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Application Research of Construction Safety Management in Engineering Risk Assessment

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Abstract: The collaborative mechanism between construction safety management and engineering risk assessment is the key path to achieving precise control of engineering risks. Research has validated through case analysis that the integrated application of BIM, IoT monitoring, and AI early warning technologies can reduce accident rates by 42%, and shorten hazard response times to within 15 minutes. However, data silos and insufficient model compatibility still constrain performance improvements. In line with policy directions such as the new safety officer qualification regulations for Guangzhou's Housing and Urban-Rural Development Bureau in 2025 and the promotion of socket-type steel pipe scaffolding technology in Jiangsu Province, this paper proposes strategies for building a unified data platform, developing adaptive risk assessment models, and enhancing "human-technology-management" collaborative training. These measures aim to promote the transformation of safety management towards data-driven and comprehensive smart practices, providing theoretical support and practical references for high-quality industry development.

Keywords: Construction safety management; Project risk assessment; Collaborative mechanism

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1. Introduction

The construction industry, as an important pillar of the national economy, has long been constrained by its high-risk characteristics and frequent safety accidents, which have hindered the sustainable development of the industry. In recent years, the country has continuously strengthened the guidance of safety production policies. On March 1, 2025, the Guangzhou Housing and Urban Rural Development Bureau officially implemented the "Interim Provisions on Strengthening the Management of Safety Production in Housing Construction Projects and Implementing the Main Responsibilities of All Parties in Construction", clarifying that safety officers must have intermediate professional titles or professional qualifications, and requiring professional subcontracting units to be fully included in the general contracting management system, further consolidating the primary responsibility of construction units.

At the same time, the Jiangsu Provincial Department of Housing and Urban Rural Development promoted the "Compulsory Use Policy for Socket type Pan buckle Steel Pipe Scaffolding", which reduces the risk of high-altitude operations through technological innovation and promotes the transformation of construction methods towards safety and efficiency. Such policy changes not only reflect the urgent need for professionalization and standardization of security management in the industry, but also reflect the upgrading trend of risk assessment from empirical judgment to data-driven.

However, in practice, there are still problems such as unclear implementation of responsibilities, insufficient technological adaptation, and difficulties in integrating multi-source data. It is urgent to systematically study the collaborative mechanism between security management and risk assessment. This article combines the latest policy requirements and typical cases to analyze the effectiveness of safety management in risk identification, hierarchical control, and technical tool application, aiming to provide theoretical support and practical reference for building a scientific and intelligent engineering safety system.

1. Overview of construction safety management

1.1. Basic connotation of construction safety management

Construction safety management is a management behavior that prevents and controls potential risks in engineering activities through systematic means [1]. Its core elements include four-dimensional coordination of systems, technology, personnel, and environment. At the institutional level, based on laws and regulations, industry standards, and enterprise rules, clarify the responsible parties and operational norms, and construct a risk prevention and control framework.

At the technical level, relying on advanced construction techniques, monitoring equipment, and information tools, precise identification and real-time intervention of hazards can be achieved. At the personnel level, emphasis is placed on the safety training, behavioral norms, and emergency response capabilities of practitioners, which are key execution units for risk prevention and control. At the environmental level, it is necessary to coordinate the layout of the construction site, climate conditions, and surrounding social factors to reduce the impact of external uncertainty on safety. The core goal of safety management is to achieve "zero accidents" and "low risks", following the principle of "prevention first, dynamic control". Through pre risk prediction, in-process supervision, and post summary feedback, a closed-loop management mechanism is formed to ultimately ensure the safety and sustainability of the entire life cycle of the project.

1.2. Current status and challenges of construction safety management

The domestic construction safety management system has gradually improved, and the regulatory system centered on the "Regulations on Safety Production Management of Construction Projects" promotes the standardization process of the industry. The dual prevention mechanism of safety responsibility system, risk grading control, and hidden danger investigation and governance is widely applied. However, there are still multiple challenges at the practical level. Firstly, insufficient implementation of responsibilities, and some enterprises have a tendency to prioritize efficiency over safety, resulting in safety management becoming a mere formality, Secondly, the application of technology lags behind, and the efficiency of traditional manual inspections and paper records is low, BIM. The popularity and integration of digital tools such as the Internet of Things are insufficient. Thirdly, the ability to respond to dynamic risks is weak, and the real-time monitoring and rapid response mechanism for emergencies in complex construction scenarios is not yet mature; Fourthly, the safety awareness of grassroots practitioners varies greatly, and the pertinence and effectiveness of safety training need to be improved. In addition, issues such as fragmented regulatory systems and insufficient cross departmental collaboration further constrain the effectiveness of safety management, and there is an urgent need to achieve breakthroughs through institutional innovation and technological empowerment [2].

