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Risk Assessment of Karst Tunnel Water Inrush Based on Combined Weighting Method

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Abstract: Sudden water inrush is the primary geological hazard in karst tunnels, which poses significant risks and seriously threatens tunnel construction and safety. To address this issue, this study takes multiple karst tunnels under construction in Guangxi as research objects. Through geological investigation and analysis of the geological conditions and tunnel characteristics in the tunnel areas, this study selects seven key factors affecting tunnel water inrush, including basic quality index of rock mass, rock mass dip angle, rock mass integrity coefficient, surrounding rock saturated uniaxial compressive strength, maximum water inrush of the tunnel, annual rainfall in the tunnel site area during the rainy season, and tunnel burial depth, as evaluation indicators. A combined weighting-TOPSIS method for karst tunnel water inrush risk assessment system is constructed. Hierarchical analysis method is used to establish a judgment matrix to determine the subjective weights of evaluation indicators. Subsequently, the objective weighting entropy method is used to calculate the objective weights, and the combination of the two is used to form a combined weighting method to calculate the combined weights. Finally, based on the combined weighting-TOPSIS method, the distance and relative closeness between the cross-sections of karst tunnels under construction and the ideal solution are obtained to evaluate the risk of water inrush in karst tunnels under construction. The evaluation results have been well validated in advance geological drilling, demonstrating the feasibility of this method for literature evaluation of karst tunnel water inrush.

Keywords: combined weighting-TOPSIS method; entropy weight method; Karst tunnel; water inrush

1 INTRODUCTION

With the rapid development of infrastructure projects and the continuous improvement of construction technology in China, the number of tunnel projects in karst areas is increasing. In recent years, the construction of tunnels in karst regions has encountered significant challenges due to the unique geological conditions. A karst tunnel refers to a tunnel constructed in regions characterized by soluble rock (such as limestone), which can result in distinctive underground drainage systems and the formation of caves. During the construction of karst tunnels, sudden water inrush disasters often occur, posing great challenges to the construction process. Karst tunnel water inrush disasters mainly occur during tunnel construction when underground aquifers are disturbed, the rock's ability to resist water is weakened, and underground water under hydraulic pressure breaks through waterproof layers and flows into the tunnel [1]. Currently, due to limited space in tunnel engineering, once a water inrush accident occurs, it is difficult to evacuate personnel and equipment, resulting in significant losses of life and property [2]. Karst tunnels, buried deep in water-rich hydrogeological units, exhibit abundant water sources, large water consumption, and high hydraulic pressure. When tunnel excavation alters the movement and discharge of groundwater, water inrush disasters exceeding 10,000 tons can easily occur instantaneously, resulting in complete destruction of the tunnel under construction, causing catastrophic mechanical damage and personnel injuries [3-5]. Therefore, conducting risk assessments and mechanism studies on tunnel water inrush is of paramount importance when constructing tunnels in high-pressure water-rich areas.

Meng Yan and Lei Mingtang [6] analyzed and summarized the research status of water inrush in karst tunnels from three aspects: prediction of water inrush volume in karst tunnel areas, geological advance prediction technology, and water inrush treatment. They believe that the water inrush in karst tunnels should fully consider the geological conditions of the tunnels and the laws of karst development. Detailed geological investigation work must be carried out, and excessive reliance on mathematical models and computer technology should be avoided.

