Research on Dynamic Monitoring and Early Warning Technology for Construction Safety Supervision in Building Projects

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Abstract： As the scale and complexity of China's construction projects continue to expand, construction safety issues have become increasingly prominent. Traditional safety supervision methods exhibit significant shortcomings in real-time responsiveness, accuracy, and preventative capabilities. To enhance construction safety management, this paper focuses on dynamic monitoring and early warning technologies. It systematically analyzes the current status and primary challenges of construction safety supervision, establishes a dynamic monitoring system based on IoT and big data, and incorporates multi-source data fusion with intelligent algorithms to develop risk early warning models. Building upon this foundation, a dynamic linkage strategy integrating monitoring data with safety supervision mechanisms is proposed, enabling real-time identification and tiered early warning of accident hazards. Research findings indicate that this technological framework effectively enhances the informatization and intelligence of safety supervision, improves accident prevention capabilities, and holds significant theoretical and practical value for optimizing construction safety management models.

1. Introduction

In recent years, with the continuous expansion of China's construction scale and the significant increase in project complexity, safety management issues at construction sites have become increasingly prominent[1]. Extensive research and engineering practice demonstrate that safety accidents not only cause severe casualties and economic losses but also have far-reaching impacts on corporate reputation and social stability. How to effectively enhance the scientific and forward-looking nature of construction safety supervision has become an urgent and critical issue for the construction industry[2].

Currently, China's construction safety supervision primarily relies on traditional manual inspections and post-incident rectifications[3]. This approach suffers from limitations such as monolithic monitoring methods, insufficient real-time capabilities, and delayed hazard identification, making it difficult to meet the demands of modern construction projects' dynamic and intelligent development. Concurrently, the rapid advancement of emerging technologies—including the Internet of Things (IoT), sensor networks, big data, and artificial intelligence (AI)—has provided new technical support for construction safety supervision[4]. By incorporating dynamic monitoring and early warning technologies, real-time perception and risk prediction of construction site environments, structural conditions, and operational behaviors can be achieved, thereby significantly enhancing accident prevention and emergency response capabilities.

While scholars worldwide have conducted extensive research on construction monitoring, risk assessment, and early warning models, overall challenges persist, including disconnects between theory and practice, insufficient system integration, and imperfect supervision mechanisms[5]. Addressing this situation, this paper examines a supervision model based on dynamic monitoring and early warning technologies, focusing on constructing a sensor monitoring system, risk early warning models, and dynamic coordination mechanisms[6]. Practical engineering cases are analyzed to evaluate their effectiveness. The research aims to provide theoretical foundations and practical references for the informatization and intelligent transformation of construction safety management.

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2. Analysis of Current Status and Issues in Construction Safety Supervision

The prevailing construction safety supervision model remains dominated by manual patrols and post-event inspections[7]. Supervisors primarily rely on experience to identify safety hazards at construction sites, documenting and rectifying issues through periodic or ad hoc inspections. While effective to some extent, this approach heavily depends on the professional competence and diligence of supervisors, making standardization and systematization challenging[8]. Additionally, manual inspections suffer from insufficient coverage and low efficiency, particularly in large-scale, complex projects. The calculation of the comprehensive safety risk index is shown in Formula (1):

$$R_i = \sum_{j=1}^{n} w_j \cdot x_{ij} \qquad (1)$$

The frequency and severity of construction site accidents reveal significant limitations in the traditional supervision model[9]. In recent years, frequent incidents such as falls from heights, scaffold collapses, struck-by objects, and machinery injuries have exposed critical issues including delayed risk identification and inefficient information flow during construction processes. This not only perpetuates high accident rates but also diminishes the preventive function of safety oversight, shifting focus from “post-incident accountability” to “pre-emptive control.”

Inadequate technical capabilities significantly constrain construction safety supervision. Traditional supervision relies on static reports, paper archives, and limited monitoring equipment, lacking real-time monitoring capabilities for environmental parameters, structural stresses, and work behaviors[10]. While some projects have introduced video surveillance and detection instruments, these are mostly scattered applications without unified data integration or risk assessment platforms, failing to form a complete dynamic monitoring and early warning chain.

