Proceedings of CONF-FMCE 2025 Symposium: AI and Machine Learning Applications in Infrastructure Engineering
DOI: 10.54254/2755-2721/2025.MH25027

Analysis of Risk Management Methods for Shield Tunnel Construction Phase

Weichen Ji

School of Civil Engineering, Southwest Jiaotong University, Chengdu, China
jwc@my.swjtu.edu.cn

Abstract. In recent years, the road network construction sector in China has witnessed remarkable progress. A large number of projects, including highway tunnels, railway tunnels, and subways, have been successfully launched. Nevertheless, given the complexity of geological conditions and construction conditions, the issues and uncertainties encountered during tunnel construction are often more diverse, thereby escalating the difficulty and the cost of risk management. This paper comprehensively reviews the methods for risk management during the construction phase of shield tunnels as reported in the relevant literature. Conducting a brief analysis of the applicable scope of different methods. The findings indicate that the Work Breakdown Structure - Risk Breakdown Structure (WBS-RBS) method, the Analytic Hierarchy Process (AHP), and the Fuzzy comprehensive Evaluation（FCE） are among the most widely employed techniques for risk evolution. Moreover, the As Low As Reasonably Practicable (ALARP) principle serves as the fundamental and precise guideline for risk management. Finally, it analyzes the remaining problems of the risk management method system and puts forward potential future research directions.

Keywords: Risk management, Breakdown Structure, Analytic Hierarchy Process, Fuzzy Comprehensive Evaluation

1. Introduction

Tunnels, serving as critical components of road network infrastructure, hold significant research and strategic value. However, tunnel design and construction are highly complex processes, and risks are pervasive across various tunnel projects. Risk management aims to identify these risks and, through technical and managerial measures, control and mitigate them to achieve the objective of safe construction. In 2023, the Office of the Safety Committee of the State Council issued relevant guidelines emphasizing the need for further strengthening safety management in tunnel engineering. Given that shield tunneling ranks among the most prevalent methods in tunnel engineering, research on risk management during shield tunnel construction has consequently emerged as a key contemporary focus.

As a vital research topic, numerous scholars have previously investigated risk management in shield tunneling construction: Zhang Songtao et al. employed the Analytic Hierarchy Process to determine risk weighting factors for the Chunfeng Tunnel in Shenzhen and established a risk

DOI: 10.54254/2755-2721/2025.MH25027

assessment index system for tunnel construction [1]. Tian Boquan integrated Bayesian Networks and Fuzzy comprehensive Evaluation using the Dalian Subway project as a case study, applying them to the risk management process for shield tunnels to derive quantitative results for the overall risk level [2]. Wang Yushi proposed risk management strategies from both corporate and project perspectives for subway projects constructed using the shield method and established a relatively comprehensive risk management system [3].

Building upon the existing literature, this paper will synthesize risk management methodologies identified in prior studies, provide concise explanations of current industry-standard approaches, and conclude by outlining prospective research directions informed by contemporary scholarship.

2. Risk evaluation

Risk evaluation during shield tunnel construction comprises two fundamental components: The first, is risk identification, which requires comprehensive detection of all potential risk factors; and the second, is risk assessment, involving probabilistic analysis of occurrence likelihood, loss impact assessment, and risk classification. This process follows a sequentially ordered workflow where identification precedes evaluation—neither phase can be omitted. Consequently, mastering these methodologies is imperative for effective risk management.

The risk management system is shown in Fig. 1.