2. Theoretical framework for engineering risk assessment

2.1. Basic concepts and processes of engineering risk assessment

Engineering risk assessment is a scientific process that identifies, analyzes, and controls potential risks throughout the entire project lifecycle through systematic methods [3]. Its theoretical framework includes four core stages: risk identification, analysis, evaluation, and control. In the risk identification stage, historical data analysis, expert experience, and on-site inspections are used to comprehensively identify the hazards and vulnerable links in construction activities. The risk analysis stage combines probability statistics and impact assessment to quantify the likelihood and severity of risk events. In the risk assessment stage, based on preset thresholds or risk matrices, the risk levels are classified and sorted, and priority control objects are identified. During the risk control phase, risks are reduced to an acceptable level through technological optimization, management strengthening, or emergency plan development. In project management, risk assessment runs through the entire process of planning, design, construction, and operation. Its role is reflected in decision support, resource optimization, and accident prevention. Through risk prediction and dynamic adjustment, it ensures the stable achievement of project goals.

2.2. Methodology system for engineering risk assessment

Engineering risk assessment methods can be divided into three categories: qualitative, quantitative, and comprehensive. Qualitative methods focus on logical analysis, such as LOPA (Layer of Protection Analysis) which evaluates residual risks through hierarchical protection mechanisms, and HAZOP (Hazard and Operability Analysis) which identifies design deviations through structured discussions, quantitative methods rely on mathematical models and data-driven approaches, such as Monte Carlo simulations that predict risk probability distributions through random sampling, and Fault Tree Analysis (FTA) that uses logic gate models to trace the root causes of risk events. The comprehensive evaluation method combines qualitative and quantitative advantages, such as fuzzy comprehensive evaluation combined with expert weights and quantitative indicators. However, its limitations lie in high data requirements, high model complexity, and susceptibility to subjective factors. The selection of different methods should be based on project scale, data completeness, and decision-making objectives. A single method is difficult to cover multidimensional risk scenarios, and complementary methods are needed to enhance the scientific and practical nature of evaluation results [4].

3. Correlation analysis between construction safety management and engineering risk assessment

3.1. The supporting role of safety management in risk assessment

3.1.1. Risk pre control mechanism of safety management system

The safety management system provides scientific basis for engineering risk assessment through standardized safety standards and risk thresholds. Safety standards are based on industry regulations, technical specifications, and enterprise systems, clarifying the bottom-line requirements for risk control in construction activities, such as high-altitude operation protection standards, temporary structure bearing limits and more.

The risk threshold is set based on safety standards to determine the acceptable level of risk, and the risk level is defined through quantitative indicators such as accident probability and loss threshold, guiding the risk classification and priority division in the evaluation process. The correlation between the two is reflected in the fact that safety standards are the basis for setting thresholds, while risk thresholds are the specific goals of standard implementation, collectively forming the pre control framework for risk assessment. By embedding safety management requirements into the risk assessment process, it is possible to achieve pre identification and analysis of risks, reducing uncertainty during the construction process [5].

3.1.2. Identification of risk factors in safety management practice

Through systematic monitoring and experience accumulation, safety management practices accurately identify key risk sources such as personnel operations, equipment status, and environmental conditions.[6] The operational risks of personnel stem from insufficient skills, illegal operations, or fatigue construction, and the probability of human errors needs to be reduced through training, assessment, and behavioral supervision; The risk of equipment status involves mechanical failures, tool defects, or delayed maintenance, and needs to rely on regular testing and real-time monitoring of the internet of things to improve reliability. Environmental condition risks include extreme weather, geological hazards, and chaotic construction site layout, which require dynamic intervention through geological surveys, meteorological warnings, and site planning [7]. The risk factor database formed in security management practice provides structured input for risk assessment, enhancing the comprehensiveness and pertinence of risk identification.

3.2. Feedback optimization of risk assessment on safety management

3.2.1. Adjustment of security management strategy based on risk assessment

The risk assessment results drive the dynamic optimization of security management strategies by quantifying risk levels and exposure levels. For high-risk operations, it is necessary to adjust emergency plans to enhance the deployment efficiency of emergency resources (such as rescue equipment and medical teams). for medium and low-risk links, redundancy costs can be reduced by optimizing resource allocation (such as manpower scheduling and material storage). For example, when the risk assessment during foundation pit construction reveals a high probability of instability in the support structure, safety management needs to increase the frequency of support monitoring and reserve emergency reinforcement materials. This “evaluation feedback adjustment” cycle mechanism shifts safety management from passive response to proactive pre control, enhancing overall risk response capabilities.

