Risk Assessment of Tunnel Construction Based on Grey Theory Optimization Model

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Abstract. Railway tunnel construction projects are typically carried out under complex geological conditions, involving substantial investment and extended construction periods. Accidents can disrupt normal construction progress while causing significant economic and human losses. Therefore, conducting a comprehensive risk assessment for tunnel construction is crucial for ensuring the timely and successful completion of railway projects. Against this backdrop, the author proposes an improved risk assessment indicator system. Utilizing an optimized AHP gray comprehensive theory model, this study conducts a comprehensive risk assessment for the construction of the Banzhulin Tunnel. The final comprehensive risk score is 2.7721, indicating a moderate risk level. Among the risks assessed, gas, natural gas, and harmful gases are classified as high risk, while cave-ins and sudden water/mud inflows are near high risk. The study demonstrates that the optimized indicator system and model enable a more comprehensive and scientific assessment of railway tunnel construction risks, providing valuable reference for risk control in railway tunnel construction.

Keywords: Risk assessment; AHP and gray evaluation method; Risk of Railway tunnel; Construction duration; Banzhulin tunnel

1 Introduction

With the rapid development of China's transportation infrastructure, railway tunnel projects have increased significantly, trending toward longer lengths and more complex geological conditions. Major engineering feats such as plateau railways and ultra-large-diameter shield tunnels continue to emerge. Tunnel construction frequently encounters unforeseeable challenges, making it a high-risk engineering endeavor. Preliminary statistics indicate that between 2014 and 2023, as shown in Figure 1 below, China experienced 86 tunnel construction accidents resulting in 269 fatalities[1]. The number of accidents followed a U-shaped distribution pattern, while the death toll fluctuated. Following the promulgation of the Nine Tunnel Safety Regulations in 2015, the number of accidents generally declined, indicating that stringent and effective safety oversight measures can effectively curb accidents. However, influenced by multiple factors, ac-

J. Zhang et al. (eds.), *Proceedings of the 2026 2nd International Conference on Engineering Management and Safety Engineering (EMSE 2026)*, Advances in Engineering Research 300,
https://doi.org/10.2991/978-94-6239-703-3_8

cidents rebounded significantly during certain periods. Analysis attributes this to inadequate implementation of primary safety responsibilities by construction enterprises and insufficient fulfillment of comprehensive safety responsibilities by all personnel. Therefore, establishing a comprehensive risk assessment methodology for tunnel construction is particularly crucial.

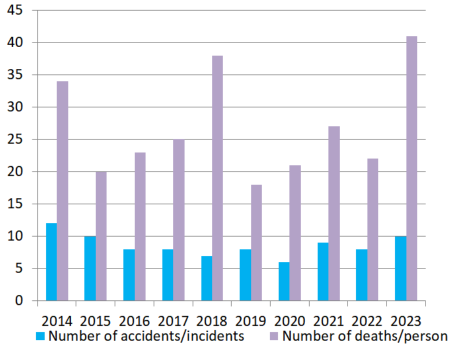


Fig. 1. Statistics on the number of accidents and fatalities in tunnels, 2014-2023

Currently, risk assessments for domestic railway tunnel projects predominantly employ qualitative evaluations with a high degree of subjectivity, analyzing various individual risk factors separately. For instance, CHU et al.[2] utilized a fuzzy comprehensive evaluation method to assess the risk of water inrush in the Qiyueshan Tunnel; Xue Yadong et al.[3] developed a model integrating the Analytic Hierarchy Process (AHP) and variable weight theory to conduct a specialized assessment of the latent karst cavern risk in the Hutoushan Tunnel; Qi Xiaogui et al.[4] employed a fuzzy hierarchical comprehensive evaluation method to assess tunnel collapse risks; Su Mubiao et al.[5] established a hierarchical weighted comprehensive method to evaluate earthquake disaster losses in railway tunnels. Other scholars have also improved single-factor assessment methods by integrating various tunnel factors for comprehensive evaluation. For instance, Chen Shaohua[6] assessed and graded the risks of Guanjiao Tunnel using expert surveys, brainstorming, and risk matrix methods; XIA et al.[7] developed an uncertainty entropy risk model for the comprehensive assessment of geological risks in Shiziyuan Tunnel; WANG et al.[8] employed an improved fuzzy analysis network model to comprehensively evaluate construction risks in Humaling Tunnel; Li Shuqiang[9] proposed a three-level fuzzy comprehensive evaluation computational model for assessing construction safety risks in high-speed railway tunnels; Dai Shiguang[10] applied a grey-contingency theory model to assess the construction safety of the Wuzhishan Tunnel. Among the extensive literature on tunnel risk research, few studies have conducted overall risk assessments that simultaneously incorporate schedule risks and evaluate sub-item risks. Therefore, an integrated assessment considering both schedule risks and sub-item risks would be more conducive to controlling overall risk.