Weaknesses persist in the institutional framework and management mechanisms of safety supervision. Some construction units prioritize progress over safety, treating safety supervision as a formality. Simultaneously, information asymmetry and blurred responsibilities between supervisors and contractors further undermine the authority and enforceability of supervision. These compounding issues urgently necessitate dynamic monitoring and early warning technologies to enhance the scientific rigor and effectiveness of construction safety supervision.

3. Theory and Methods of Dynamic Monitoring and Early Warning Technology

As construction processes grow increasingly complex, manual inspections alone can no longer meet the demands for real-time and precise safety management. The core of dynamic monitoring and early warning technology lies in leveraging the Internet of Things (IoT), sensor networks, big data, and intelligent algorithms to achieve real-time perception of multidimensional information at construction sites, risk prediction, and emergency coordination. This involves establishing a dynamic monitoring technology system covering the environment, structures, and work behaviors to ensure comprehensive and reliable data collection. Exploring early warning model methodologies based on multi-source data fusion and intelligent algorithms provides theoretical support for risk classification and dynamic threshold setting; designing supervision mechanisms and dynamic coordination strategies embeds monitoring results into construction safety management workflows, forming a closed-loop system of “monitoring-early warning-response.” These three aspects collectively constitute the technological foundation for intelligent and informatized safety supervision in construction projects.

3.1 Construction of Dynamic Monitoring Technology System

Deploying sensor networks is the core component of the dynamic monitoring system. Given the complex construction site environment and widespread distribution of various risk sources, multiple sensor types must be deployed to monitor critical factors such as structural stress, vibration displacement, environmental parameters (e.g., temperature, humidity, hazardous gas concentration), and personnel operational status. A rational deployment plan must not only cover critical areas of the construction site but also ensure sensor redundancy and fault tolerance. This guarantees the stability and integrity of the monitoring system even when some devices fail. The reliability function of construction monitoring sensors is expressed in Formula (2):

$$R(t) = e^{-\lambda t} \quad (2)$$

The probability distribution of accident occurrence is defined in Formula (3):

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (3)$$

Data acquisition and transmission technology directly determines the real-time capability and reliability of the monitoring system. Through IoT and wireless transmission technologies, real-time collection and remote transmission of sensor data can be achieved, avoiding delays and errors caused by manual intervention. Simultaneously, edge computing enables preliminary processing and filtering of raw data at the collection point, reducing redundancy and accelerating system response times to provide efficient data support for subsequent risk alerts.

Establishing a scientifically sound monitoring indicator system is fundamental to dynamic surveillance. Given the diverse and dynamic nature of risk factors at construction sites, a comprehensive, tiered indicator system must be developed across three dimensions: structural safety, environmental safety, and personnel safety. For instance, structural safety monitoring should prioritize stress and deformation of load-bearing components; environmental safety should focus on hazardous gas concentrations and noise levels; while personnel safety could incorporate positioning and behavior recognition technologies to enhance monitoring comprehensiveness and targeting. The construction safety risk index is illustrated in Figure 1:

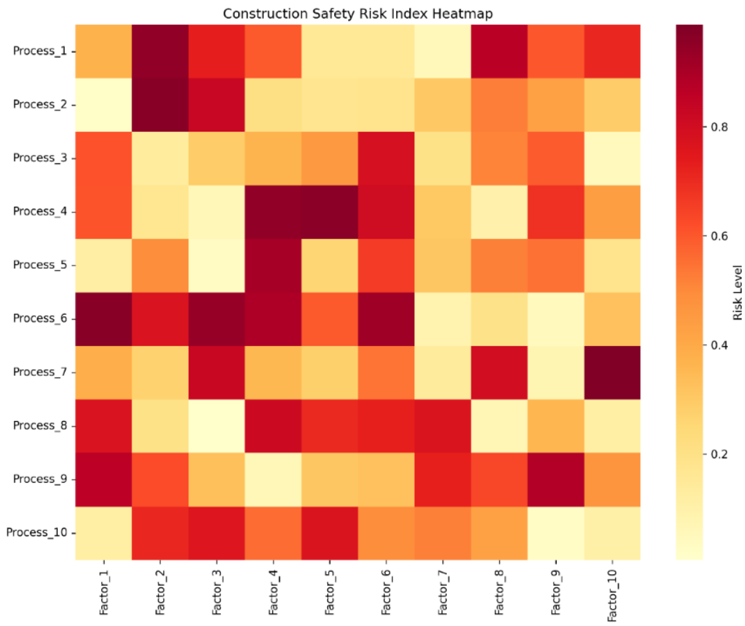

Figure 1 Construction Safety Risk Index Heatmap

Data platforms and visualization systems serve as the integration and application layer of the monitoring framework. By constructing a unified data management platform, multi-source monitoring information can be aggregated, stored, and analyzed. Combined with big data and artificial intelligence algorithms, this enables pattern recognition and trend forecasting. Simultaneously, leveraging 3D visualization and mobile terminal technologies, supervisors can gain real-time visibility into risk conditions at construction sites, achieving the dynamic supervision objectives of "visible, manageable, and controllable." This not only enhances supervision efficiency but also provides technical support for subsequent early warning and emergency response coordination.

3.2 Early Warning Models and Algorithm Applications

Risk assessment methods form the foundation for constructing early warning models. Safety risks at construction sites often exhibit ambiguity and uncertainty, making them difficult to measure precisely with a single indicator. To address this, methods such as fuzzy comprehensive evaluation, the analytic hierarchy process, and grey correlation analysis can be introduced. These techniques quantify and weight multidimensional monitoring indicators, enabling a comprehensive evaluation of risk levels. These approaches effectively address the challenges of diverse indicators and incomplete data in construction environments, providing a scientific basis for subsequent early warning. The safety warning threshold is determined according to Formula (4):

$$T = \mu + k \cdot \sigma \quad (4)$$

Intelligent algorithms play a central role in risk prediction and early warning. With the advancement of big data technology, machine learning and deep learning are increasingly applied to safety monitoring. By jointly modeling historical accident data and real-time monitoring data, algorithms can automatically identify potential hazard patterns, enabling advance prediction of accidents. For instance, neural network-based models can uncover complex nonlinear relationships, while support vector machine models excel at classification and prediction under small-sample conditions, thereby enhancing the accuracy and adaptability of early warnings.

Multi-source data fusion technology provides more comprehensive support for early warning models. Construction sites generate diverse data streams, encompassing structural sensors, environmental monitoring equipment, video surveillance, and worker behavior recognition. Methods like Bayesian networks, Kalman filtering, and multimodal deep learning enable unified modeling and dynamic fusion of these disparate sources, thereby enhancing the reliability and robustness of early warning outcomes. This integration not only improves risk identification accuracy but also reduces misclassification rates caused by anomalies in single data streams.

Dynamic threshold setting is a critical component for the practical application of early warning systems. Traditional fixed thresholds often struggle to adapt to the complex and variable conditions of construction sites, frequently leading to false positives or false negatives. By introducing adaptive threshold setting methods that combine real-time statistical features with historical patterns, risk levels can be dynamically adjusted. For instance, the system can automatically modify threshold ranges during different construction phases or under varying weather conditions to ensure warnings better align with actual circumstances. This mechanism endows the warning model with scientific rigor, flexibility, and practical utility.