Sun, X. et al. [7] proposed a rapid assessment method for the safety of karst tunnels. By analyzing the influencing factors of water inrush disasters in karst tunnels, factors such as hydrodynamic conditions, adverse geological conditions, anti-inrush thickness, and surrounding rock characteristics were selected. A rapid assessment method for water inrush and mud inrush in karst tunnels was established by categorizing the influencing factors into primary, secondary and corrective factors. Through the evaluation of the water inrush project in the Yakouzhai large tunnel of the Shanghai-Kunming high-speed railway, it was concluded that this assessment method addresses the shortcomings of traditional water inrush risk assessment by considering the surrounding rock characteristics and thickness. The method was validated and achieved certain research results in assessing water inrush risk and its mechanisms in tunnels. Hou and Li proposed a comprehensive weighted TOPSIS method for assessing water inrush risk in tunnels [8, 9]. This approach addresses issues in existing methods such as result ambiguity and insufficient quantification of evaluation criteria. By integrating the TOPSIS method, AHP method, and coefficient of variation method, they conducted comprehensive weighting of subjective and objective factors, constructing four samples of tunnel water-inrush risk levels. They established a tunnel water-inrush risk assessment system based on the TOPSIS method and applied it to the Xiangyun Tunnel of the railway, evaluating water-inrush risk across eight sections. The results indicate that the comprehensive weighted-TOPSIS method yields more accurate assessments. Zhang Weizhong [10] proposed a comprehensive weighted method-based system for sudden water inrush risk assessment, targeting the complex geological conditions of underground engineering. Based on the theory of attribute mathematics, an interval evaluation theory and attribute recognition analysis method were established for quantitative evaluation. Seven typical factors influencing karst sudden water inrush disasters were selected, and a risk assessment index system and model were constructed. The comprehensive weighted method was used to analyze the weights of sudden water inrush risk indicators. The rationality and feasibility of the index system and evaluation model were validated by case studies. Liu Guiwei [11] conducted research on the sudden water influx mechanism in deeply buried karst tunnels. Li Dandan [12] predicts and analyzes the risk, hazard level and control ability of sudden water disaster in tunnels by establishing a back-propagation neural network model and a radial basis function neural network model, and compares the stability and error values of the models. Jang Yingli [13] established the reliability measurement weights for the risk assessment of karst tunnel water disasters and improved the extended cloud model based on reliability measurement methods and extended cloud theory. The study focused on the development of underground karst and analyzed the main forms of karst development. It investigated the interaction between surface water, groundwater, and rock in the tunnels, and elucidated how rock fracture induced by fault mechanics leads to the failure of rock surrounding the tunnel, the formation of water inflow channels, and subsequent tunnel flooding. The mechanism of sudden water influx was analyzed in detail.

Assessing and investigating the risk of sudden water intrusion during tunnel construction in karst areas has become a major challenge. This study focuses on the karst tunnels under construction on the Yizhou-Donglan Expressway section. Through geological surveys, the hydrogeological characteristics of karst areas were analyzed to understand the occurrence and migration patterns of groundwater, and to identify the main causal and influencing factors of sudden water intrusion disasters in karst tunnels. By judiciously selecting the influencing factors of sudden water inrush and their respective weights, a comprehensive weighted TOPSIS method for tunnel sudden water inrush risk assessment was constructed. Validation of the assessment system was conducted through on-site excavation tests, while finite element analysis software was used to analyze the mechanism of sudden water inrush in karst tunnels. This study aims to provide a basis for sudden water inrush risk assessment and mechanism research in deeply buried karst tunnels with abundant water resources.

2 INTRODUCTION TO THE PRINCIPLE OF COMBINATION WEIGHT-TOPSIS METHOD

2.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a method of evaluating models by dividing them into different levels, such as the goal level, criterion level, and alternative level. It involves pairwise comparison of factors at the same level to systematically evaluate the importance of various interrelated factors at each level, ultimately determining the overall characteristics of their impact. This method treats the evaluation of the importance of indicators among experts as an expert panel, quantifying the subjective judgments of experts using a certain scale to build a judgment matrix. By calculating the maximum eigenvalue and corresponding eigenvector of the judgment matrix, the weights of each evaluation indicator can be obtained [14-16].

2.2 Entropy Weight Method

The entropy weight method is a technique for determining the weights of multiple factors based on the principle of information entropy, used to assess the importance of various indicators in a multi-criteria system. Its fundamental principle states that when a certain indicator contributes more to the problem, its information entropy is smaller, and vice versa, when the contribution is smaller, its information entropy is larger. By calculating the information entropy of each indicator, its weight can be determined [17, 18]. Below are the specific calculation steps and formulas of the entropy weight method in risk assessment:

2.2.1 Calculate the Relative Entropy of the Indicator Values

First of all, for each indicator i, it is necessary to standardize its individual evaluation value X_{ij} to the relative value P_{ij}, usually using linear standardization or logarithmic standardization and other methods, the calculation formula is as follows:

$$P_{ij} = \frac{X_{ij} - \min\left(X_i\right)}{\max X_i - \min\left(X_i\right)} \tag{1}$$

where X_{ij} is the observed value of the i-th indicator in the j-th sample, X_i is all the observed values of the i-th indicator, and P_{ij} is the relative value of the i-th indicator in the j-th sample.

Then, the information entropy S_i, of each indicator *i is* calculated using the relative values The information entropy is calculated as:

$$S_i = -\sum_{j=1}^{m} P_{ij} \log\left(P_{ij}\right) \tag{2}$$

where m is the sample size of indicator i and P_{ij} is the relative value of indicator i in the j-th sample.