Based on this, the author evaluates tunnel construction risks using the improved risk assessment indicator system and the optimized AHP grey comprehensive theory model, taking the Banzhulin Tunnel on the Xuyong-Bijie Railway as an example. This approach enhances the comprehensiveness and practicality of railway tunnel construction risk assessment.

2 Optimization of Tunnel Risk Evaluation Indicator System

Based on the key risk identification factors outlined in the Technical Specifications for Risk Management in Railway Tunnel Engineering, tunnel construction risk assessments primarily focus on safety, environmental impact, investment, and schedule during the construction process. Existing literature indicates that most tunnel construction risk assessments emphasize safety risk evaluation, with some incorporating environmental risk considerations. However, few address schedule risk assessment. During tunnel construction, complex environmental conditions frequently lead to various issues causing schedule delays, which typically result in significant negative impacts and economic losses. Therefore, schedule risk analysis is essential in comprehensive tunnel construction risk assessments. Schedule risks interact with and constrain safety, environmental, and investment risks. Assessing schedule risks can further validate and measure the accuracy of safety and environmental risk assessments while also providing valuable reference for investment risk analysis.

Regarding the schedule risk indicator, the author proposes incorporating it as a primary indicator within the comprehensive assessment framework. This indicator comprises two sub-indicators: schedule delays caused by construction organization arrangements and schedule delays triggered by construction accidents. The specific methodology involves expert analysis and scoring, followed by quantitative processing through a mathematical model for integration into the overall indicator analysis. The assessment scores for schedule risks stemming from construction organization arrangements and accident-induced schedule risks will inform the impact of other risks, enabling corresponding adjustments to be made. The specific operational process is illustrated in Figure 2 below.

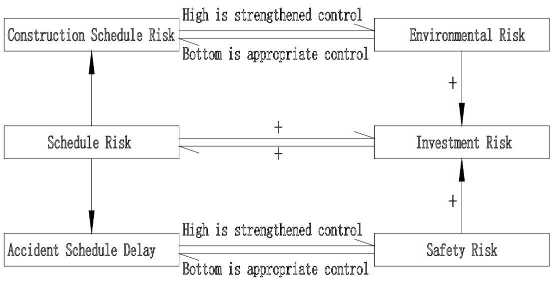


Fig. 2. Risk adjustment diagram of construction period

When the risk assessment score for construction delays caused by unreasonable construction organization is high, efforts should be intensified to control environmental risks—both internal and external—to create a favorable construction environment. If environmental risks are high, focus should be placed on optimizing the construction organization design and improving the construction technical plan. When the score for construction accident-related schedule delay indicators is high, safety risk control should be strengthened. If safety risks are elevated, efforts should concentrate on managing factors with high risk scores within secondary indicators, establishing targeted monitoring protocols and construction technical solutions.

3 AHP Gray Comprehensive Theory Evaluation Model

3.1 Overview of AHP Gray Synthesis Theory

Railway tunnel construction risks are not determined by a single risk factor but are influenced by multiple risk factors, requiring comprehensive consideration of the interrelationships among these factors. The Analytic Hierarchy Process (AHP) assigns weights to each indicator through comparative analysis among them. Grey theory research operates under conditions where some information is known and some is unknown. Gray theory evaluates risk by first defining several categories. Based on the state of the evaluated object, quantitative analysis determines its category, ultimately yielding the overall risk category of the object[11]. Given that tunnel construction risks involve numerous interconnected factors and that risk indicator information exists in a gray state, this method is highly suitable for tunnel construction safety risk assessment. Furthermore, integrating AHP with grey theory mitigates the qualitative nature of AHP, enhances data objectivity, and yields more scientifically reliable evaluation outcomes.

