Journal of World Architecture, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research Progress on Risk Assessment in Construction Sites

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Abstract: Construction work is an important component of social development, and its safety management is crucial for the protection of employees' lives, the efficient development of enterprises, and the social harmony and stability. Therefore, this paper explores the risk identification, risk estimation, risk evaluation, and control strategies of construction sites. It analyzes the research progress, current issues that need optimization, and future development directions, aiming to provide insights for the development of risk evaluation in construction sites.

Keywords: Construction work; Risk identification; Risk evaluation; Construction engineering

Online publication: June 30, 2025

1. Introduction

After the reform and opening-up, the construction industry in China gradually grew and developed at an exceptionally fast pace. Today, the construction industry has become a crucial sector in China's economic development, with a significant impact on societal progress. According to statistics from China's construction industry, there were 151,901 construction enterprises with active projects in 2024. While the industry has developed rapidly, it has also posed certain challenges to the safety management of construction projects, particularly during the construction phase. Compared to other professional activities, the construction industry is one of the most accident-prone sectors in terms of fatalities and injuries, due to its inherent complexity, diverse forms of work, and the high-altitude nature of many tasks. It ranks among the industries with the highest number of safety incidents globally. Therefore, the safety risk assessment of construction sites is of paramount importance. Its objective is to identify, analyze, and quantify potential hazards through a systematic risk assessment approach, and to develop effective risk control measures to reduce the likelihood and consequences of accidents, ensuring the safety, compliance, and sustainability of construction activities.

In 1966, international scholars first discussed safety risk assessment at an academic symposium, and based on this, they developed an initial theoretical framework for safety management. Over the years, many international scholars have applied safety risk assessment methods in various ways to conduct safety management research in the field of construction engineering, yielding a substantial body of work. For instance, Nazeer Ahamed *et al.* studied the safety management status of the Indian construction industry, combining literature reviews and expert interviews to systematically identify 140 human-factor-related errors from three perspectives: senior management, safety supervisors, and workers [1]. This study not only enriched the theoretical framework of human factor-related accidents but also provided significant additions and expansions to the existing literature [2]. Waqar *et al.* studied the seven major obstacles faced by BIM in safety risk management and evaluation applications, considering the complexity of construction. The study indicates that to ensure the safe implementation of projects, it is necessary to enhance technical capabilities, integrate BIM with other risk management frameworks, increase stakeholder participation, and establish a standardized BIM practice system. Wang *et al.* addressed the gaps in existing research on dynamic risk assessment of robotic construction [3]. They examined the entire lifecycle, from site deployment and operational processes to equipment removal.

Through accident causation analysis, they identified 13 risk dimensions and 52 detailed indicators. Using an improved TS-FTA and Bayesian network hybrid modeling approach, they quantified risk intensity and identified three major priorities for improvement: the lack of an effective risk warning mechanism on construction sites, delayed emergency responses to sudden incidents, and the absence of dynamic management of work zones. Their study provides a systematic solution for risk classification and resource optimization in the application of construction robots. Policies such as the "Guidelines for Safety Risk Identification and Control in Construction" and the "Construction Safety Risk Management System" issued by China have also promoted the development and improvement of safety risk identification in construction.

As shown in **Figure 1**, a preliminary programmatic risk assessment process has been developed. First, the various risks that may exist during the construction process are identified. Then, by analyzing the probability of these risks and their potential consequences, a risk evaluation system is established. Based on this, the risk level is assessed by combining the probability and severity of loss. Finally, appropriate risk control strategies and measures are proposed based on the evaluation results. However, research on safety awareness related to human factors remains insufficient, and with the increasing complexity of construction projects and the use of new technologies and materials, there is still a need for further research into the safety risk evaluation of construction sites. Based on existing research findings, this paper provides a systematic review of the main processes of construction site risk assessment, focusing on risk identification, risk estimation, and risk evaluation and control strategies. It also discusses future development trends.

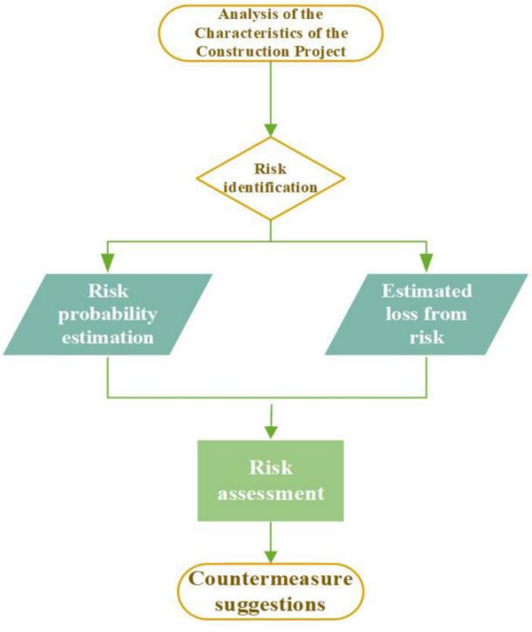

Figure 1. The basic process of risk assessment.

