Research on Supervision Strategies for Quality Monitoring and Risk Early Warning in High-Rise Construction

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Abstract: With the acceleration of urbanization, high-rise buildings have assumed increasingly vital roles in engineering projects. However, the complex construction processes and numerous procedures involved in high-rise construction, coupled with the hidden and sudden nature of quality issues and safety risks, present new challenges for project management and supervision. How to enhance construction management through effective quality monitoring and risk warning mechanisms has become a critical issue requiring urgent resolution in the construction engineering field. This paper focuses on high-rise building construction, systematically analyzes the core elements of quality monitoring, constructs a full-process supervision strategy based on risk identification, risk assessment, and warning models, and proposes corresponding risk intervention and emergency response measures. Building upon this foundation, the feasibility and effectiveness of the proposed strategy in actual construction are validated through case studies of typical projects. The research demonstrates that a scientific quality monitoring system combined with a multi-level risk early warning system can significantly reduce construction risks, enhance overall project quality and safety levels, and provide theoretical reference and practical guidance for high-rise building construction supervision.

1. Introduction

With the continuous advancement of urbanization, high-rise buildings have become the primary form of urban spatial development. Due to their complex structures, extended construction cycles, and high technical requirements, construction quality and safety issues in high-rise buildings have gradually become a focal point in the engineering construction field[1]. Compared to ordinary buildings, high-rise construction involves more specialized processes and cross-disciplinary operations. Errors in any may lead to quality defects or even major safety accidents[2]. Achieving comprehensive quality monitoring throughout construction and implementing scientific risk early warning systems are critical to ensuring smooth project execution and long-term operational safety.

Domestic and international research has explored construction quality management, risk control, and supervision models. Overseas studies emphasize systematic and information-based risk management systems, such as big data and AI-driven construction risk identification and prediction[3]. Domestic research focuses more on on-site quality monitoring methods, the implementation of supervision responsibilities, and the application of BIM technology during construction. Existing research requires further refinement in comprehensively addressing the unique complexities of high-rise construction, enhancing the dynamism of early warning models, and strengthening the systematic nature of supervision measures[4].

This paper focuses on high-rise construction, examining quality monitoring and risk early warning dimensions. It analyzes core elements of quality monitoring in high-rise construction, develops a supervision strategy integrating risk identification, assessment, and early warning models, and validates the strategy's feasibility and effectiveness through case studies[5]. This paper aims to provide theoretical support and practical references for quality management and supervision in high-rise

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construction, driving optimization and innovation in the construction industry's quality monitoring and risk early warning systems[6].

2. Core Elements of Quality Monitoring in High-Rise Construction

The complexity of the construction process necessitates systematic quality monitoring. High-rise buildings typically feature large structural volumes and multiple construction processes, involving cross-disciplinary coordination among civil engineering, MEP installation, curtain walling, and other specialties[7]. Minor deviations in any construction phase may be amplified in subsequent stages, ultimately compromising overall structural safety and functional integrity. Therefore, quality monitoring must span the entire construction lifecycle—from material delivery and process handover to finished product protection—forming a closed-loop quality control system that ensures compliance with design specifications and regulatory standards at every stage[8]. The overall monitoring efficiency can be expressed mathematically as follows:

$$D=\frac{\left|X-X_0\right|}{X_0}\times 100\% \qquad (1)$$

Critical areas and specialized processes demand heightened monitoring. High-rise construction imposes stringent technical requirements on foundation works, main structure erection, and fireproofing, waterproofing, and seismic resistance[9]. For key operations like deep excavations, super-long spans, reinforced concrete core walls, and elevated work, supervisors must intensify process inspections and sampling frequencies[10]. Implementing specialized monitoring measures prevents localized construction defects from escalating into project-wide risks. The relationship between project risk factors and monitoring efficiency is illustrated in Figure 1:

