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Impact of Safety Management Measures on Engineering Risks at Construction Sites

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Abstract: The risk prevention and control in construction projects heavily relies on the systematic optimization of on-site safety management measures. Studies show that technical means such as safety education and training, dynamic monitoring of hazard sources directly reduce the probability of accidents. The full-staff responsibility system and performance evaluation indirectly enhance the resilience of risk prevention and control by shaping a culture of risk awareness. Based on the new local safety officer qualification regulations and the mandatory promotion of digital tools by 2025, case analysis indicates that the collaborative application of BIM and AI early warning platforms can reduce the risk of falls from height by 45%. The rigid constraints of systems, technological innovation and iteration, and the cultivation of cultural ecosystems form a multi-dimensional collaborative mechanism. In the future, it is necessary to integrate intelligent perception with green construction standards to achieve an upgrade in risk management efficiency.

Keywords: Construction site safety management; Project risk control; Multi-dimensional coordination mechanism

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1. Introduction

The high risk of construction projects stems from their complex environmental interactions and dynamic operational characteristics. In recent years, frequent safety accidents have highlighted the limitations of traditional management models. With the intensive introduction of new regulations in 2025, such as the requirement of Guangzhou Housing and Urban Rural Development Bureau that safety officers must have intermediate professional titles or professional qualifications, and all professional contracting units will be included in the unified management of the general contractor, the professionalization and synergy of the safety management system have been elevated to a new height. The policy of mandatory promotion of buckle scaffolding in Jiangsu Province further demonstrates the core role of technical standardization in risk prevention and control. Although existing research has revealed the direct impact of security management measures on risks, there is still a lack of systematic exploration of the collaborative mechanisms of institutional innovation, technological iteration, and cultural shaping. The new regulations emphasize the primary responsibility of the construction unit and the independence of third-party supervision, while promoting the deep application of digital tools such as BIM and

AI warning platforms, providing new opportunities for the integration of theory and practice. This study aims to analyze the role path of multidimensional security management measures and propose optimization strategies that are adapted to the trends of intelligence and greening, based on policy guidance and empirical cases. It provides theoretical support and practical reference for improving the efficiency of industry risk management and control.

2. Overview of risk and safety management in construction engineering

2.1. Characteristics and classification of construction project risks

Construction project risks are characterized by their diversity, dynamism, and complexity, with sources that can be categorized into four main types: natural, technological, managerial, and anthropogenic [1]. Natural risks stem from uncontrollable environmental factors such as geological conditions and meteorological disasters. For example, landslides caused by earthquakes or heavy rainstorms can severely impact construction sites. Technological risks are directly related to design flaws, improper construction techniques, or equipment failures. Structural calculation errors, for instance, can lead to insufficient bearing capacity, jeopardizing the integrity of the project. Management risks arise from organizational coordination failures, inadequate safety systems, or inefficient resource allocation. Compressed schedules, for example, can lead to safety hazards due to rushed work. Human risks involve operational errors, illegal operations, or weak safety awareness, often manifested as failure to wear protective equipment during high-altitude operations.

To effectively manage these risks, it is essential to quantify their potential impact. Probability impact matrices are widely used for risk level classification. By evaluating the cross-results of the probability of risk events occurring (low, medium, high) and potential losses (mild, moderate, severe), risks can be classified into acceptable, monitored, or prioritized intervention levels. This classification provides a scientific basis for risk management decisions, enabling project managers to allocate resources efficiently and implement targeted mitigation measures. Additionally, continuous monitoring and regular risk reassessment are crucial to adapt to changing conditions and ensure the ongoing safety and success of construction projects.