2. Research on risk identification at construction sites

2.1. Overview of risk identification

In 1985, American scholar Haynes first introduced the concept of risk, defining it as the possibility and uncertainty of loss occurring during a certain activity. Risk identification is the first step in construction risk evaluation and forms the foundation of the entire risk evaluation process. Throughout the project's lifecycle, systematically collecting and analyzing relevant information can effectively identify potential risk factors and events, categorizing and assessing them. This process lays the groundwork for subsequent risk control measures. The core purpose of risk identification is to identify and assess the various risks at construction sites, thereby providing a scientific basis for risk management.

2.2. Risk identification methods

The current methods for risk identification are primarily divided into two categories: qualitative analysis and quantitative analysis. Common qualitative methods include literature analysis, the Delphi method, Work Breakdown Structure (WBS), scenario analysis, and Fault Tree Analysis (FTA). However, qualitative methods rely heavily on expert experience and subjective judgment, which may introduce some bias. Quantitative analysis involves accident statistics, a systematic research method based on historical accident data. By collecting and analyzing multidimensional data on accident causes, personnel casualties, economic losses, and other factors, potential future accident risks can be evaluated. In-depth statistical analysis of this data helps identify high-risk factors in specific processes or activities, providing a scientific basis for formulating targeted prevention and control measures. Fault Tree Analysis (FTA) relies on large amounts of complete and accurate data. If the data is insufficient or biased, it can lead to inaccurate analysis results. **Table 1** summarizes and analyzes the advantages and disadvantages of commonly used risk identification methods.

Table 1. Risk identification methods

Risk identification methods	Method characteristics	Advantages	Disadvantages	Applicable scenarios
Literature analysis	Summarizes existing research to identify potential risks related to the subject.	Scientifically rigorous with comprehensive risk coverage.	Time-consuming; may overlook project-specific risks.	Suitable for projects with existing research foundations.
Delphi method	Relies on expert opinions through iterative anonymous feedback to reach consensus.	Flexible and adaptable.	Time-intensive; subjective bias possible	Ideal for complex projects with uncertain risks.
Work Breakdown Structure, WBS	Hierarchically decomposes projects into manageable subcomponents.	Systematic and comprehensive risk identification.	Cumbersome for large-scale projects; high cost.	Effective for structurally defined projects.
Scenario analysis	Simulates multiple scenarios for proactive risk identification	Highly flexible with broad coverage.	Subjective assumptions; resource-intensive.	Suited for uncertain and complex external environments.
Fault Tree Analysis, FTA	Clarifies causal relationships between events via backward deduction.	Qualitative and quantitative integration; logical clarity.	Labor-intensive.	Appropriate for single-risk analysis.
Accident statistics	Analyzes historical accident data for objective insights	Objective with proven preventive value	Data-dependent; lagging indicators	Ideal for high-risk projects requiring quantitative assessment.

2.3. Progress in risk identification research at construction sites

The application of risk identification in construction site safety management has become relatively mature. For example, Tao *et al.* used the WBS-RBS method to conduct a detailed analysis of risk factors at prefabricated structure construction sites [4]. Wang focused on metro construction projects as a case study [5]. Through expert interviews and the Delphi method, he identified 61 risk factors related to equipment upgrade construction risks across four dimensions: personnel, equipment, environmental health, and management, and developed a risk map. Ardeshir *et al.* used Fault Tree Analysis (FTA) to systematically identify risks associated with underground pipeline leakage accidents at construction sites, starting from the "human-machine-material-method-environment" framework [6]. Rabbi *et al.* analyzed 53 articles on the application of AI in construction sites, identifying risk detection as a key area for AI applications in construction safety [7]. By 2025, significant progress will have been made in risk identification at construction sites, particularly with advancements in intelligent systems, big data, and BIM technologies. A systematic and standardized risk identification framework will be gradually perfected, leading to significant improvements in construction safety.

3. Risk estimation at construction sites

3.1. Overview of risk estimation at construction sites

Risk estimation, as the next phase following risk identification, is the process of quantitatively analyzing the identified risk factors. It is the most crucial step in the entire risk evaluation process. To ensure comparability, risk estimation is typically expressed as risk magnitude, which is generally considered to be the product of the probability of risk occurrence and the potential risk loss. In practice, risk estimation methods can generally be divided into three major paradigms: qualitative, quantitative, and integrated analysis, based on differences in analytical dimensions. These methods show significant differences in theoretical foundations, implementation paths, and applicability to engineering projects.