2.2.2 Calculate the Weights

Using the results calculated from the information entropy, the weight of each indicator *i is* further calculated W_i, and the weight calculation formula is:

$$W_i = -\frac{1 - S_i}{\sum_{k=1}^{n}\left(1 - S_i\right)} \tag{3}$$

where n is the total number of indicators and W_i is the weight of indicator i.

Through the above steps, the weights of each indicator can be obtained for the risk evaluation of tunnel water influx.

2.3 Combined Assignment Weight Calculation

The combination weighting method combining the hierarchical analysis method and entropy weighting method is used to establish the risk evaluation model of water influx in karst tunnels. The multiplicative set multiplication method is used, and its combination weight formula is:

$$M_j = -\frac{u_i w_i}{\sum_{j=1}^{n} u_i w_i} \tag{4}$$

where M_j is the portfolio weight, u_i is the subjective weight obtained by hierarchical analysis and W_i is the objective weight obtained by entropy weighting.

2.4 TOPSIS (Ideal Point Method) Analysis Step

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a multi-criteria decision analysis method. It involves normalizing the data into a normalized matrix, identifying the optimal (also known as ideal solution) and worst (also known as anti-ideal solution) targets among multiple objectives. Distances between each evaluation target and the anti-ideal and ideal solutions are calculated, generating proximity values to the ideal solution. These values are then sorted to evaluate the superiority of the targets. Proximity values range from 0 to 1, with a value closer to 1 indicating that the evaluation target is closer to the optimal level, and a value closer to 0 indicating closer proximity to the worst level [19]. Firstly, construct a decision matrix. Assume a multiple attribute decision-making problem with m alternative solutions, denoted as $B = (B_1, B_2, ..., B_\mathrm{m})$, and simultaneously, there are n decision attribute indicators denoted as $D = (D_1, D_2, ..., D_\mathrm{n})$, with their evaluation values forming the decision matrix $E = (e_{ij})_{m\times n}$. The specific steps are as follows:

Step 1, standardized decision matrix.

Normalize the raw data sequence as follows:

$$f_{ij} = -\frac{e_{ij} - \min\left(e_{1j}, e_{2j}, ..., e_{mj}\right)}{\max\left(e_{1j}, e_{2j}, ..., e_{mj}\right) - \min\left(e_{1j}, e_{2j}, ..., e_{mj}\right)} \tag{5}$$

Construct a dimensionless matrix.

$$F = \left(f_{ij}\right)_{m\times n} \tag{6}$$

Step 2 involves computing the weighted normalized decision matrix.

Weighted Decision Matrix Value

$$A_{ij} = F_i \times w_j \tag{7}$$

where w_j is the weight of D_j, and $\sum_{j=1}^{n} w_j = 1$.

Step 3, determine the positive and negative ideal solutions.

The positive ideal solution A^+ consists of the maximum value in each column of A, i.e.:

$$A^+ = \left\{\max A_{i1}, \max A_{i2}, ..., \max A_{in}\right\} \tag{8}$$

The negative ideal solution A^- consists of the minimum value in each column of A, i.e.:

$$A^- = \left\{\max A_{i1}, \max A_{i2}, ..., \max A_{in}\right\} \tag{9}$$

Step 4, calculate the distance S_i^{+} to the ideal point and the distance S_i^{-} to the negative ideal point for each scenario with:

$$D_i^+ = \sqrt{\left(\max A_{ij} - A_{ij}\right)^2},\ i = 1, 2, ..., m \tag{10}$$

$$D_i^- = \sqrt{\left(\max A_{ij} - A_{ij}\right)^2},\ i = 1, 2, ..., m \tag{11}$$

Step 5, calculate the relative closeness of the alternatives to the positive ideal solution, the relative closeness of the alternatives to the positive ideal solution are G_i calculated as follows:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-},\ 0 \le C_i \ll 1,\ i = 1, 2, ..., m \tag{12}$$

$C_i \to 1$, indicating that the object of evaluation is closer to a positive ideal solution, and $C_i \to 0$, which means that the evaluation object is closer to the negative ideal solution.