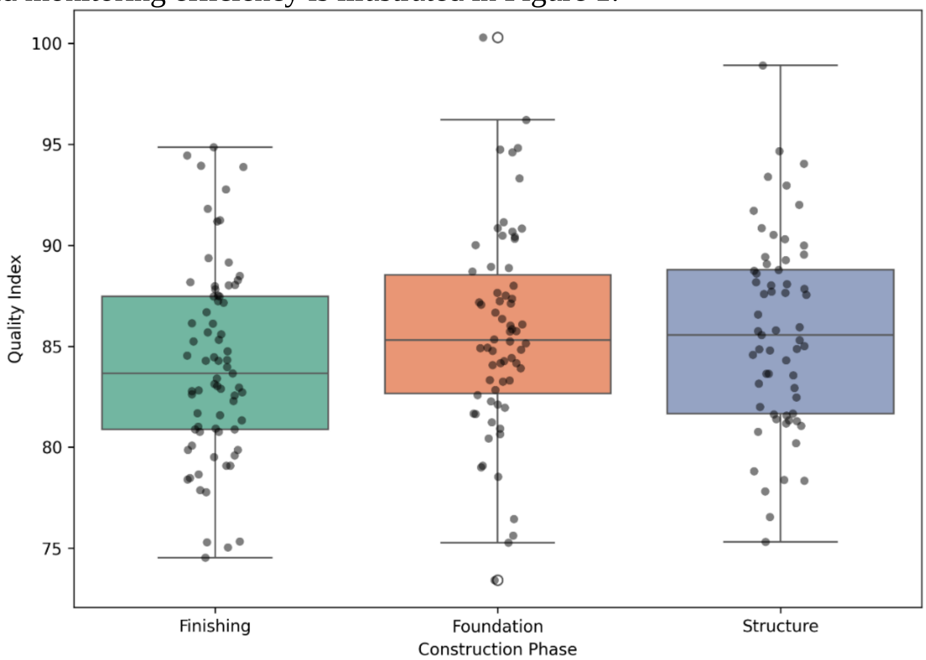

Figure 1 Quality Index Distribution by Construction Phase

The application of information technology and intelligent tools enhances the scientific rigor of quality monitoring. BIM technology, IoT sensors, and drone inspections are widely adopted in high-rise construction, enabling real-time data collection and dynamic monitoring. Continuous tracking of critical indicators—such as structural stress, temperature variations, and settlement displacement—allows timely identification of potential hazards, providing data-driven support for quality control. The integration of big data analytics and AI predictive models further enhances precision in construction quality monitoring decision-making.

Robust supervision mechanisms and management systems form the foundation of quality control. High-rise construction quality management relies not only on on-site inspections and technical tools but also requires comprehensive institutional support at the organizational level. Supervision units should establish a tiered responsibility system, clearly defining monitoring duties for each position, improving information reporting and feedback mechanisms, and promoting collaboration among construction, design, and supervision entities. Emphasis should be placed on training construction personnel and enhancing quality awareness, jointly safeguarding project quality through both management and cultural approaches.

3. Construction Risk Early Warning Mechanism and Supervision Strategy

The construction process of high-rise buildings is characterized by high risk and uncertainty. Any quality defect or management oversight may lead to severe safety and economic losses. Establishing a scientific risk early warning mechanism and a systematic supervision strategy is crucial. Construction risk early warning not only involves the comprehensive identification and classification of potential risks but also requires reasonable assessment and model construction to predict their probability of occurrence and impact severity. Based on this, practical supervision countermeasures and emergency measures should be formulated. This paper analyzes three key aspects—risk identification and classification, risk assessment and early warning models, and supervision strategies and countermeasures—to establish a comprehensive high-rise construction risk early warning and supervision system.

3.1 Risk Identification and Classification

Risk identification forms the foundation of the early warning mechanism for high-rise construction. Given the complex structures, frequent overlapping work processes, and unique operational environments characteristic of high-rise buildings, the potential risk factors encountered during construction are highly diverse. Risk identification requires not only technical and process-level analysis but also comprehensive assessment considering management, environmental, and external conditions. Only through systematic identification can reliable grounds be established for subsequent risk classification and early warning. The optimization of resource allocation is formulated by the following equation:

$$P(R)=\frac{N_r}{N_t} \qquad (2)$$

The probability of project delay can be modeled as shown below:

$$R=\sum_{i=1}^{n} w_i \cdot r_i \qquad (3)$$

From a structural and process perspective, common risks in high-rise construction primarily include foundation engineering risks, structural stability risks, and specialized process risks. Deep foundation pit construction may encounter collapse or seepage issues; steel structure hoisting may involve component deformation or connection failure; and large-volume concrete pouring may result in cracking. Failure to control these risks promptly will directly threaten the overall quality and safety of the project. The clustering of monitoring strategies across different project phases is demonstrated in Figure 2:

Figure 2 Correlation Matrix of Construction Risk Indicators

From a management and organizational perspective, construction risks often stem from issues such as unreasonable scheduling, inconsistent workforce quality, and inadequate supervision. Delayed material supply may cause project delays, insufficient safety training may lead to falls from heights, and chaotic site management may disrupt construction sequences. While less immediately apparent than technical risks, these management risks are significant contributors to accidents.

External environmental and societal factors also impact high-rise construction, including weather, geological conditions, and policy regulations. Extreme weather can halt tower crane operations or compromise concrete curing quality, while adverse geological conditions may cause foundation settlement. Policy adjustments or stricter oversight can elevate compliance risks. Effective risk identification requires a multidimensional framework encompassing technical, managerial, environmental, and policy dimensions to achieve comprehensive coverage of all potential sources.

3.2 Risk Assessment and Early Warning Model

Risk assessment is a critical component of construction risk management, centered on quantifying the probability of risk events and their potential impacts. High-rise construction involves numerous uncertainties, necessitating a combined qualitative and quantitative approach during risk assessment. Experts evaluate the nature and severity of potential risks based on experience, then employ tools like the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation Method for quantitative calculations, yielding scientifically sound risk assessment outcomes. The effectiveness index of monitoring strategies is calculated using the following formula:

$$\mu(x)=\frac{1}{1+e^{-k(x-x_0)}} \qquad (4)$$

The relationship between cost and quality is described by the equation:

$$\beta=\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}} \qquad (5)$$

Establishing a risk assessment indicator system is fundamental to achieving scientific early warning. For high-rise construction, this system must encompass multiple dimensions including structural safety, material quality, construction environment, personnel management, and schedule control. By creating multi-level, multi-dimensional evaluation metrics, the system comprehensively reflects the status of potential risks throughout the construction process. Given the interdependencies among indicators, weighting allocation and comprehensive calculations are necessary to form a rational risk assessment model.

The establishment of an early warning model enables dynamic risk monitoring and tiered management. Construction site data is characterized by real-time fluctuations. By integrating IoT sensors, monitoring instruments, and information platforms, critical data can be continuously collected and compared against the early warning model. When monitored values exceed preset thresholds, the model automatically triggers alerts of varying severity levels. If settlement observation data exceeds permissible limits, yellow or red alerts can be immediately activated, enabling supervisors and construction personnel to take timely countermeasures.

Predictive models based on big data and artificial intelligence offer new approaches to risk warning. By mining and analyzing historical construction project data, risk prediction models are trained to identify potential hazards and provide advance warnings. Machine learning algorithms uncover patterns within complex datasets, enabling trend-based predictions of high-rise construction risks. These models enhance the accuracy and timeliness of risk warnings, providing decision-making support for optimizing supervision strategies.

3.3 Supervision Strategies and Countermeasures

Establishing a tiered supervision intervention mechanism is crucial for risk management. Based on the risk warning model's tiered results, supervision units can implement interventions of varying intensity. For low-level risks, routine inspections and regular spot checks suffice. Medium-level risks warrant increased testing frequency and require contractors to develop specialized remediation plans. High-level risks necessitate immediate work stoppage orders or emergency plan activation to prevent escalation. Tiered management not only enhances the precision of supervision but also prevents resource wastage. The integrated risk assessment model can be expressed as follows:

$$L(R)=R<R_{1}\\R_{1}\leq R<R_{2}\\R\geq R_{2} \quad (6)$$

Refining emergency response mechanisms effectively mitigates damage from sudden risks. Common accidents in high-rise construction—such as falls from heights, crane malfunctions, or sudden groundwater surges in excavation pits—all demand rapid emergency measures. Supervision units should collaborate with contractors to establish contingency plans, clearly defining personnel responsibilities, material preparations, and response procedures. Regular drills must be conducted to ensure efficient, orderly responses during emergencies, minimizing losses to the greatest extent possible.