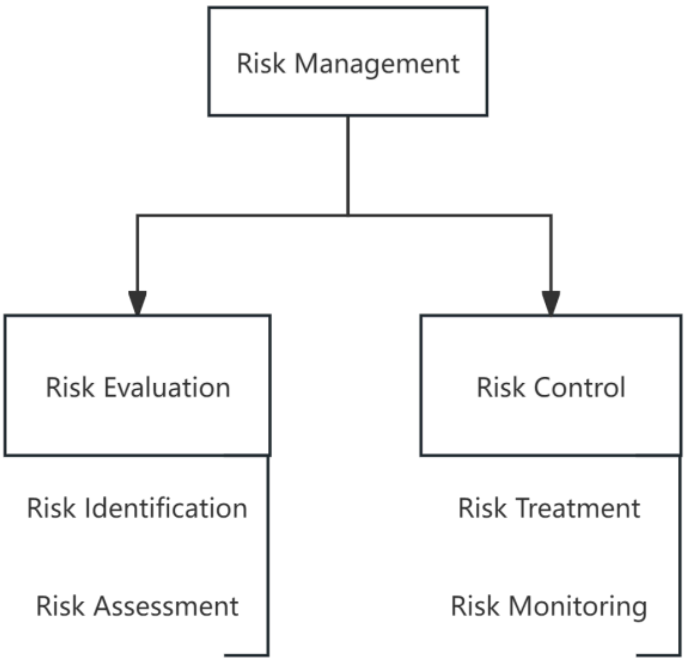

Figure 1: Risk management system

2.1. Risk identification

While empirical judgment may suffice for identifying certain risk factors in tunnel construction, the majority of tunneling risks exhibit inherent complexity and latent characteristics. Consequently, accurate risk identification necessitates a systematic methodology framework. Given the diverse

DOI: 10.54254/2755-2721/2025.MH25027

array of available identification methods, selecting context-appropriate analytical methods yields an efficiency multiplier effect. Common analytical approaches are cataloged in Table 1 (as referenced in [4]).

Table 1: Methods of risk identification

Method	Principle	Advantages & Limitations
Delphi method	Systematized expert consultation facilitates predictive risk identification and informed decision-making.	+ Demonstrates notable authoritative rigor and empirical robustness, effectively mitigating groupthink bias. - Entails time-intensive implementation and exhibits inherent subjectivity.
WBS-RBS method	Decomposes and correlates work deliverables with risk structures.	+ Covers full project lifecycle; enables team collaboration– lacks dynamic adaptability
Hierarchical Holographic Modeling (HHM)	Comprehensively identifies and assesses systemic risks through multi-tiered, multi-perspective decomposition and integration.	+ Suitable for highly complex systems; captures cross-hierarchical interdependencies– Methodological complexity; high data integration challenges
Fault Tree Analysis (FTA)	Visually maps risks' pathways and compound mode via tree diagrams.	+ Intuitive visualization; compatible with complementary methods- Operational difficulties with oversized models; lacks dynamic adaptability
Checklist Method	Converts risk factors and experience/standards into binary ("Yes/No") judgments via structured lists.	+ Requires no specialized tools; standardized workflow reduces training costs- Effectiveness compromised by incomplete check items or unforeseen risks

The methodologies outlined in Table 1 exhibit distinct application domains. Among these, the WBS-RBS method and Hierarchical Holographic Modeling (HHM) demonstrate broader utility in risk identification due to their inherent comprehensiveness.

The WBS-RBS method is particularly suitable for large-scale project management. In a metro project in City S, structural decomposition enables a visual representation of risk relationships, as employed in Cao Peng et al.'s study [4].

The procedure first decomposes shield tunneling processes using a Work Breakdown Structure (WBS): dividing construction into six sequential phases—from "Shield Launch Preparation" to "Shield Dismantling and Removal"—with further subdivision into discrete activities. Subsequently, a Risk Breakdown Structure (RBS) categorizes potential risks into five domains as "Man, Machine, Material, Method, Environment", further decomposed into specific risk scenarios.

A WBS-RBS coupling matrix is then established, designating potential risks as "1" and non-applicable risks as "0", thereby visualizing correlations between construction phases and risk factors.

Take "Shield Launch" and "Shield Launch" as an example. Table 2 presents the coupling matrix analysis for "Shield Launch" (WBS) and "Environmental Factors" (RBS), explicitly mapping their risk interdependencies.

DOI: 10.54254/2755-2721/2025.MH25027

Table 2: WBS-RBS coupling matrix

RBS WBS		Shield Launch			
		Sealing Gasket Installation	Retaining Structure Demolition	Tail Seal Greasing	Negative Ring Assembly
Environmental Factors	Overlying Environment Changes	1	1	0	0
	On-site Protection Deficiencies	1	1	1	1
	Geological Anomalies	1	1	0	0
	Poor Site Environmental Management	1	1	1	1

2.2. Risk assessment

Following risk identification, subsequent risk assessment is required to delineate both the probability of occurrence and potential loss magnitude. Common methodologies for risk evaluation are summarized in Table 3 [5].