2.2. Connotation and framework of construction site safety management

The core objective of construction site safety management is to systematically control hazards, covering four major elements: system, technology, personnel, and environment. At the institutional level, it is necessary to establish a safety responsibility system and operating procedures, clarify the responsibilities of all parties, and standardize the operation process. At the technical level, reliance is placed on safety protection facilities, monitoring equipment, and information tools (such as BIM technology) to reduce operational risks. Personnel management focuses on safety training and behavior supervision, enhancing the skills and risk awareness of practitioners. Environmental management ensures physical space safety through site planning, ventilation and lighting optimization, and waste disposal. Compared to domestic and international standards, the Occupational Safety and Health Administration (OSHA) in the United States emphasizes immediate risk management at work sites, with a focus on technical specifications and accident accountability; The Chinese "Code for Quality Management of Engineering Construction Enterprises" (GB/T 50430) places more emphasis on the full cycle coverage of the management system, requiring enterprises to establish a closed-loop mechanism from planning, implementation to improvement. Although the two types of standards have different focuses, both aim to reduce the accident rate as the core goal, reflecting the multidimensional integration of safety management theory and practice [2].

3. The direct impact mechanism of safety management measures on engineering risks

3.1. Construction of risk prevention mechanism

The risk prevention mechanism reduces the probability and degree of harm of potential risk events through proactive intervention. Safety education and training are the core means of reducing human errors. Systematic training courses can enhance the awareness of operators on operating procedures, the use of safety protective equipment, and emergency evacuation procedures, thereby correcting habitual violations [3]. For example, specialized training for high-altitude operations can reduce the rate of falling accidents by more than 30%. Hazard identification and dynamic monitoring technology systematically analyzes the physical environment and operation process of the construction site, identifies high-risk nodes such as collapse, electric shock, and mechanical injury, and uses IoT sensors, drone inspections, and BIM models to track changes in hazard status in real time. The data feedback of dynamic monitoring technology can support managers to adjust construction plans or suspend high-risk operations in a timely manner, forming a closed-loop management of "identification warning disposal", and increasing the elimination rate of accident hazards by 40%–60%.

3.2. Risk control effectiveness of accident emergency response

The formulation and exercise of emergency plans directly affect the severity of the consequences of accidents. A scientifically designed contingency plan should comprehensively cover various accident types, clearly define the division of responsibilities among personnel, establish effective communication processes, and specify safe escape routes. The operability of such plans must be verified through regular simulation exercises [4]. Research has shown that projects conducting quarterly emergency drills can significantly shorten the average response time for accidents by up to 50% and reduce the casualty rate by over 25%. These findings underscore the importance of regular training and preparedness in mitigating the impact of emergencies.

The optimization strategy for emergency rescue resource allocation emphasizes the rationality of resource layout and the ability to quickly allocate resources when needed. This includes strategically setting up emergency stations, firefighting equipment, and escape routes in layers throughout the construction site. Additionally, GIS technology is utilized to analyze the accessibility of external rescue resources such as medical and firefighting services within the area, ensuring that help can arrive promptly. The introduction of a modular emergency material reserve and intelligent scheduling system further enhances preparedness. This system ensures that rescue equipment and personnel can reach the core area of an incident within 15 minutes of an accident occurring, thereby maximizing the control of the spread of accident losses and minimizing potential damage and harm. By integrating these advanced strategies, construction sites can significantly improve their emergency response capabilities and overall safety performance.

4. Analysis of the indirect impact of safety management measures on engineering risks

4.1. The synergistic effect of management behavior and risk culture

4.1.1. Strengthening the risk awareness of all employees through the safety responsibility system

The safety responsibility system transmits the pressure of risk prevention and control to individuals step by step by clarifying job responsibilities and reward and punishment mechanisms. The management and frontline employees jointly undertake safety goals, forming a "horizontal to edge, vertical to bottom" responsibility network. For example, project managers are responsible for overall safety performance, while team leaders supervise specific operational compliance [5]. Responsibility decomposition combined with regular safety meetings and accident retrospective analysis encourages operators to actively identify hidden dangers and report anomalies, transforming passive compliance with rules into active participation in risk management. Research has shown that implementing a full staff safety responsibility system can increase the self-inspection and self-correction rate of hidden dangers by more than 50%, and shorten the timeliness of accident reporting by 70%. The accountability mechanism strengthens its binding force through economic penalties or job adjustments, avoiding the breeding of lucky mentality and gradually shaping a cultural consensus of "everyone manages safety".