3 ESTABLISHMENT OF A TUNNEL SUDDEN WATER NRUSH RISK ASSESSMENT INDEX SYSTEM

The main reasons for tunnel water inrush include complex geological conditions, unfavorable hydrogeological conditions, insufficient tunnel design and construction quality, changes in surrounding environment, and human factors. These factors lead to groundwater leakage or sudden inflow into the tunnel, increasing the risk of tunnel water inrush. There are many factors affecting sudden water inrush in practical engineering, and it is impossible to consider every factor. By analyzing part of the geological survey data and geophysical exploration data of tunnels under construction, a risk assessment index system for karst tunnel water inrush was established. The tunnel investigated in this study is less affected by structure, so structural influences are not considered, mainly including geological characteristics of surrounding rocks, hydrogeological conditions, and tunnel conditions. Data collection methods included questionnaire surveys to gather expert opinions, field measurements for precise geological data, and database searches (such as Scopus and Web of Science) to compile existing research data. Evaluation indicators include basic quality indicators of rock mass, rock dip angle, rock mass integrity coefficient, uniaxial compressive strength of rock mass, maximum water inrush of tunnel, average annual rainfall in the rainy season, and tunnel burial depth, totaling seven main influencing factors, establishing a risk assessment system for karst area tunnel water inrush (Tab. 1).

Table 1 Karst Tunnel Sudden Inrush Risk Assessment Index System

target level	condition layer	indicator layer
Risk assessment of karst tunnel water inrush	Structural characteristics of rock mass	I_1 Rock Basic Quality Index BQ.
		I_2 Rock Inclination / °.
		I_3 rock integrity coefficient K_v.
		I_4 Rock saturated uniaxial compressive strength R_c / MPa.
	hydrogeological condition	I_5 Maximum water influx in tunnel / m^3/d.
		I_6 Average annual rainfall during the rainy season.
	Tunnel condition	I_7 Tunnel Depth.

Based on quantifiable influencing factors, establish standards for surge water risk levels, categorizing tunnel surge water risks from high to low into four levels: Level I (high risk), Level II (medium risk), Level III (low risk), and Level IV (minimal risk). The evaluation indicators and corresponding grading criteria are shown in Tab. 2.

Table 2 Risk indicators and grading criteria for tunnel water emergence evaluation

Evaluation indicators.	I (high)	II (Medium)	III (low)	IV (tiny)
I_1 Rock Basic Quality Index BQ.	≤ 250	251 - 350	351 - 450	＞ 450
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25
I_2 Rock dip φ / °.	$45° \leq \varphi \leq 60°$	$30° \leq \varphi \leq 45°$	$15° \leq \varphi \leq 30°$	$0° \leq \varphi \leq 15°$
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25
I_3 rock integrity coefficient K_v.	< 0.2	0.2 - 0.45	0.45 - 0.75	0.75 - 1.0
value of a score.	75 - 100	50 - 75	25 -50	0 - 25
I_4 Saturated uniaxial compressive strength of rock body R_c / MPa.	$5 < R_c \leq 15$	$15 \leq R_c \leq 30$	$30 \leq R_c \leq 60$	R_c ＞ 60
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25
I_5 Maximum water influx in tunnel / m^3/d	＞ 10000 m³/d	3000 – 10000 m³/d	500 – 3000 m³/d	< 500 m³/d
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25
I_6 Average annual rainfall during the rainy season / mm	＞ 2000	1000 - 2000	500 - 1000	< 500
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25
I_7 Tunnel burial depth / m.	≤ 50	50 - 100	100 - 200	＞ 200
value of a score.	75 - 100	50 - 75	25 - 50	0 - 25

3.1 Structural Characteristics of the Surrounding Rock Mass

The geological structure characteristics of surrounding rock are one of the primary factors influencing the risk of tunnel water inrush, encompassing fundamental quality indicators (BQ), dip angle, integrity coefficient, saturated uniaxial compressive strength, among others. Tab. 3 shows the classification table of the structural characteristics of the surrounding rock mass.