Strengthening information-based supervision methods is a key pathway to enhancing risk response efficiency. With the widespread application of technologies like BIM, IoT, and big data, supervision work can achieve information sharing and dynamic oversight. Utilizing BIM platforms enables visual management of the construction process, sensors facilitate structural health monitoring, and big data analytics provide dynamic assessments of construction progress and quality. These information-based methods enhance the scientific rigor of supervision work, offering real-time, precise data support for risk response.

Enhancing personnel competence and management coordination forms the foundation for implementing supervision strategies. Supervision units should intensify training for professionals to improve their capabilities in risk identification, emergency response, and IT application. Collaborative mechanisms should be established among construction, design, and supervision units to create a multi-party risk prevention and control framework. Only with dual safeguards of technical measures and organizational management can supervision strategies be effectively implemented, thereby comprehensively elevating the quality and safety standards of high-rise construction.

4. Case Study and Practical Application

To validate the practical feasibility of construction quality monitoring and risk warning strategies, a super-high-rise complex project was selected as a research case. This project, exceeding 200 meters in total height, featured a lengthy construction cycle involving cross-disciplinary operations across civil engineering, MEP installation, and curtain walling. Given the project's large scale and complex construction environment, the client prioritized quality control and risk prevention from the outset.

They required the supervision unit to establish a comprehensive quality monitoring system and utilize information technology for dynamic risk early warning. This case study is both typical and representative, offering significant practical value for research on supervision strategies.

Regarding construction quality monitoring, the supervision unit developed specialized inspection plans for critical phases such as material delivery, structural construction, concrete pouring, and steel structure installation. All raw steel materials required third-party inspection approval before use. During large-volume concrete pouring, sensors continuously monitored internal temperature and stress changes to prevent cracking. For main structure construction, a BIM platform verified component dimensions and installation positions against design drawings. These measures ensured controllable quality throughout construction and reliable outcomes.

For risk early warning and control, the project team established a tiered alert mechanism combined with dynamic predictions using big data analysis and AI models. By continuously collecting and analyzing real-time data on site settlement, crane operation, and meteorological conditions, the supervision system provides advance warnings of potential risks. When monitoring data indicated foundation pit displacement approaching warning thresholds, the system automatically issued an orange alert. The supervision unit immediately required the contractor to reinforce the support structure and restricted operations in the affected areas, successfully averting the risk of foundation pit instability. Additionally, regular safety training and emergency drills enhanced construction personnel's risk awareness and emergency response capabilities.

The project achieved its quality objectives without major quality or safety incidents during construction, maintaining progress within controlled parameters. Practice demonstrates that a scientific quality monitoring system coupled with a multi-tiered risk warning mechanism not only enhances controllability during construction but also significantly reduces the probability of sudden risks. The case also highlights the need for site-specific supervision strategies. For instance, under complex geological conditions or extreme climatic environments, warning models and supervision measures require further optimization. Deeply integrating supervision strategies with actual project conditions is a crucial pathway for advancing high-rise construction management standards.

5. Conclusion

High-rise construction demands heightened standards for quality assurance and risk management due to its large scale, complex processes, and extended timelines. Research indicates that comprehensive quality monitoring must span the entire construction cycle, with critical focus on key stages and specialized procedures to effectively safeguard overall project quality and safety. Concurrently, supervision must integrate conventional methods with information-driven and intelligent technologies to enable dynamic monitoring and scientific decision-making. Establishing a risk early-warning mechanism is central to enhancing construction safety. A multidimensional monitoring system based on risk identification, assessment, and early-warning models enables tiered risk management and dynamic alerts. This empowers supervision units to intervene at the earliest stages of risk emergence, preventing accidents from escalating. Practical cases demonstrate that this mechanism significantly reduces risk occurrence probabilities in real-world applications, ensuring construction quality and progress remain under control.

The effective implementation of supervision strategies relies on dual support from organizational management and personnel competence. Supervision units should strengthen institutional frameworks, enhance collaborative mechanisms, and prioritize skill development and quality awareness training for professionals. Looking ahead, with the advancement of artificial intelligence, big data, and smart construction technologies, quality monitoring and risk warning models for high-rise construction will become more precise and efficient, providing a more robust foundation for construction project management.

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