3.2.2. Collaborative mechanism between risk management and safety culture

Risk assessment provides data support for the construction of safety culture by revealing the distribution and causes of risks. Risk education based on risk assessment conclusions can customize training content for different positions such as technicians and workers. For example, through accident case simulation and risk visualization tools, to enhance practitioners’ awareness of high-frequency risks such as high-altitude falls and mechanical injuries. At the same time, risk communication mechanisms such as safety meetings and risk bulletin boards will make the evaluation results transparent and promote the participation of all staff in risk prevention and control.

The synergy between safety culture and risk management not only enhances individual safety awareness, but also promotes the formation of a collective behavior model of "risk sharing and responsibility governance" in organizations, ultimately achieving sustainable improvement in safety management efficiency [8].

4. Practical case analysis of construction safety management in risk assessment

4.1. Case background and project overview

4.1.1. Basis and representativeness of case selection

The selected case for this study is a landmark super high-rise complex project in a coastal city, with a total construction area of 420,000 square meters and a building height of 368 meters. It includes multifunctional commercial, office, and hotel formats. The selection criteria for the case include three aspects. Firstly, the complexity of the project, covering high-risk operation scenarios such as deep foundation pits (excavation depth of 26 meters), large-span steel structures (single truss span of 45 meters), and installation of high-altitude curtain walls (300 meters above the ground). Secondly is the technological integration. The project adopts BIM full lifecycle management, real-time monitoring of the internet of things, and AI risk warning system, reflecting the cutting-edge application of digital technology in security management. Third is the typicality of risks, involving complex geological conditions including soft soil foundation, high groundwater level, frequent typhoons, climate impacts, and management challenges of multi contractor collaborative operations. This case is listed as a "smart construction site" demonstration project in the industry, and its safety management mode and risk assessment method have universal reference value for similar large-scale projects, especially in dealing with extreme environments and technological innovation integration scenarios, demonstrating typical characteristics [9].

4.1.2. Project risk characteristics and safety management requirements

The risk characteristics of the project are characterized by multidimensional interweaving: in terms of geological risk, soft soil foundation is prone to cause deformation of foundation pit support, and the fluctuation of groundwater level exacerbates the probability of slope instability. In terms of construction technology risks, steel structure hoisting is significantly affected by wind force, and welding quality deviations may lead to node failure; In terms of managing collaborative risks, the cross operation of 12 subcontracting units has caused schedule conflicts and blurred safety responsibilities. In terms of environmental risks, the passage of six typhoons per year poses a threat to the stability of high-altitude equipment such as tower cranes and climbing models. The safety management requirements focus on three points: firstly, establishing a dynamic risk assessment mechanism to achieve risk warning through real-time data collection such as foundation pit settlement and wind speed monitoring. The second is to strengthen multi-party collaboration and integrate risk information from design, construction, and supervision parties through the BIM platform. Third is to enhance emergency response capabilities, develop graded contingency plans for sudden scenarios such as typhoons and fires, and equip unmanned aerial vehicle inspection and intelligent evacuation systems.

4.2. Application process of security management measures in risk assessment

4.2.1. Implementation steps for risk identification and graded control

The project adopts a progressive process of "full element identification quantitative grading closed-loop control". In the risk identification stage, expert opinions, historical accident database comparisons, and on-site hazard investigations are summarized using the Delphi method to form a risk list consisting of four categories including technical, management, environmental, personnel and 28 subcategories, such as "steel structure hoisting wind speed exceeding the limit" and "delayed foundation pit monitoring data". In the quantitative grading stage, combined with the LEC risk matrix (likelihood x exposure rate x consequences) and the fuzzy comprehensive evaluation method, the risks are divided into three levels: red (immediate shutdown), orange (time limited rectification), and yellow (tracking and monitoring). Among them, there are 3 red risks (such as tower cranes not locked during typhoon periods) and 9 orange risks. In the closed-loop control stage, the red risk is directly intervened by the project commander, and a special plan review and emergency resource allocation are initiated, where orange risk will be monitored and rectified through daily safety meetings, and included in the progress safety linkage model of the BIM collaborative platform. The yellow risk is reported by the team through the mobile app, and the system automatically generates a rectification work order and tracks the closed loop.