3.2 Determination of Indicator Weights by AHP Method

To minimize the impact of subjectivity on results, a multi-expert scoring approach was adopted, with averages calculated to establish a judgment matrix. Therefore, to facilitate questionnaire surveys and improve pairwise comparisons between indicators, a new 9-point scale questionnaire was developed based on the AHP 1–9 scale methodology. The conversion relationship between the two scales is shown in Table 1 below:

Table 1. Corresponding table of questionnaire scale 9 and AHP9 scale transformation

Questionnaire Qualitative Items	Corresponds to Questionnaire 9 Scale	Corresponds to AHP9 Scale
Minimal	1	1/9
Smaller	3	1/5
Same e	5	1
Larger	7	5
Very Large	9	9

After averaging the expert scores and converting them to AHP9 scale scores, establish the judgment matrix A:

$$A = (\partial_{ij})_{n\times m} = \begin{bmatrix} \partial_{11} & \partial_{12} & \cdots & \partial_{1n} \\ \partial_{21} & \partial_{22} & \cdots & \partial_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \partial_{n1} & \partial_{n2} & \cdots & \partial_{nn} \end{bmatrix} \tag{1}$$

Then compute the decision matrix using the square root method:

1)Calculate the product of each row element in the decision matrix, denoted as Mi:

$$M_i = \prod_{j=1}^{n} a_{ij}, i = 1, 2, \cdots, n \tag{2}$$

2)Calculate the nth root of Mi:

$$\overline{Wi} = \sqrt[n]{Mi} \tag{3}$$

3) Normalize the vector $\overline{W_i} = \left[\overline{W_1}, \overline{W_2}, \cdots, \overline{W_n}\right]^T$:

$$\overline{W_i} = \overline{W_i} \Big/ \sum_{j=1}^{n} \overline{W_j} \tag{4}$$

this is the required eigenvector

$$\overline{W_i} = \left[\overline{W_1}, \overline{W_2}, \cdots, \overline{W_n}\right]^T;$$

4)Calculate the largest characteristic root of the judgment matrix λmax:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{5}$$

where (AW)i denotes the ith element of the vector.

5)the consistency test of the judgment matrix:

$$CR = (\lambda_{max} - n) / RI(n-1) \tag{6}$$

If CR<0.1,the test is passed, yielding the primary indicator weights A = (ω1, ω2,⋯,ωn) and the secondary indicator weights Fi =(ωi1, ωi2,⋯,ωin).

3.3 Establish the Sample Matrix

According to the Technical Specifications for Risk Management in Railway Tunnel Engineering, the comprehensive safety risk rating index for tunnel construction is divided into four score segments from highest to lowest: {Extremely High (Level I), High (Level II), Moderate (Level III), Low (Level IV)}, with corresponding scores S={4, 3, 2, 1}. Organize n experts to score the project's risk index, then compile the scores into an evaluation sample matrix D:

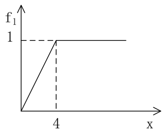
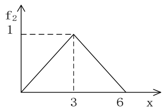
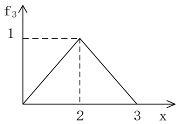
$$D=\begin{bmatrix} d_{111} & d_{112} & \cdots & d_{11n} \\ d_{121} & d_{122} & \cdots & d_{12n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{ij1} & d_{ij2} & \cdots & d_{ijn} \end{bmatrix} \tag{7}$$

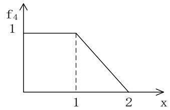
3.4 Establishment of Gray Numbers and Whitening Weight Functions

The risk assessment indicators developed by the author are all qualitative. To accurately and reasonably evaluate tunnel construction risks, these qualitative indicators must be converted into quantitative indicators for analysis. Based on the established scoring criteria, the gray levels are categorized into four classes. Corresponding whitening weight functions are developed to facilitate the transition from qualitative to quantitative assessment, with threshold values of 4, 3, 2, and 1 for each gray level. The resulting whitening weight functions and their corresponding schematic diagrams are presented in Table 2 below:

