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Safety-Risk Assessment for TBM Construction of Hydraulic Tunnel Based on Fuzzy Evidence Reasoning

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Abstract: Due to multiple factors influencing the construction safety of TBM hydraulic tunnels, risk assessment is a critical point of a construction management plan to avoid possible risks. In this paper, a safety-risk evaluation index system of TBM construction for hydraulic tunnels is built based on the identification and analysis of possible sources of risk in techniques, geologic, equipment, management, and accidents. Considering the influence of factors such as the experience level and the expertise of decision makers, a combination assignment method of index weights is proposed based on binary semantics. On the basis of a fuzzy normal distribution used as the subordinate function distribution of fuzzy evaluation levels, the subordinate function distribution of fuzzy evaluation levels under multi-level intersection situations is introduced, and a comprehensive evaluation model of safety risks for TBM tunnel construction is built. The validity and practicality of the evaluation model is examined with the combination of a long-distance water conveyance tunnel project. Results show that the construction safety-risk of the TBM hydraulic tunnel project belongs to the middle-high level, and the safety accident risk belongs to the low level. The study provides guidance of evaluation and control of risks for this tunneling construction being successfully completed.

Keywords: TBM construction; water conveyance tunnel; safety; risk assessment; fuzzy evidence reasoning

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1. Introduction

A Tunnel Boring Machine (TBM) is a large-scale special type of equipment for modern tunnel construction that integrates machinery, electrical appliances, hydraulics, guidance, sensing, and information technology. Compared with the traditional drilling and blasting method, a TBM has the characteristics of being fast, being efficient, quality assurance, and high-level safety [1,2]. This provides advanced equipment and methods for the construction of long-distance water conveying tunnels under complex geological conditions [3,4], especially in conditions of tunnel with high geostress [5]. Meanwhile, the precast segmental lining of a TBM water conveyance tunnel provides regular sections, which is convenient for constructing the internal concrete lining subject to high internal water pressure [6]. Therefore, along with the construction of numbers of long-distance inter-basin water conveyance projects, shield technology has been more and more widely applied in China, and corresponding specifications have been formulated [7–9]. However, due to the complexity and variable geological conditions faced by inter-basin water conveyance projects and the limited practice of TBM technology in this area of China, the safety of a TBM tunnel construction is still a prominent problem [10,11]. This is a reminder that theoretical exploration and engineering practice are significant for the evaluation and control of safety-risk in TBM tunnel construction.

At present, many researchers have conducted investigations related to TBM construction risks. Gu et al. [12] established a two-level fuzzy comprehensive evaluation model to evaluate the construction risk level of the right line of the West Qinling Railway Tunnel. Afradi et al. [13,14] conducted a study on TBM construction models. Results show that linear regression, nonlinear regression, and the gene expression programming method can effectively predict the number of TBM consumed disc cutters considering machine and ground conditions, while the support vector machine method has superiority; the ant colony optimization, bee colony optimization, and the particle swarm optimization can realistically predict the TBM penetration rate, while the particle swarm optimization yields more precise and realistic findings. Song et al. [15] proposed a new model of risk evaluation for TBM construction based on nonlinear fuzzy hierarchical analysis. Huang [16] applied the Analytic Hierarchy Process (AHP) and fuzzy theory to build a construction risk assessment model to analyze the risk assessment of hydraulic TBM tunnels. Wang et al. [17] suggested appropriate risk-control techniques to control deep-buried, long-distance TBM tunneling construction.

Traditional comprehensive risk-assessment methods mainly include the Bayesian network method [18], fuzzy comprehensive evaluation method [19], cloud model method [20], and Topsis method [21]. Fuzzy evidence inference is an evidence fusion method based on decision-makers' evidence theory to deal with the decision analysis of uncertain information [22]. Fuzzy set theory and evidence theory have been deeply studied [23–25], and fuzzy evidential reasoning was developed with the combination of evidential reasoning [26]. In this aspect, Jiang et al. [27] used the fuzzy evidence inference technique and proposed a specific algorithm and processing operation flow for system-risk analysis and evaluation based on fuzzy evidence inference; Xiao et al. [28] built an evaluation model of a complete emergency response plan based on the fuzzy evidence theory; Zhang et al. [29] achieved an effective evaluation of the navigational safety of inland river vessels to solve the problem that indicators have randomness and fuzziness by applying a fuzzy evidence inference model. Meanwhile, Wei et al. [30] studied the combined probability distribution function and the redistribution method of fuzzy intersection confidence for fuzzy evaluation levels with triangularly distributed affiliation functions in the case of two intersections. However, none of the studies has considered the combined probability distribution function of fuzzy evaluation levels in the case of two intersections when the affiliation function is a fuzzy-normal distribution. Comparatively, fuzzy evidence inference is an evidence fusion method based on decision-makers' evidence theory which can directly express uncertain or incomplete information. Therefore, the fuzzy evidence reasoning method is more suitable for dealing with risk-assessment problems under uncertainty.