3.3 Dynamic Coordination with Supervision Mechanisms

Refining supervision mechanisms provides the institutional foundation for dynamic monitoring and early warning systems to function effectively. Traditional construction safety supervision primarily relies on post-event inspections and rectifications, lacking foresight and real-time responsiveness. With the integration of dynamic monitoring technologies, supervision should transition toward comprehensive, real-time control models. This necessitates clearly defining the responsibilities of supervision units and construction units at the institutional level, strengthening safety accountability mechanisms, and ensuring supervision data becomes a crucial basis for decision-making and execution. The optimization objective function for dynamic monitoring is given in Formula (5):

$$P(Y = 1|X) = \frac{1}{1+e^{-(\beta_0+\beta_1 X_1+\cdots+\beta_n X_n)}} \quad (5)$$

The integration of monitoring data into the safety supervision process is key to transforming supervision methods. By establishing unified data interfaces and information platforms, supervisors can access real-time dynamic information from construction sites and organically combine it with routine inspections, risk assessments, and safety briefings. This mechanism not only enhances the scientific rigor and precision of supervision but also provides robust data support for timely identification and correction of safety hazards. The dynamic prediction of construction accident probability is presented in Figure 2:

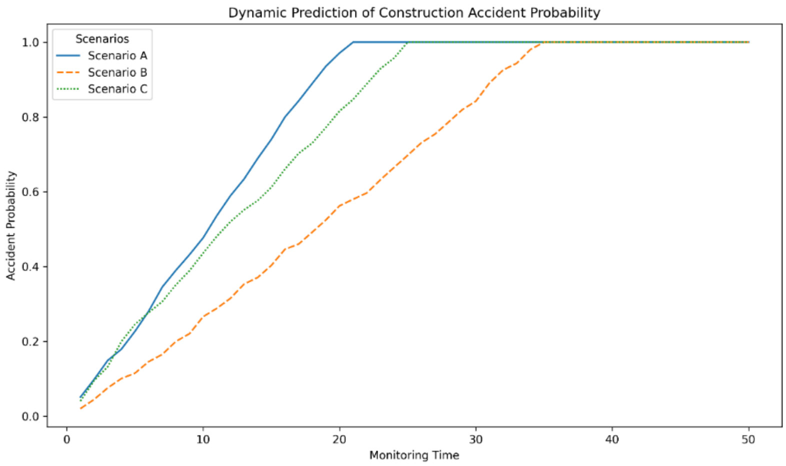

Figure 2 Dynamic Prediction of Construction Accident Probability

The emergency response linkage mechanism is an indispensable component of the supervision system. When the monitoring system triggers an alert, a multi-tiered coordinated response should be immediately activated, encompassing on-site handling by the construction unit, oversight verification by the supervision unit, and emergency coordination by the management department. By establishing a closed-loop mechanism of “monitoring-alert-response-feedback,” response times to incidents are shortened, the potential for risk propagation is reduced, and a shift from reactive management to proactive prevention is achieved.

Information sharing and collaboration mechanisms further enhance the effectiveness of dynamic coordination. Through data interoperability with government regulatory platforms, industry databases, and third-party inspection agencies, a cross-entity, cross-level safety supervision network is formed. This multi-party collaborative model facilitates comprehensive coverage and multidimensional oversight of construction safety supervision, while also providing a robust institutional framework and technological foundation for the digital and intelligent advancement of safety management in the construction industry.

4. Application Research on Dynamic Monitoring and Early Warning Systems for Construction Safety Supervision

The design of the system's overall architecture forms the foundation for achieving dynamic monitoring and early warning of construction safety. The system typically adopts a multi-layer architecture comprising the “perception layer—transmission layer—application layer—decision layer.” The perception layer employs multi-type sensors for real-time collection of construction environment data, structural status, and personnel activity. The transmission layer leverages wireless communication, edge computing, and cloud platforms for data transfer and preliminary processing. The application layer utilizes big data and AI algorithms for comprehensive analysis and risk prediction. The decision layer provides decision support and emergency response plans for supervisors and managers. This layered architecture ensures operational efficiency and stability while enhancing scalability and cross-project applicability. The correlation model between monitoring variables and safety outcomes is described in Formula (6):