3.5 Calculation of Grey Evaluation Weight Vectors and Weight Matrices

Table 2. Schematic diagram of each whitening weight functions and corresponding functions

Gray Class e	Gray Number $\otimes_e$	Whitening Weight Function $f_e(d_{ijk})$	Schematic of Function
e=1	$\otimes_1 \in (0,4,+\infty)$	$f_1(d_{ijk})=\begin{cases} d_{ijk}/4, d_{ijk}\in[0,4] \\ 1, d_{ijk}\in[4,+\infty] \\ 0, d_{ijk}\notin[0,4] \end{cases}$	
e=2	$\otimes_2 \in (0,3,6)$	$f_2(d_{jik})=\begin{cases} d_{ijk}/3, d_{ijk}\in[0,3] \\ (6-d_{ijk})/3, d_{ijk}\in[3,6] \\ 0, d_{ijk}\notin[0,6] \end{cases}$	
e=3	$\otimes_3 \in (0,2,4)$	$f_3(d_{ijk})=\begin{cases} d_{ijk}/2, d_{ijk}\in[0,2] \\ (4-d_{ijk})/2, d_{ijk}\in[2,4] \\ 0, d_{ijk}\notin[0,4] \end{cases}$	

e=4	$\otimes_4 \in (0,1,2)$	$f_4(d_{ijk}) = \begin{cases} 1, d_{ijk} \in [0,1] \\ 2 - d_{ijk}, d_{ijk} \in [1,2] \\ 0, d_{ijk} \notin [0,2] \end{cases}$	

Calculate the e-th grey category evaluation coefficient for indicator Fi:

$$X_{ije} = \sum_{k=1}^{h} f_e(d_{ijk}) \tag{8}$$

and then calculate the total gray category coefficient of the gray category of the evaluation indicator:

$$X_{ij} = \sum_{e=1}^{4} X_{ije} \tag{9}$$

then the grey evaluation weight for the grey categories of the evaluated indicator is:

$$r_{ije} = X_{ije} / X_{ij} \tag{10}$$

Thus, the gray evaluation weight vectors rij = rije (e = 1, 2, 3, 4) for the four gray categories are obtained. Similarly, the gray category weight matrices Ri corresponding to all secondary indicators of tunnel construction risk can be derived:

$$R_i = \begin{bmatrix} r_{i1} \\ r_{i2} \\ r_{i3} \\ r_{i4} \end{bmatrix} = \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & r_{in3} & r_{in4} \end{bmatrix} \tag{11}$$

Conduct a comprehensive clustering evaluation matrix for the first-level indicators of the evaluation project:

$$B_i = C_i \cdot R_i = (b_{i1}, b_{i2}, b_{i3}, b_{i4}) \tag{12}$$

Thus, the gray evaluation weight matrix R for the gray evaluation of the first-level indicators is obtained as follows:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ \vdots & \vdots & \vdots & \vdots \\ b_{m1} & b_{m2} & b_{m3} & b_{m4} \end{bmatrix} \tag{13}$$

3.6 Comprehensive Evaluation and Algorithm Optimization

The results of the comprehensive evaluation matrix B for the evaluated items are as follows:

$$B = A \cdot R = (b_1, b_2, b_3, b_4) \tag{14}$$

To make the comprehensive evaluation matrix results more intuitive, the results are normalized to obtain the comprehensive evaluation value Z by multiplying the comprehensive evaluation matrix with the grey-class score vector:

$$Z = B \cdot S^T \tag{15}$$

The improvement to the aforementioned algorithm primarily involves multiplying Equation (11) by the evaluation grade score matrix ST after calculating Equation (11) to obtain the evaluation results for secondary indicators. Subsequently, the evaluation results for primary indicators are derived by multiplying the weights of primary indicators by the evaluation results of secondary indicators. Finally, the overall evaluation result is obtained. The calculation process is as follows:

First, calculate the evaluation results for each secondary indicator:

$$Z_{F_i} = R_i \cdot S^T \tag{16}$$

Then, calculate the evaluation results for each primary indicator:

$$Z_i = C_i \cdot Z_{C_i} \tag{17}$$

Finally, derive the overall evaluation result:

$$Z' = Z_{C_i} \cdot A^T \tag{18}$$

4 Case Study Analysis

4.1 Overview of Ban Zhu Lin Tunnel

The Banzhulin Tunnel, with a total length of 12,758 meters, is situated in the low-to-medium mountain eroded terrain zone of the northern Yunnan-Guizhou Plateau. Characterized by steep topography crisscrossed by ravines and valleys, it traverses the eastern Yunnan fold belt with a maximum burial depth of 580 meters.