4.2.2. Application of security management technology tools

BIM technology runs through the entire process of risk assessment, during the design phase, 4D simulation is used to simulate construction conflicts and reduce the risk of falling objects at 23 locations; During the construction phase, the BIM + GIS integrated platform is used to correlate real-time monitoring data of the foundation pit such as inclinometers and osmometers with the 3D model. When the deviation exceeds the limit, an alarm is automatically triggered and pushed to the intelligent terminal of the management personnel. In terms of deployment of IoT monitoring system, 182 stress sensors are installed on steel structure nodes, and the data is uploaded to the cloud analysis platform every 5 minutes, combined with AI algorithms to predict the fatigue life of welds; The high-altitude work area is equipped with UWB positioning chips and intelligent safety helmets to monitor personnel movement in real-time. The electronic fence triggers 156 cross-border alarms, and the efficiency of correcting violations is improved by 70%. In addition, the drone patrols three times a week to capture full field images, and uses image recognition algorithms to identify issues such as damaged protective nets and illegal material stacking, with an accuracy rate of 89% for defect recognition. The application of technological tools has upgraded the traditional experience driven mode to data-driven decision-making, reducing the risk assessment response time to within 15 minutes and lowering the accident rate by 42% compared to the industry average [10].

4.3. Application effect evaluation and improvement suggestions

4.3.1. Effectiveness analysis

The project achieved significant results by integrating safety management and risk assessment technology tools: the accident rate decreased by 42% compared to the industry average, including a 58% reduction in high-altitude falling accidents and a 37% reduction in mechanical injury accidents. The efficiency improvement is reflected in the reduction of risk assessment response time to within 15 minutes and the compression of hazard rectification cycle from an average of 48 hours to 12 hours. The collaborative application of BIM and IoT monitoring optimizes resource allocation, reduces material waste by 12%, and lowers project delay rates by 25%. The AI risk warning system predicted the risk of tower crane overturning 72 hours in advance during typhoon season, successfully avoiding 3 potential major accidents. The intelligent safety helmet and positioning system corrected 320 violations, and the personnel training and assessment pass rate increased to 98%. The deep intervention of technical tools has promoted the shift of security management from "post disposal" to "pre control", reducing risk control costs by 18% and significantly improving the overall benefits of the project.

4.3.2. Existing problems and optimization directions

There are still limitations in current practice. Firstly, there is insufficient integration of multi-source data, and BIM models, IoT monitoring, and manual inspection data have not been fully integrated, resulting in some risk analysis relying on manual cross validation. Secondly, the adaptability of the model needs to be improved. The prediction deviation rate of AI algorithms under extreme weather conditions such as sudden changes in instantaneous wind speed is as high as 21%, and the simulation ability of BIM models for nonlinear risks such as psychological fatigue of personnel is limited. The third issue is the high threshold for operating technical tools, and the uneven acceptance and proficiency of grassroots personnel in using the new system, which affects the integrity of data collection.

The optimization direction includes: building a unified data platform, developing cross system interface standards and data cleaning specifications. Develop an adaptive risk assessment model and introduce transfer learning techniques to enhance the algorithm's generalization ability, establish a collaborative training mechanism of "technology management personnel" and enhance practical skills through virtual simulation exercises. In addition, it is necessary to explore blockchain technology to strengthen the traceability and credibility of risk data, and promote the evolution of security management from local optimization to global intelligence.

5. Summary

The collaborative mechanism between construction safety management and engineering risk assessment is the core path to ensure engineering safety. Research has shown that the security management system provides structured support for risk assessment through multi-dimensional collaboration of systems, technology, and personnel. Risk assessment optimizes security management strategies through quantitative analysis and dynamic feedback, forming a closed-loop management of "identification control improvement". Case studies have verified that the application of BIM, IoT, and AI technologies can significantly improve risk assessment accuracy and control efficiency, reduce accident rates by over 40%, and shorten hazard response time to 15 minutes. However, issues such as data silos, insufficient model generalization ability, and technical application thresholds still constrain the release of efficiency. Future research needs to focus on multi-source data fusion, development of adaptive risk assessment models, and construction of a "human technology management" collaborative training system to promote the transformation of security management from experience driven to data-driven. With the deepening application of technologies such as blockchain traceability and digital twins, building safety risk management will gradually move towards global intelligence, providing sustainable guarantees for the high-quality development of the industry.

Disclosure statement

The author declares no conflict of interest.

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