$$\Delta S = \alpha(S_{target} - S_{actual}) \quad (6)$$

The rational division of functional modules is crucial for practical implementation. The system should include data acquisition and processing, risk assessment and early warning, supervision coordination and emergency response, and visualization modules. The data acquisition and processing module focuses on standardizing and integrating multi-source heterogeneous data to prevent data silos. The risk assessment and early warning module employs multi-level algorithmic models for real-time calculation and risk classification of monitored data. The supervision coordination and emergency response module rapidly establishes a collaborative response mechanism between construction and supervision units upon risk signal activation. The visualization module employs 3D modeling, virtual simulation, and large-screen displays to enable supervisors to intuitively grasp the dynamic safety status of the construction site.

Practical engineering applications have validated the feasibility and effectiveness of this system. For instance, during a major bridge construction project, sensors deployed on critical load-bearing components, deep excavation slopes, and tower cranes enabled real-time monitoring of key parameters like stress, settlement, and tilt angles. When readings approached or exceeded dynamic thresholds, the system automatically triggered alerts, simultaneously pushing notifications to mobile devices, the supervision platform, and the emergency command center. On-site construction personnel could immediately implement reinforcement or halt operations, while supervisors verified the execution of these measures, forming an efficient closed-loop risk control system.

In pilot projects for high-rise construction, the system integrated video recognition technology with personnel positioning systems. This not only monitored whether workers entered hazardous zones but also identified violations such as failure to wear safety helmets or overloaded transport. This integration of behavioral recognition and dynamic monitoring enables early detection and correction of safety hazards, significantly reducing accident risks caused by human violations. Following system implementation, violation rates and accident occurrences at construction sites decreased markedly, while supervision efficiency improved by approximately 30%.

Further analysis indicates the system delivers substantial economic and social benefits. On one hand, the dynamic monitoring and early warning system effectively reduces economic losses from safety incidents and mitigates project delay risks. Through real-time information sharing and coordinated mechanisms, supervisors can manage sites more efficiently, optimizing human resource allocation. The system application fosters a safety-conscious culture within construction enterprises, promoting a shift from “reactive response” to “proactive prevention” and elevating the industry's overall safety management standards.

However, challenges persist: equipment deployment and maintenance costs remain high, posing investment pressures for some small and medium-sized construction enterprises; the massive scale of data processing and storage demands greater computational power and network stability from the platform; and insufficient familiarity with the new technology among some supervisors and construction personnel has hindered the system's full utilization. Further integration of artificial intelligence, BIM and GIS fusion, digital twins, and 5G technology is needed to enhance the system's intelligence, visualization, and real-time interactive capabilities. Policy guidance and industry standardization should drive broader adoption of this system, providing more comprehensive technical support for construction safety management.

5. Conclusion

Analysis of current construction safety supervision practices and research into dynamic monitoring and early warning technologies reveal limitations in traditional approaches—reliance on manual labor, insufficient real-time capabilities, and delayed hazard identification—which struggle to meet the demands of modern large-scale and complex construction projects. Dynamic monitoring and early warning technologies based on IoT, sensor networks, big data, and artificial intelligence offer new approaches and tools for construction safety management. By establishing a multidimensional monitoring indicator system, constructing intelligent early warning models, and forming a coordinated mechanism between supervision and construction, the efficiency of hazard identification and the level of risk prevention and control can be significantly enhanced. Practical engineering application cases demonstrate that this system can effectively reduce accident rates, improve supervision efficiency, and show promising prospects in terms of economic and social benefits.

However, research also identifies current limitations in technology application, such as high equipment investment and maintenance costs, room for improvement in data processing capabilities, and demanding operational skill requirements. Further efforts should focus on integrating dynamic monitoring and early warning technologies with cutting-edge approaches like BIM, GIS, and digital twins to advance system intelligence, standardization, and widespread adoption. Supported by policy regulations and industry standards, a new collaborative framework for safety supervision should be established. This will provide a more robust foundation for the digital and intelligent transformation of construction safety management.

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