The tunnel site encompasses three major regional structures, one syncline, three anticlines, seven faults, and six types of adverse geological conditions.

Karst formations account for 62.13% of the tunnel's rock mass, with a karstic horizontal flow zone spanning 5.740 km. The entire tunnel features a V-shaped gradient, with the longest single-sided slope reaching 8.937 km. The shallow-buried section passes beneath the Yangtze River Middle-Upper Reaches Rare Fish Conservation Area, imposing stringent environmental requirements. Non-coal strata exhibit high gas content with irregular natural gas outbursts. Through investigation, risks associated with the Banzhulin Tunnel were categorized into three key areas based on assessment priorities: safety, environment, and schedule. Primary risk types include:

Table 3. Main construction risks of Banzhulin Tunnel

Target risk	Risk name	Risk components (manifestations)
Environment	Surface water loss risk	The shallowly buried section passes beneath residential areas. During construction and operation, groundwater discharge may impact surface water used for production and daily life by local residents.
	Risk of Tailings Disposal	Steep terrain complicates tailings pond site selection. Disposing tailings in ravines poses risks during heavy rainfall, as surface runoff from gully erosion may threaten the tailings pond.
Safe	Tunnel opening instability	The portal terrain is steep and rugged, characterized by interbedded sandstone and mudstone formations. Adverse geological conditions such as portal alignment deviation and lateral pressure exist, making the portal prone to instability.
	Rockfall and falling rocks	The portal cross-slope is steep, with exposed bedrock severely weathered, posing risks of rockfall and falling debris.
	Collapse	The tunnel body traverses seven faults, with a total fault fracture zone length of 465m, accounting for approximately 4% of the total tunnel length.
	Water and mud outbursts	The tunnel primarily traverses a clastic rock fissure aquifer with moderate groundwater development and a karst aquifer with intense groundwater development; both are phreatic-to-confined water types.
	Gas, natural gas, and toxic gases	The tunnel traverses sandstone containing manganese ore, with underlying carbonaceous shale and phosphatic sandstone potentially harboring toxic gases. Geological drilling has also detected the presence of natural gas.
	Rockburst risk	The maximum cover depth is 580m, located at the intersection of three major tectonic systems, posing a potential risk of rock bursts during construction.
	Reservoir leakage risk	The tunnel passes beneath the Huifeng Reservoir, with the shallow-buried section traversing the reservoir's flood discharge influence zone, posing certain impacts on tunnel construction and operation.
	Other risks	Unforeseen risks stemming from untimely material supply, management issues, weather conditions, and technical personnel.
Construction Schedule	Schedule Delays Due to Construction Organization Arrangements	The tunnel exceeds 10 kilometers in length, with extensive karst formations posing challenges for reverse slope construction. The construction timeline is fixed and relatively tight.
	Schedule Delays Caused by Accidents	Accidents occurring during the construction process can easily lead to schedule delays.

4.2 Development of the Risk Evaluation System

Based on Table 3, the following risk assessment model structure is established, which is shown in Figure 3 below:

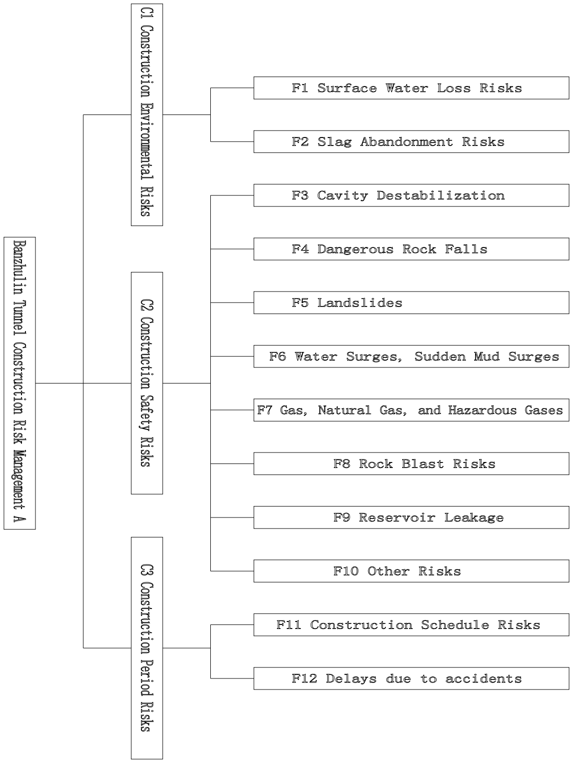


Fig. 3. Safety risk assessment model for construction in Banzhulin Tunnel

The model was established by integrating expert risk identification results with AHP principles, with Construction Risk A of the Banzhulin Tunnel serving as the ultimate evaluation target. This target is determined by the Ci indicator, whose factors are defined by Fi.

4.3 Case Study Calculations and Results

4.3.1 Determination of Indicator Weights. Thirteen experts were invited, including 4 tunnel design experts, 7 technical leaders of the construction unit, 1 chief supervisor and 1 technical leader of the construction unit representative, to provide qualitative risk assessments for the relative occurrence probabilities of paired risk indicators. The average scores for each indicator were calculated based on the questionnaire's 9-point scale scores from different experts. These were then converted to AHP 9-point scale scores to form the judgment matrix A. Weights for each factor were calculated and consistency verified using Equations (1) to (6), as shown in Table 4 below.

Table 4. Weight of each risk index in Banzhulin Tunnel

Total Debris Disposal Indicator	Primary Indicator	Secondary Indicator
Banzhulin Tunnel Construction Risk Management (A) (1)	Construction Environmental Risks (C_1) (0.1062)	Surface Water Loss Risks (F_1) (0.2000)
		Slag Abandonment Risks (F_2) (0.8000)
	Construction Safety Risks (C_2) (0.6333)	Cavity Destabilization (F_3) (0.0559)
		Dangerous Rock Falls (F_4) (0.0786)
		Landslides (F_5) (0.1157)
		Water Surges, Sudden Mud Surges (F_6) (0.3023)
		Gas, Natural Gas, and Hazardous Gases (F_7) (0.2153)
		Rock Blast Risks (F_8) (0.0277)
		Reservoir Leakage (F_9) (0.0391)
		Other Risks (F_{10}) (0.1655)
	Construction Period Risks (C_3) (0.2605)	Construction Schedule Risks (F_{11}) (0.2500)
		Delays due to accidents (F_{12}) (0.7500)

4.3.2 Establish the Sample Matrix. Based on the tunnel's fundamental conditions, 13 experts who participated in the preliminary survey were invited to score the risk levels for each indicator, yielding the following gray judgment matrix D:

$$D=\begin{bmatrix} 3&2&3&3&2&1&1&2&1&1&1&4&2\\ 2&1&2&1&2&1&2&1&1&1&1&1&2\\ 2&1&3&2&1&1&1&2&1&2&2&2&2\\ 1&1&3&1&2&1&2&2&1&2&3&2&3\\ 3&2&3&3&2&2&1&2&1&2&2&2&2\\ 3&2&3&3&3&3&2&3&1&2&4&3&3\\ 3&2&3&3&4&3&3&4&1&4&1&4&3\\ 2&1&3&2&1&2&1&1&1&3&1&1&1\\ 3&2&3&1&2&2&1&1&1&1&1&1&2\\ 3&2&3&3&4&2&1&2&3&3&2&2&2\\ 2&2&1&1&2&2&3&2&1&1&2&2&1\\ 4&2&3&2&2&2&3&3&2&2&2&2&2 \end{bmatrix}$$