Table 3 Classification of the structural characteristics of the surrounding rock mass

risk level	Rock Basic Quality Index BQ	Rock dip φ / °	Rock integrity factor K_v	Rock saturated uniaxial compressive strength R_c / MPa
I	≤ 250	$45° \leq \varphi \leq 60°$	< 0.2	$5 < R_c \leq 15$
II	251 - 350	$30° \leq \varphi \leq 45°$	0.2 - 0.45	$15 \leq R_c \leq 30$
III	351 - 450	$15° \leq \varphi \leq 30°$	0.45 - 0.75	$30 \leq R_c \leq 60$
IV	＞ 450	$0° \leq \varphi \leq 15°$	0.75 - 1.0	$R_c > 60$

3.2 Hydrogeological Conditions

The hydrogeological conditions primarily consider the maximum water inrush of the tunnel and the annual maximum rainfall in the rainy season of the tunnel site area. Water inrush is a crucial factor affecting the risk of water gushing in karst tunnels. Quantitative estimation of water inrush is conducted based on preliminary geological survey data and advanced geological prediction data [8]. Due to the presence of numerous surface gullies in the tunnel site area, significant water inrush occurs in the shallow-buried sections of the tunnel when encountering joints and fracture zones, especially during the rainy season, leading to seasonal water bursts.

Table 4 Classification of the structural characteristics of the surrounding rock body

risk level	Maximum water influx in tunnel / m^3 /d	Average annual rainfall during the rainy season / mm
I	＞ 10000 m³/d	＞ 2000
II	3000 - 10000 m³/d	1000 - 2000
III	500 - 3000 m³/d	500 - 1000
IV	< 500 m³/d	< 500

Therefore, the maximum water inrush of the tunnel and the annual maximum rainfall in the rainy season are key factors for karst tunnel water bursts, as detailed in Tab. 4 of the hydrogeological classification table.

3.3 Tunnel Conditions

During the construction of karst tunnels, burial depth is a critical factor. The shallower the tunnel is buried, the weaker the natural arch of the surrounding rock and its own stability become. Consequently, excavation further affects the shallow surface layer [18]. Based on the severity of disasters caused by the burial depth of shallow cover tunnels, they are quantitatively divided into four levels: ≤ 50 m, 50100 m, 100200 m, and > 200 m, as detailed in Tab. 5.

Table 5 Classification of tunnel conditions

risk level	Tunnel depth / m
I	≤ 50
II	50 - 100
III	100 - 200
IV	＞ 200

4 ENGINEERING APPLICATIONS

4.1 Summary of Works

The Yizhou to Donglan Highway is an important segment of the new "Horizontal 5" line, as outlined in the "Guangxi Expressway Network Plan (2018-2030)," which has been implemented by Guangxi. It is also a vital component in the construction of the Western Land-Sea New Corridor and the acceleration of transportation infrastructure development in the northwest region of Guangxi. This route is located in Yizhou District of Hechi City, northern Guangxi, situated in the transitional slope zone from the Guizhou Plateau to the hilly basin of Guangxi. The terrain generally slopes from west to east, influenced by the Guangxi mountain-shaped structural control, with an east-west arc-shaped structure dominated by fault structures, mainly northwest-trending faults. The route traverses through areas with northwest-trending structural development, primarily characterized by elongated fold structures and high-angle thrust faults, with broad axial sections and steeply inclined wings, presenting a drawer-like configuration. The geological and structural activity in the region along the route is significant, with well-developed rock joints and fractures. The topographical conditions are conducive to the collection of atmospheric precipitation and surface water drainage, with abundant groundwater, making it highly susceptible to geological hazards such as sudden water influx and mudslides [20].

The entire route is located in karst mountainous areas, characterized by landforms primarily formed through erosion and dissolution processes. Based on morphological combinations, the landforms can be classified into low hills and ridges, peak clusters and depressions, and peak-forest-valley landscapes. Karst segments constitute 100% of the route, with pure soluble rock comprising 68%, and interspersed sections of soluble and insoluble rocks making up 32%. Karst terrain represents the predominant adverse geological feature along the route. Karst formations mainly develop in Permian, Carboniferous, and Devonian limestones, dolomites, and dolomitic limestones, particularly flourishing within the Permian and Carboniferous strata. Surface karst features mainly include dissolution depressions, subterranean rivers, and caves. Subterranean rivers typically develop along structural lines, with the Jiumo subterranean river tracing the thrust fault development along the short axis anticline, while the Bakuang subterranean river develops along the extensional fractures on the gentle limb of the anticline.

4.2 Evaluation of the Risk of Water Surges in Tunnels Along the Yizhou-Donglan Highway

With the engineering context of the Yizhou to Donglan Highway, four representative tunnel entrances are selected. Based on the geological background summary of each section and supplemented by regional geological maps, geophysical exploration results, and tunnel engineering geological profile data, evaluation criteria for the four entrance sections are obtained, as detailed in Tab. 6.