Table 3: Methods of risk assessment

Method	Principle	Advantages & Limitations
Analytic Hierarchy Process (AHP)	Decomposes complex decisions into hierarchical structures and criteria (1-9 scaling system).	+ Integrates qualitative-quantitative analysis; clear hierarchical framework– Susceptible to subjective judgment bias
Fuzzy Comprehensive Evaluation (FCEM)	Converts qualitative indicators into quantitative metrics for analysis.	+ Delivers objective, persuasive evaluations; handles complex systems– Computationally intensive
Entropy Weight Method	Derives objective weights by calculating information entropy of indicators.	+ Eliminates subjective bias via data dependency– Fails to capture inter-indicator correlations
LEC Risk Assessment	Quantifies personnel hazard levels using three operational risk factors.	+Simple implementation; intuitive quantification– Subjectivity-limited; confined to occupational hazards
Failure Mode and Effects Analysis (FMEA)	Identifies failure modes, causes, and impacts during construction processes.	+ Enables proactive risk prevention; prioritizes risks quantitatively– Expert-dependent; high analysis costs
Bayesian Network	Graphically models probabilistic dependencies among variables.	+ Enables multidimensional analysis with high data credibility– Computationally intensive

The Analytic Hierarchy Process (AHP) represents the most extensively applied methodology, followed by Fuzzy Comprehensive Evaluation (FCEM). However, integrated multi-method approaches prevail in practical engineering applications. As demonstrated in Nie Renjie et al.'s research [6], a hybrid risk evaluation framework combining AHP and FCEM was employed for multi-criteria decision problems. Both methodologies establish qualitative-to-quantitative relationships across diverse risks through systematic procedures. The initial qualitative risk assessment involves stratifying risks into five likelihood tiers and categorizing consequence severity

DOI: 10.54254/2755-2721/2025.MH25027

into five levels. A two-dimensional coupling matrix is then developed correlating likelihood and severity parameters, enabling risk classification into Levels I-IV.

Subsequently, the Analytic Hierarchy Process (AHP) is applied to determine risk weights. Based on risk identification outcomes, a hierarchical structure is established with Shield Tunnel Construction Safety Risk as the goal layer, risk events as the criterion layer, and specific risk factors as the factor layer. For criteria associated with multiple factors (denoted as "i", "u", "j"), pairwise comparisons ("i" vs. "u") are conducted using a 1-9 quantification scale—where 1 denotes "equally important," 3/5 indicate "moderately more important," and 7/9 represent "extremely more important." Experts are convened for scoring, followed by consistency validation; upon confirming acceptability, risk weight vectors are calculated.

Fuzzy Comprehensive Evaluation is employed to estimate and score risk likelihood and consequence severity, ultimately determining the final risk level. The procedure initiates by defining the factor universe comprising identified risk elements, followed by establishing an evaluation set partitioned into five severity tiers—from "catastrophic" to "negligible"—based on risk consequence magnitude. Subsequently, a membership matrix is constructed through expert scoring, allocating weights summing to unity for each factor-evaluation pair. The M(•,+) operator is then applied via SPSSAU to generate an Elements×Evaluation weight judgment matrix R. Risk classification is finally determined by synthesizing likelihood estimates and consequence severity assessments.

3. Risk control

3.1. Risk treatment

Risk treatment encompasses diverse measures addressing the "Man, Machine, Material, Method, Environment" framework, with distinct strategies tailored to specific risk categories. This study focuses on methodologies for how to determine optimal risk treatments.

Four fundamental treatment levels exist: risk acceptance, risk mitigation, risk transfer, and risk avoidance. Selection among these strategies is guided by prior risk assessment outcomes.For risks with a low level of danger, are considered negligible and require no treatment measures; for moderate risks, they are deemed tolerable and no treatment measures are necessary, but active risk monitoring is required; for high risks, they are considered undesirable and demand implementation of treatment measures coupled with intensified monitoring; for extremely high risks, they are intolerable, and at this point, great attention must be paid and efforts should be made to avoid them; failing which reduction to acceptable levels must be pursued. For elevated-risk scenarios, the ALARP (As Low As Reasonably Practicable) principle governs decision-making, which intrinsically balances the cost of further risk reduction against potential loss magnitude [7]. Quantified risk evaluation outcomes inform "potential loss" assessments, while determining additional treatment measures requires enhanced stakeholder communication with contractors or expert consultation to establish organizational risk tolerance thresholds.

