), dynamically simulate and warn against construction processes, realize virtual pre-evaluation and optimization of construction schemes, and perform pre-intervention for possible risks; during the operation period, it becomes the digital base for structural health monitoring and assessment management, capable of real-time damage diagnosis, performance degradation prediction, and providing a basis for scientific maintenance decision-making, thus achieving a leap from "passive maintenance" to "predictive maintenance and management".

4.3 Implement whole-process, refined risk control from survey and design to maintenance and repair

It is particularly important to strengthen front-end risk source identification. In the scheme design stage, in-depth geological surveys, environmental impact assessments, and special arguments for construction safety should be carried out. During the construction process, establish a "dynamic safety risk early warning model" based on the fusion of multi-source information to monitor major risk sources in real-time and implement hierarchical control, achieving differentiated and precise resource investment. In terms of emergency preparedness, it is necessary to deeply rely on the digital twin platform, frequently carry out immersive simulation drills and no-script emergency exercises for 特大 risk scenarios, continuously optimize emergency plans, and temper collaborative rescue capabilities.

4.4 Build a "safety value community" that transcends contract boundaries

Establish a joint safety production committee composed of core participants, and implement incentive and restraint mechanisms closely linked to the overall safety performance, deeply binding the economic interests of all parties to safety outcomes. At the same time, it is necessary to promote the safety culture from form to substance, and from the management layer to the operation layer. Widely carry out activities such as "Behavioral Safety Observation" and "Team Safety Construction" to create a safety atmosphere where all staff participate and care for each other. Use virtual reality technology to create a safety accident experience system, allowing practitioners to personally experience the serious consequences of 违规 operations. Finally, through the combined force of system design, education and training, and cultural cultivation, the pursuit of excellent safety performance becomes the intrinsic gene and professional dignity of every bridge builder and guardian.

5 Conclusion and outlook

The safety management of bridge engineering is a complex and dynamic systematic project that runs through its entire life cycle. It is not only a test of engineering technical strength but also a concentrated manifestation of modern project management level. This study demonstrates that to cope with the increasingly complex safety challenges of modern bridge engineering, we must not rely on partial improvements to traditional methods, but must carry out a systematic reshaping and profound transformation from concepts, technologies, organizations, to culture. The modern safety management system to be built should be an organic living body with "resilience defense" as the value orientation, "digital twin" as the technical core, "whole-process integration" as the control context, and "cultural synergy" as the spiritual foundation, possessing self-perception, self-decision, and self-adaptive capabilities. Only through such top-level system design and persistent practical exploration can we effectively manage risks and ensure that each bridge is not only a magnificent structure connecting geographical spaces but also a safe, durable, and reliable engineering model that can stand the test of history, providing a solid guarantee for economic and social development. Future research should further focus on specific areas such as the application of resilience design theory in bridge construction, the standardization and fusion algorithms of digital twin data, and intelligent decision support for human-machine collaboration, to continuously deepen and improve this management system.

References

[1] Liu Faquan. Digital + Internet of Things Technology in Intelligent Bridge Construction Management [J]. China Science and Technology Information, 2025(09).

[2] Ma Ningzhuo. Exploration of Problems and Countermeasures in Municipal Road and Bridge Design [J]. China Construction, 2025(09).

[3] Li Qingliang. Difficulties and Technical Countermeasures in Road and Bridge Tunnel Engineering Construction [J]. China Construction, 2025(09).

[4] Ge Huanhuan, Yue Yaoqi. Strategies for Improving the Accuracy of Concrete Strength Test and Detection for Highway Bridges [J]. China Construction, 2025(09).

[5] Gong Huangwen, Li Yufei, Wang Xi. Research on Key Monitoring Points for In-situ Demolition and Reconstruction of Expressway Bridges under Traffic Conditions [J]. China Construction, 2025(09).

[6] Wang Xiongbiao, Liu Junhua, Yan Jianpeng, et al. Analysis of Running Safety of Higher-Speed Trains on Bridges under Crosswind Conditions [J/OL]. Journal of East China Jiaotong University: 1-10[2025-09-26].

[7] Liu Aidi. Bridge Crack Recognition Based on Deep Learning [D]. Dalian: Dalian Jiaotong University, 2025.

[8] Gu Zhenbao. Research on the Weight of Technical State Evaluation of Arch Bridges Based on Arch Bridge Load Test [D]. Dalian: Dalian Jiaotong University, 2025.

[9] Zhang Yitong. Research on Bridge Deterioration Prediction and Maintenance Decision-Making in Groundwater Funnel Areas [D]. Dalian: Dalian Jiaotong University, 2025.

[10] Zheng Haoyuan. Bridge Crack Detection Technology and System Based on Multiple UAVs [D]. Jinan: Shandong Jiaotong University, 2025.