Table 6 Evaluation index values for tunnels along Yizhou-Donglan highway

Sections of the tunnels	quality indicators	dip	integrity factor	Saturated uniaxial compressive strength of rock	Maximum water influx	quantity of rainfall	tunnel burial depth
K4 + 355 ～ K4 + 500	288	60	0.5	38.5	3984	1371	30
K16 + 720 ～ K17 + 900	229	55	0.2	63.6	11712	1771	21
K38 + 175 ～ K38 + 300	201	35	0.4	41.3	10447	1726	64
K99 + 580 ～ K99 + 790	250	47	0.4	38.1	1196	1588	32

4.3 Tunnel Inrush Risk Assessment Based on TOPSIS Method with Combination Weighting

The weight vector of each breakthrough water evaluation index obtained based on the Analytic Hierarchy Process (AHP) and Entropy Weight Method is determined. Assuming there are 7 breakthrough water evaluation indices, their evaluation values constitute a decision matrix. The Comprehensive Weight Method is utilized to process the values of each index, and an initial evaluation matrix is established from 4 different level samples. Due to the existence of certain differences in dimension and magnitude among the various breakthrough water evaluation indices, some evaluation indices have higher values while others have lower values. To avoid the influence of different dimensional units of each evaluation index on the calculation results, standardization is applied to each evaluation index. The initial evaluation matrix is separated into positive and negative indicators, and each evaluation index is standardized. The standardized decision matrix is obtained, and then combined with the initial weighted matrix to yield the weighted standardized decision matrix. By solving for the distance from each breakthrough water level to the positive ideal solution and the negative ideal solution, the relative proximity of each breakthrough water level is calculated according to the formula. This forms the corresponding judgment intervals for each breakthrough water level.

4.3.1 Subjective Weight Calculation Based on Analytic Hierarchy Process (AHP)

Translate into professional English, utilizing the Analytic Hierarchy Process (AHP), to conduct a comparative analysis of factors including basic quality indicators of rock mass, rock strata dip angle, rock mass integrity coefficient, rock mass saturated uniaxial compressive strength, maximum estimated water inrush in tunnels, annual average rainfall at tunnel sites during the rainy season, and tunnel depth. Establish a judgment matrix based on the importance of water bursting evaluation indicators proposed by experts. Utilize the eigenvector method and SPSS software to solve for the maximum eigenvalue and corresponding eigenvector of the matrix. According to the calculation results of each evaluation index by hierarchical analysis method, the subjective weights of water-surge evaluation indexes u = (0.0363, 0.0233, 0.0369, 0.0445, 0.0893, 0.0351, 0.734).

4.3.2 Entropy Weight Method for Objective Weight Calculation

The entropy weight method is an objective weighting approach. The smaller the entropy of the results, the greater the differences in indicators, and the greater the role and weight in comprehensive evaluation. By establishing the original data matrix of evaluation indicators and evaluation objects, calculating the proportions of each evaluation indicator, and establishing a proportion matrix based on the proportion data, the entropy values and information effect values of each indicator are calculated to obtain the evaluation weights of each indicator. Tab. 7 provides the weights of flood evaluation indicators based on the entropy weight method.

First, standardize each evaluation indicator using Eq. (1) to obtain the relative values of each indicator. Then, utilize these relative values with Eq. (2) to calculate the information entropy S for each indicator i, where S = (0.743, 0.837, 0.87, 0.845, 0.786, 0.873, 0.76). Finally, apply Eq. (3) to derive the weights W of each indicator, resulting in W = (0.199, 0.126, 0.101, 0.12, 0.166, 0.098, 0.186).

The assessment of sudden water inrush risk in the Tingshe Tunnel section was conducted utilizing the Combined Weighting Technique for Order of Preference by Similarity to Ideal Solution (CW-TOPSIS). This approach yielded the distances and relative closeness of typical sections to the ideal solution. Tab. 8 presents the evaluation results of sudden water inrush risk for typical sections.

4.3.3 Weight Calculation Using the Combination Weighting Method

The weight values obtained through the Analytic Hierarchy Process (AHP) and Entropy Weight Method are utilized to calculate the combined weights of various evaluation indicators using Eq. (4), resulting in the weight values of the evaluation indicator combination as follows: w = (0.0416, 0.0176, 0.0228, 0.0334, 0.0955, 0.0247, 0.784).