3.2. Risk monitoring

Risk monitoring requires conducting timely surveys of strata which not be excavated ahead of the tunnel face during excavation, known as advanced geological prediction. Current common prediction methods include TSP, infrared detection, and ground-penetrating radar. TSP, a seismic wave reflection-based detection method, utilizes depth migration imaging technology for data processing, delivering high prediction accuracy and long forecasting range [8]. Infrared

DOI: 10.54254/2755-2721/2025.MH25027

detection operates by sensing infrared radiation fields generated from molecular vibrations in underground rock masses or water bodies, featuring portable equipment and simple operation [9]. Ground-penetrating radar employs reflections of high-frequency electromagnetic pulse waves, characterized by high resolution, non-destructiveness, efficiency, and strong anti-interference capabilities [10]. In the advanced geological prediction for the Huanghouling Tunnel, Yong Haoming applied these three methods across different tunnel mileage sections [11]. After consolidating existing survey data to preliminarily determine the geological characteristics of the Huanghouling area, he comprehensively implemented all three methods supplemented by fuzzy evaluation to establish a complete advanced geological prediction scheme.

4. Conclusion

In risk identification, the WBS-RBS method is most prevalent, which decomposes risk sources and construction activities into granular components, and constructs a coupling matrix using binary notation ("0” or "1") to represent potential risk factors, providing an intuitive and efficient visualization approach. Regarding risk assessment and evaluation, the primary objective involves quantifying qualitative risk analysis outcomes, typically achieved through the Analytic Hierarchy Process to score accident risks across hierarchical levels, complemented by fuzzy comprehensive evaluation to define factor sets, rating sets, and weight distributions, with final weights determined via aggregation operators.

Risk treatment fundamentally requires balancing mitigation costs against potential losses, guided by the ALARP principle, with solutions formulated through contractor coordination. Risk monitoring necessitates geological prospecting technologies to survey rock mass properties ahead of the tunnel face, forming advanced geological prediction schemes.

Through synthesizing risk assessment approaches, the paper identifies some key research gaps: Excessive reliance on expert scoring in certain tunnel risk assessments may introduce subjectivity and cause some certain issues despite expert experience has its merits; concurrently, cumbersome data processing in some methods impedes field adoption due to the high cost for a technician to learn it; moreover, existing monitoring studies often prioritize high-probability risks while neglecting low-probability/high-impact events such as gas explosions.

Consequently, future efforts should develop integrated methodologies balancing operational efficiency with data reliability while ensuring accessibility for technical personnel and easy for the contractors to understand. Simultaneously, monitoring methods for low-probability risks require refinement to optimize potential losses for broader implementation to costs relative.

References

[1] ZHANG Songtao, HU Zhongchun, WANG Gongzhong, et al. Risk assessment of large-diameter shield tunneling through bustling urban areas [J]. Industrial Safety and Environmental Protection, 2020, 46(5): 36-39.
[2] TIAN Boquan. Research on construction risks of shield tunneling in Dalian Metro tunnels [D]. Master's Dissertation, Dalian University of Technology, 2016.
[3] WANG Yushi. Research on risk management of shield tunneling in metro engineering [D]. Master's Dissertation, Beijing Jiaotong University, 2021. DOI: 10.26944/d.cnki.gbfju.2021.000780.
[4] CAO Peng. Research on risk management of shield tunneling for Line 6 of C City Metro [D]. Master's Dissertation, Zhejiang University, 2021.
[5] WANG Pengfei. Research on safety risk management of metro shield tunneling construction [D]. PhD Dissertation, University of Chinese Academy of Sciences (School of Engineering Science), 2024: 61.
[6] NIE Renjie. Research on construction risk management of shield tunneling in S City Metro [D]. Master's Dissertation, Dalian University of Technology, 2020: 31-37.

DOI: 10.54254/2755-2721/2025.MH25027

[7] Hurst, John.A summary of the 'ALARP' principle and associated thinking [J].Journal of Nuclear Science and Technology.2019-2.242-243.
[8] ZHOU Liming, QIU Dongming, FU Daiguang, et al. TSP advanced geological prediction technology and its 3D results research and application [J]. Journal of Yangtze River Scientific Research Institute, 2016, 33(10): 72-78.
[9] TIAN Rong, WU Yingming. Application of infrared detection technology in advanced water exploration for tunnels [J]. Railway Standard Design, 2007(S2): 107-110.
[10] BAI Bing, ZHOU Jian. Development and application status of ground-penetrating radar testing technology [J]. Chinese Journal of Rock Mechanics and Engineering, 2001(4): 527-531.
[11] YONG Haoming. Comprehensive application research of advanced geological prediction methods in Huanghouling Tunnel [D]. Master's Dissertation, Southwest Jiaotong University, 2021. DOI: 10.27414/d.cnki.gxnju.2021.003281.