Qualitative analysis methods are typically applied in the early evaluation stage when data is limited. Among them, expert scoring methods use a Delphi-based consultation mechanism to construct interdisciplinary expert groups. These groups rely on domain knowledge to rank risk factors using Likert scales, which is particularly suitable for risk prediction in innovative projects such as high-rise buildings. While this method has the advantage of ease of implementation, its evaluation validity is susceptible to expert cognitive biases and over-reliance on subjective experience. Complementing this, Fault Tree Analysis (FTA) uses deductive reasoning, starting from top events (such as structural collapse) and working backward to basic events. By using Boolean algebra to calculate minimal cut sets, this method provides a visual tool for analyzing risk propagation paths in high-risk scenarios such as tunnel engineering. However, its analytical effectiveness heavily depends on the completeness of historical accident databases.

In new construction scenarios, there may be issues of missing underlying events. The evolution of quantitative analysis methods marks a shift in risk estimation from empirical judgment to mathematical modeling. Monte Carlo simulations create three-dimensional probability models that include random variables such as weather fluctuations and material price variations. By using sampling techniques to generate iterative computations, these models can provide probability distribution curves for risk impacts in complex projects, such as offshore bridges. The accuracy of this method is positively correlated with the computational resources invested. In contrast, the risk matrix method uses a two-dimensional Cartesian coordinate system of probability and consequences to divide risk levels into manageable control zones. This method demonstrates a decision-making efficiency advantage in standardized residential construction projects. The evolution of integrated analysis methods reflects the practical needs of managing complex engineering systems. The Analytic Hierarchy Process (AHP) introduces a judgment matrix using a 9-level scale and combines it with the characteristic root method to solve for the maximum eigenvalue. This approach demonstrates multi-criteria decision-making advantages in carbon emission risk trade-offs in green building projects. The latest improvement, Interval AHP, uses triangular fuzzy numbers to reduce the uncertainty in expert judgment. The Bayesian Network method constructs dynamic conditional probability tables, combined with Gibbs sampling algorithms to achieve parameter learning. This method has successfully reduced the risk warning response time in BIM-enabled smart construction sites.

Current methods of risk estimation at construction sites show three major trends: mixed reality technology based on digital twins is reconstructing the risk simulation paradigm, such as coupling BIM point cloud data with Monte Carlo simulations; machine learning algorithms are being used to optimize the weight distribution process in expert scoring methods; and blockchain technology provides a new path for trustworthy risk data certification. The integration of these technologies not only overcomes the limitations of traditional methods but also drives the transformation of risk management from static evaluation to real-time, intelligent evolution.

3.2. Progress in risk estimation research at construction sites

Due to its simplicity, efficiency, and maturity, expert scoring methods still occupy an important position in risk estimation at construction sites. In identifying risks in shield tunneling construction, Zhou aimed to reduce the subjectivity of expert surveys and the limitations of determining probability [8]. He replaced specific probability values with multiple probability intervals, designing a risk factor survey form based on probability intervals and using expert surveys to calculate the probability distribution of risk factor probability levels. With the development of information technology, BIM technology, which enhances efficiency through technological platforms and standardized processes, has become increasingly mature. Darko analyzed the use of BIM both independently and in combination with other sensing and tracking technologies, as well as 3D model creation and comparison techniques [9]. However, BIM applications in MiCRM still predominantly focus on the design phase, and dynamic risk management requires technological integration. At the same time, there are issues of insufficient multi-source technology integration, a singular risk dimension, and low levels of automation. Currently, there are two major trends in risk identification: the integration of multiple methods and the empowerment of technology. These include the combination of risk matrices with Monte Carlo simulations, as well as the use of the Internet of Things (IoT) and AI to drive dynamic and intelligent evaluations.

4. Research on risk evaluation and control measures for construction sites

4.1. Overview of risk evaluation and control measures for construction sites

In the risk evaluation system, the evaluation stage serves as the core decision-making phase. It defines risk levels and prioritizes control measures based on the results of risk identification and analysis using systematic methods. Specifically, this stage integrates a “probability-severity” two-dimensional assessment model (such as the risk matrix method), numerical calculation methods (such as the LEC method), and multi-criteria decision tools (such as the analytic hierarchy process) to categorize risks into low, medium, and high levels of control. Based on critical project nodes, it matches differentiated response measures. Among them, qualitative methods, due to their ease of operation, are suitable for initial screening, while quantitative methods achieve precise quantification through fault tree probability calculations. Semi-quantitative methods rely on fuzzy mathematical theory to balance subjective and objective evaluation biases. It is worth noting that dynamic evaluation mechanisms empowered by modern technologies, such as BIM-IoT real-time monitoring and data-driven risk threshold warnings, are gradually replacing traditional static evaluation models. These mechanisms establish a closed-loop feedback system of "data collection - threshold determination - level correction." This stage, through the integration of multi-source heterogeneous data and intelligent algorithms, effectively addresses the issues of subjectivity and fragmented data in traditional evaluations, ultimately achieving the visualization of risk status and the scientific allocation of control resources.