4.3.3 Calculate Gray Evaluation Coefficients. Substitute the values from the gray judgment matrix into the corresponding whitening weight function. Using Equations (8) to (10), derive the gray weight matrices for each secondary indicator:

$$R_1=\begin{bmatrix} 0.2364 & 0.2909 & 0.2909 & 0.1818\\ 0.1636 & 0.2182 & 0.3273 & 0.2909 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.1964 & 0.2679 & 0.3571 & 0.1786 \\ 0.2143 & 0.2857 & 0.3214 & 0.1786 \\ 0.2389 & 0.3186 & 0.3717 & 0.0708 \\ 0.3097 & 0.3894 & 0.2655 & 0.0354 \\ 0.3585 & 0.3774 & 0.1887 & 0.0755 \\ 0.1807 & 0.2410 & 0.2892 & 0.2892 \\ 0.1892 & 0.2523 & 0.3063 & 0.2523 \\ 0.2857 & 0.3571 & 0.3214 & 0.0357 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0.1979 & 0.2635 & 0.3594 & 0.1796 \\ 0.2776 & 0.3463 & 0.3761 & 0 \end{bmatrix}$$

4.3.4 Comprehensive Evaluation Results. Calculations were performed separately for the traditional algorithm and the improved algorithm.

1. Traditional Algorithm Calculation: After deriving the grey weight matrices for each secondary indicator, the grey evaluation weight matrix for the sample matrix was computed using Bi = CiRi:

$$R = \begin{bmatrix} 0.1782 & 0.2327 & 0.3200 & 0.2691 \\ 0.2860 & 0.3489 & 0.2823 & 0.0829 \\ 0.2576 & 0.3256 & 0.3719 & 0.0449 \end{bmatrix}$$

Then, from equation (14), we calculate that

$$B = \begin{bmatrix} 0.2671 & 0.3305 & 0.3096 & 0.0928 \end{bmatrix}$$

Finally, the comprehensive evaluation result Z = 2.7721 is obtained from Equation (15).

2. Improved algorithm calculation: The evaluation results for secondary indicators are computed via Equation (16):

$$Z_{F1} = R_1 \cdot S^T =$$

$$\begin{bmatrix} 0.2364 & 0.2909 & 0.2909 & 0.1818 \\ 0.1636 & 0.2182 & 0.3273 & 0.2909 \end{bmatrix} \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 2.5818 \\ 2.2545 \end{bmatrix}$$

Similarly, the evaluation results for other secondary indicators are: ZC2=[2.4821 2.5357 2.7257 2.9735 3.0187 2.3133 2.3784 2.8929]T, ZC3=[2.4790 2.015]T.

Then, the evaluation results for the primary indicators are calculated using Equation (17):

$$Z_1 = C_1 \cdot Z_{C1} = \begin{pmatrix} 0.2000 & 0.8000 \end{pmatrix} \begin{bmatrix} 2.5818 \\ 2.2545 \end{bmatrix} = 2.3200$$

Similarly, the evaluation results for other primary indicators are:Z2=2.8381, Z3=2.7959.

Finally, the comprehensive evaluation result is calculated:

$$Z' = Z_i \cdot A^T =$$

$$\begin{bmatrix} 2.3200 & 2.8381 & 2.7959 \end{bmatrix} \begin{bmatrix} 0.1062 \\ 0.6333 \\ 0.2605 \end{bmatrix} = 2.7721$$

Table 5. Comprehensive risk assessment results of the improved algorithm

Total Indicator	Weights	Evaluation Results	Primary Indicator	Weights	Evaluation Results	Secondary Indicator	Weights	Evaluation Results
A	1	2.7721	C_1	0.1062	2.3200	F_1	0.0212	2.5818
						F_2	0.0849	2.2545
			C_2	0.6333	2.8381	F_3	0.0354	2.4821
						F_4	0.0498	2.5357
						F_5	0.0732	2.7257
						F_6	0.1915	2.9735
						F_7	0.1363	3.0189
						F_8	0.0175	2.3133
						F_9	0.0247	2.3784
						F_{10}	0.1048	2.8929
			C_3	0.2605	2.7959	F_{11}	0.0651	2.4790
						F_{12}	0.1954	2.9015

Both the improved algorithm and the traditional algorithm yielded Z=2.7721, resulting in a consistent moderate risk assessment level. However, compared to the traditional approach, the improved algorithm also presents the evaluation results for each indicator, offering a more comprehensive and detailed analysis.