4.1.2. The normative effect of safety performance assessment on construction behavior

Safety performance assessment incorporates risk control indicators into the employee evaluation system, driving behavior change through quantitative scoring and salary linkage. The assessment covers dimensions such as the usage rate of personal protective equipment, the number of violations, and the efficiency of hazard rectification. A dynamic evaluation system is used to identify high-risk individuals or teams [6]. For example, after the introduction of a safety credit system in a certain tunnel project, violations of electricity usage were reduced by 80%, and the coverage of safety inspections increased to 95%. The performance feedback mechanism stimulates healthy competition among teams through public ranking and targeted training, while providing a basis for management to optimize resource allocation. Long term practice has shown that continuous safety performance evaluation can increase the standardization rate of construction behavior by 60%, indirectly reducing the derivative risks caused by operational arbitrariness.

4.2. Enhancement of technological innovation and risk control capability

4.2.1. Application cases of intelligent security monitoring technology

The fusion application of BIM technology and IoT sensors reconstructs the risk management mode through digital modeling and real-time data collection. In a super high-rise project in Shanghai, the BIM model integrates structural stress, wind speed, and personnel positioning data, and the system automatically warns of the risk of tower crane overload or lack of edge protection, reducing the high-altitude falling accident rate by 45%. IoT devices such as smart helmets have built-in GPS and vital sign monitoring functions, which can track the location and health status of personnel in real time. Based on this, heatstroke workers can be evacuated in a timely manner during a subway construction to avoid casualties. This type of technology transforms post disposal into pre prediction through multi-source information fusion and intelligent algorithms, significantly improving the accuracy and response speed of risk identification [7].

4.2.2. The substitution effect of mechanized construction on high-risk operation risks

Mechanized construction reduces the probability of personnel being exposed to hazardous environments from the source by replacing manual labor in high-risk processes with equipment. For example, in bridge engineering, automated welding robots are used for steel box girder operations to eliminate the risks of falling and burns caused by manual high-altitude welding; The application of full face rock boring machine (TBM) in shield tunnel excavation reduces traditional blasting operators by 90%. In a deep foundation pit project, intelligent unmanned excavators and 3D scanners work together to achieve zero manual excavation of soil, and the risk of collapse accidents approaches zero. Mechanization not only reduces the probability of direct injury, but also reduces human errors through standardized operations, and its comprehensive risk control efficiency is 3–5 times higher than traditional manual modes.

5. Empirical research and strategic suggestions on optimizing security management measures

5.1. Typical case analysis

5.1.1. Successful case: Risk reduction effect of safety management measures in a high level project

A landmark super high-rise project in a certain city achieves precise risk control through the integration of BIM technology, real-time monitoring of the Internet of Things, and a full staff safety responsibility system [8]. During the construction period, the BIM model dynamically simulates structural stability and conflicts with the construction process, avoiding 12 design collision risks in advance; IoT sensors monitor tower crane load and wind speed exceeding limits, triggering automatic shutdown commands and reducing 3 equipment overturning accidents. The overall safety performance assessment will reduce the violation rate from 8% to 1.5% and shorten the hidden danger rectification cycle to within 24 hours. The final project delay rate was reduced by 40%, and there were no serious injuries or accidents, which verified the systematic suppression effect of technology and management collaboration on risks.

5.1.2. Failure case: Lessons learned from major accidents caused by lack of safety management

A certain subway tunnel project did not establish a dynamic identification mechanism for hazards, ignored abnormal geological exploration data, and did not install real-time settlement monitoring equipment during construction. At the management level, in order to catch up with the progress, the budget for safety training was reduced, and the operators lacked emergency response capabilities for water inrush symptoms, ultimately leading to a collapse accident and causing 12 casualties. The accident investigation showed that the third-party supervision agency failed to stop illegal excavation in a timely manner due to limited independence, exposing fatal flaws in loose system implementation and lack of responsibility tracing. This case shows that the failure of risk control often stems from the combined effect of lagging technological means and broken management chains.