4.3.4 Combination Weighted-TOPSIS Method for Model Evaluation

Firstly, based on Tab. 6, establish samples for tunnel water inrush levels I, II, III, and IV. Utilize Eq. (7) to obtain the weighted decision matrix A. Then, employ Eq. (8) and Eq. (9) to derive the positive ideal solution A^+ and the negative ideal solution A^-. Using Eq. (10) and Eq. (11), calculate the distances D_i^+ and D_i^- between the indicators and the positive and negative ideal solutions, respectively. Thus, D^+ = (0.5257, 0.8483, 0.7087, 0.5655), D^- = (0.5851, 0.3781, 0.5460, 0.5137).

Finally, according to Eq. (12), compute the proximity C_i to the positive ideal solution. Detailed evaluations are provided in Tab. 7.

Table 7 The distance between ideal values and approximate values

risk level	Relative proximity of positive ideals
I	1
II	0.53 - 1
III	0.43 - 0.58
IV	0 - 0.42

Table 8 Evaluation results of the risk of water breakout in a typical tunnel section

Typical Tunnel Sections	positive ideal value	negative ideal	Relative proximity of positive ideals	risk level
K4 + 355 ～ K4 + 500	0.53	0.59	0.53	II
K16 + 720 ～ K17 + 900	0.85	0.38	0.31	IV
K38 + 175 ～ K38 + 300	0.71	0.55	0.44	III
K99 + 580 ～ K99 + 790	0.57	0.51	0.48	III

Practical verification conducted on April 22, 2022, at the right entrance of Tongde Tunnel on the Yizhou to Donglan Highway, at the face of the pilot hole at K4 + 375, yielded the following geological forecasts: Within the range of 0 to 30 meters ahead of the face, electromagnetic waves are predominantly of medium to low frequency, with localized strong amplitudes and numerous strong reflection interfaces. Localized parallel oscillation signals are present. Radar imaging indicates strong reflection signals in the range of 2 to 6 meters to the left of the face, suggesting the development of joint fractures in the surrounding rock in that area. Similarly, strong reflection signals are observed in the range of 9 to 12 meters ahead of the face, indicating relatively developed joint fractures in the surrounding rock in that area. Subsequent excavation revealed fragmented surrounding rock, well-developed bedding and dissolution fractures, poor combination, localized water seepage at the crown, high water pressure, posing a risk of major water inrush. Additionally, a filled karst cave was discovered at K4 + 423. Based on the classification of water inrush in this study, it is categorized as level II water inrush, consistent with the evaluation results of the combined weighting method-TOPSIS.

5 CONCLUSION

Sudden water inrush disasters are the primary geological hazard during the construction of highways and tunnels in karst areas, posing significant risks to tunnel construction and safety. This study focuses on the karst tunnels of the Yizhou to Donglan expressway, analyzing the geological characteristics of surrounding rocks, hydrogeological features, and tunnel burial depth through geological surveys. The main causative and influencing factors of sudden water inrush disasters in karst tunnels are identified. By reasonably selecting the influencing factors of sudden water inrush and their weights, a combined weighted-TOPSIS method is employed to establish a tunnel sudden water inrush risk assessment system. Field excavation tests are conducted to validate the assessment system, and finite element analysis software is used to analyze the mechanism of sudden water inrush in karst tunnels. This study provides a basis for the evaluation of sudden water inrush risks and the study of sudden water inrush mechanisms in deep-buried karst tunnels.

Compared to traditional methods, the combined weighting method offers several advantages, such as a more comprehensive consideration of various factors, increased flexibility to adapt to different geological conditions, and more efficient use of limited geological data. However, it also presents some disadvantages, including higher complexity, potential subjectivity in weight combination and parameter settings, and strong dependence on data quality and completeness. This study analyzed only seven factors deemed to have relatively significant impacts, which may result in limitations regarding the selection and weighting of indicators. Therefore, further exploration and research are necessary to enhance the assessment of sudden water inrush risks in tunnels.

Future research should focus on optimizing the method using advanced algorithms and technologies like machine learning and artificial intelligence to enhance accuracy and efficiency, developing techniques for multi-source data integration to improve data coverage and accuracy, constructing real-time risk warning systems leveraging IoT and big data technologies for dynamic monitoring and early warning, and expanding the application of this method to other types of underground engineering projects to validate its applicability and generalizability. Through continued research and practical application, the combined weighting method's advantages in assessing water inrush risk in karst tunnels can be fully realized, providing robust technical support for the safe construction and management of tunnel engineering projects.

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