Table 5 shows the risk level ranking for each indicator in the Banzhulin Tunnel: F7 > F6 > F12 > F10 > F5 > F1 > F4 > F3 > F11 > F9 > F8 > F2. Among these, F7 indicates a high risk level, while F6 and F12 approach high risk. Corresponding construction technical plans and risk control measures should be prepared in advance.

4.4 Risk Response Countermeasures

For the assessed high-risk F7 and near-high-risk F6 and F12 hazards, the following countermeasures should be implemented:

4.4.1 For risks related to gas, natural gas, and harmful gases (F7). trengthen advance geological prediction and forecasting efforts. During construction, establish harmful gas monitoring, alarm, and ventilation systems to dilute and exhaust harmful gases from the tunnel, preventing accumulation. During operation, utilize manual and automated monitoring methods based on construction-phase gas monitoring data to ensure safety.

4.4.2 For water and mud outburst risks (F6). *G*iven the karst development in this tunnel, organize slope-following construction and drainage through auxiliary tunnels such as cross passages, horizontal drifts, and drainage tunnels to mitigate construction hazards. This approach also accommodates drainage needs during operation. Implement a dynamic risk management system covering the entire process—from advance geological forecasting to excavation and support—throughout construction.

4.4.3 The risk of schedule delays due to accidents (F12). involves the probability and severity of safety and environmental incidents, as well as construction accidents caused by rushed work or non-compliant operations. For the former risk, a risk monitoring system should be established during project construction, with specialized construction technical plans developed for indicators assessed as high risk or approaching high risk. For potential risks arising from long tunnel construction sections and tight schedules, the following measures should be implemented:

1. Develop a dynamic construction organization plan integrated with tooling and equipment. Adopt a "mechanization + information technology" approach for critical path construction, deploying multi-functional drilling rigs and other machinery to optimize key processes such as advance geological forecasting, excavation, spoil removal, and support installation.
2. Establish auxiliary tunnels including cross passages, entrance horizontal access tunnels, and exit horizontal access tunnels to create working faces for main tunnel construction. Implement the "long tunnel, short excavation" strategy to balance schedules across all critical paths as much as possible.
3. Employ reverse slope construction for shallow-buried tunnel sections when safety can be assured.

4.5 Results Verification

The author applied the aforementioned theory to determine the risk level rankings for the Banzhulin Tunnel. Prior to construction, an expert review concluded that classifying gas, natural gas, and harmful gases (F7), water and mud outburst risks (F6), and project delay risks due to accidents (F12) as high or near-high risk levels was reasonable. Throughout the construction of the Banzhulin Tunnel, the results of advance geological forecasting, the actual water inflow volume in the karst sections (which did not exceed the maximum estimated during the survey and design phase), and the configuration of auxiliary tunnels (including cross passages and cross-drifts designed to serve drainage functions during both construction and operation) all validated the accuracy of the risk level assessments. Targeted countermeasures implemented based on the risk levels of each indicator effectively mitigated various risk events during construction. The Banzhulin Tunnel is now operational as scheduled.

5 Conclusion

Through the 9-scale questionnaire survey method established by the author, combined with the improved tunnel risk assessment indicator system and the optimized AHP gray comprehensive model, the comprehensive risk of tunnel construction and the risk assessment results of each sub-item indicator can be obtained. This approach not only evaluates the comprehensive risk of tunnel construction but also comprehensively grasps the risks of each sub-item indicator, thereby enabling the formulation of targeted technical solutions and risk control measures based on risk levels. Compared with other assessment methods, this method has the following advantages:

1. The novel 9-point questionnaire scale is more adaptable for multi-expert scoring than traditional methods, reducing evaluator subjectivity.
2. Optimizes the tunnel construction risk assessment indicator system by incorporating schedule risk indicators into the comprehensive risk assessment framework. This addresses shortcomings in traditional tunnel construction assessment systems, making the comprehensive risk assessment more thorough and rational. It provides significant reference value for rational schedule planning, construction plan formulation, and risk control.
3. It constructs an optimized model for railway tunnel construction risk assessment. Unlike traditional models, it presents both the overall evaluation results and the individual indicator evaluations. This enhances the directionality and practicality of project risk assessment outcomes, thereby enabling more effective comprehensive risk control for the project.

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