Based on a systematic risk management theoretical framework, after identifying and evaluating the levels of risk factors, a multi-dimensional risk prevention and control system should be established to address these risks. This system should systematically integrate preventive control mechanisms, tiered response plans, and continuous education and training programs. By implementing a full-cycle risk management strategy, it effectively controls safety hazards during the construction process. Current research in the field of project management focuses on: using the PDCA (Plan-Do-Check-Act) management cycle to establish a dynamically optimized risk control matrix, building an intelligent early warning system based on BIM technology, and developing tiered and categorized emergency response protocols. Empirical studies show that adopting a prevention-oriented full-cycle management concept, along with modular emergency plans and regular emergency drills, can reduce the occurrence of safety hazards while significantly improving accident response efficiency. Additionally, by establishing a "pre-job certification - on-the-job training - skills assessment" three-level education system, the compliance rate of construction workers' safe operation standards can be significantly increased. This creates a multi-layered protection system that covers the "human-machine-environment-management" four elements, ensuring that risks throughout the entire project lifecycle remain under control.

4.2. Progress in research on risk evaluation and control measures at construction sites

In the field of risk evaluation and control at construction sites, scholars have proposed innovative solutions for different scenarios. To address the issue of frequent accidents caused by weak safety supervision at small construction sites, Na *et al.*developed an AI-based intelligent analysis system using full-cycle aerial imagery data [10]. This system uses multi-objective correlation modeling to intelligently identify fall-risk areas, providing innovative safety control measures for construction projects with limited scale. On the other hand, Chen addressed the challenges of dynamic risk assessment in tunnel underpass projects by constructing a hybrid framework that integrates a trapezoidal cloud model with a Bayesian network [11]. Based on 12 risk indicators, the framework establishes an evaluation system and optimizes the risk parameter discretization and prior probability estimation accuracy through fuzzy membership degree conversion in TCM. The framework also performs multi-dimensional risk simulation and sensitivity diagnosis of key factors, providing targeted solutions. This framework has been validated in the practice of the Wuhan Metro project, demonstrating the improved accuracy of risk level prediction and the effectiveness of real-time dynamic control. It provides an evaluation paradigm that combines algorithmic innovation with practical engineering application value for construction under complex geological conditions.

5. Development trends in risk evaluation for construction sites

With technological innovation, the improvement of policies and regulations, and the deepening of globalization, construction site risks are evolving in multiple dimensions. Intelligent technologies such as BIM, AI, and the Internet of Things (IoT) enhance risk prediction capabilities through real-time monitoring and simulation optimization. However, the application of green materials and complex construction processes has introduced new types of technical risks. The pressure of ESG (Environmental, Social, and Governance) compliance has driven companies to establish full-process management systems, strengthening safety production, and environmental protection standards. Additionally, supply chain fluctuations and labor shortages have exacerbated the risks related to project costs and timelines, promoting the development of automated equipment and resilient supply chains. International construction projects are facing compounded challenges from geopolitical factors, regulatory differences, and extreme environmental conditions, requiring companies to localize their risk management strategies. Moreover, risk control is expanding from the construction phase to the entire lifecycle, including design and operation, with a focus on technological integration and the development of multidisciplinary talents. In the future, risk prevention and control at construction sites will need to integrate technology, management, and policy resources to establish a dynamic, cross-dimensional collaborative mechanism.

6. Conclusion

This review synthesizes significant advancements in construction site risk assessment, encompassing risk identification, estimation, evaluation, and control. While traditional qualitative methods remain foundational, research increasingly focuses on overcoming their limitations, particularly subjectivity and data dependency, through technological integration. The emergence of BIM, IoT, AI, and digital twins enables dynamic, real-time risk monitoring, simulation, and intelligent early warning systems, shifting risk management from static to proactive paradigms. Progress is evident in sophisticated hybrid frameworks for complex scenarios like tunneling or robotic construction, enhancing prediction accuracy and resource optimization. However, challenges persist, including insufficient attention to human-factor safety awareness, fragmented multi-technology integration, and adapting to novel risks from green materials and complex processes. Future development hinges on lifecycle risk management, resilient strategies for global projects and supply chains, and holistic solutions merging technology, policy, and multidisciplinary talent to establish dynamic, cross-dimensional collaborative safety mechanisms. Continuous innovation in risk assessment is crucial for ensuring construction safety and sustainability amidst evolving industry demands.

Disclosure statement

The author declares no conflict of interest.

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