5.2. Institutional level of optimization strategy

5.2.1. Improve safety management regulations and standardized processes

The current regulations need to refine the operational standards for hazardous work permits, cross construction coordination, and other scenarios, and mandate that project risk assessment reports be included in the approval requirements for construction permits [9]. Drawing on the integration path of OSHA and GB/T 50430, establish a standardized process covering the entire design, construction, and operation cycle, such as including BIM conflict detection as a pre-construction procedure for structural construction. The revision of regulations should strengthen the main responsibility of enterprises, clarify the provisions for holding management criminally responsible in accidents, and force the implementation of the system to shift from “formal compliance” to “substantive effectiveness”.

5.2.2. Strengthen the independence of third-party safety supervision

By legislation, it is stipulated that the supervision fee shall be paid by an independent fund pool to avoid the construction unit interfering with the supervision decision through economic means. Granting supervisory agencies the authority to directly report major hidden dangers to regulatory authorities, establishing a blacklist system for supervisory personnel, and imposing lifetime bans on concealed risk behaviors. At the same time, the implementation of professional qualification grading certification and regular assessment for supervisory personnel requires them to master the use of intelligent monitoring tools, ensuring that their technical review capabilities are upgraded synchronously with construction innovation.

5.3. Technical and cultural aspects of optimization strategies

5.3.1. Promoting digital security management systems

The AI risk warning platform integrates historical accident data, real-time sensor information, and meteorological and geological data to construct a multidimensional risk prediction model. In a smart construction site pilot in Shenzhen, the platform gave an early warning 48 hours in advance of the risk of rainstorm water accumulation in deep foundation pit, and started the automatic drainage system to avoid collapse; The system can also analyze personnel trajectory data, identify unauthorized entry into high-risk areas, and trigger voice warnings in a timely manner. This type of technology compresses the risk intervention window from the hourly level to the minute level, driving security management from experience-driven to data-driven.

5.3.2. Building a "prevention-oriented" corporate safety culture ecology

The safety culture ecology needs to be constructed through a dual path of institutional constraints and value infiltration. Enterprises should incorporate safety goals into their strategic planning, regularly organize management and frontline employees to participate in risk and table simulations, and cultivate a sense of risk co-governance. Implement the "safety points" system, where employees who proactively report hidden dangers or propose improvement plans can receive rewards, and the points are linked to promotion qualifications. A certain state-owned enterprise has transformed the slogan of "zero casualties" into a code of conduct for all employees through the selection of "safety stars" and VR immersive education on accident cases. The accident rate has decreased by 76% within three years, confirming the lasting effectiveness of cultural soft constraints on risk control [10].

6. Conclusion

In the risk management of construction projects, safety management measures significantly reduce the level of risk through direct and indirect pathways. The direct mechanism is reflected in the immediate control of accident probability and losses through preventive training, hazard monitoring, and emergency resource optimization, while the indirect mechanism relies on a responsibility system, performance evaluation, and technological innovation to form long-term risk prevention and control capabilities. Empirical research has shown that the full staff safety responsibility system can increase the self inspection rate of hidden dangers by more than 50%, and the collaborative application of BIM and IoT technology can reduce the rate of high-altitude falling accidents by 45%, confirming the collaborative value of multidimensional measures. Practical insights emphasize the need to construct a safety management system through institutional rigidity constraints, technological innovation iterations, and cultural ecology cultivation, such as improving regulatory responsibility traceability clauses, promoting AI warning platforms, and establishing safety point incentive mechanisms. The future trend will drive the deep evolution of safety management towards intelligence and greenness. The integration of intelligent sensors, digital twin technology, and renewable energy construction equipment can achieve all-weather perception of hidden risks and synchronous control of carbon emission risks. The integration of green construction standards and safety regulations will become a new research direction to adapt to the evolving needs of engineering risk characteristics under low-carbon transformation.

Disclosure statement

The author declares no conflict of interest.

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