Based on the above discussion, this study is rare in addressing safety-risk assessment by the fuzzy evidence reasoning method for TBM construction of a hydraulic tunnel with the features of long distance passed through different geological conditions [5,11,31]. In this paper, the evaluation indices of construction safety-risk with the characteristics of TBM tunnel construction were first analyzed while an evaluation index system was built. Considering uncertainties including random uncertainties and cognitive uncertainties in the process of TBM tunnel construction, the affiliation function distribution of fuzzy evaluation levels is introduced as a fuzzy normal distribution in the case of a multi-level intersection, and a new comprehensive risk assessment model is proposed. The validity and practicality of the evaluation model are proved by an example analysis on a 11.822 km-long TBM water conveyance tunnel passing through complex geological conditions. The tunnel is a branch line of the main channel of the South to North Water Transfer Project of China to the region of Anyang City, Henan province of China.

2. Safety-Risk Sources of TBM Tunnel Construction

The geological environment for construction of TBM tunnels is complex and volatile. Due to the participation of many construction teams, and the complexity of construction technology, many factors exist that give rise to different risk accidents [32,33]. On the basis of data collection, expert surveys, and field research, risk factors can be identified by using factor analysis based on the principles of comprehensiveness, independence, importance, and goal-oriented principles of index system construction.

2.1. Technical Risk

TBM equipment is a highly interrelated and complex automated system. Correct technical operation by construction personnel during the tunneling process is required to guarantee the safety of the tunnel project [7–9]. The technical risks of TBM tunnel construction mainly include lining leakage, TBM tunneling offset, and anchor shaft force monitoring failing to meet the requirements. Meanwhile, a delay of pea-gravel backfilling and grouting may induce a lack of timely support to surrounding rock, which increases the risk of TBM jamming [34,35].

2.2. Geological Risk

Complex hydrogeological conditions are one of the main factors affecting the construction of TBM tunnels. Complexity will greatly increase with the length of tunnel which passes through different geological structures, especially unfavorable geological sections including fracture collapse zones, water inrush, and unstable surrounding rock [4,6]. This correspondingly increases the geological risk of tunnel construction with a selected TBM [11,31]. Due to the uncertainty of hydrogeological environments during construction, a TBM is prone to various geological hazards when digging in poor geological sections, which affects the construction progress. Generally, the geological risks mainly include bad rock surroundings, cave-entrance landslide, high groundwater level, rock explosion, karst gushing water, and fault fracture zones, as well as old mine workings [36–38].

2.3. Equipment Risk

A TBM is a common technical tool for tunnel construction. Choosing the right model for operating and maintaining the equipment not only determines the tunnel construction schedule, but also directly affects the safety of personnel at the construction site. Equipment risks include failure of the pipe assembly, failure of the jacking system, failure of the grouting system, mismatch of the operation model selection, consumption of disc cutters, and failure of the shield tail seal [1,7,13].

2.4. Management Risk

As highly integrated large-scale equipment, a TBM requires the cooperation of various departments and places high demands on the management level of the construction site. The timely improvement of corresponding regulations and specifications for problems that are prone to occur in site management is important to ensuring smooth construction operations and reducing the probability of safety accidents [14,33,39]. Generally, management risks mainly include an imperfect construction control plan, low quality of management personnel, non-implementation of organization, poor construction control information, and backward effective control methods.

2.5. Safety Accident Risk

Due to the complex geology of the TBM tunnel construction site, the narrow underground construction environment, and poor lighting conditions, safety accidents occur involving personnel and equipment [32,33]. The risks of safety accidents mainly include oxygen-deprivation poisoning of construction personnel, falls from height, mechanical traffic accidents, and collapse.

Based on the above discussion, the TBM tunnel construction safety-risk evaluation index system is built as shown in Figure 1.

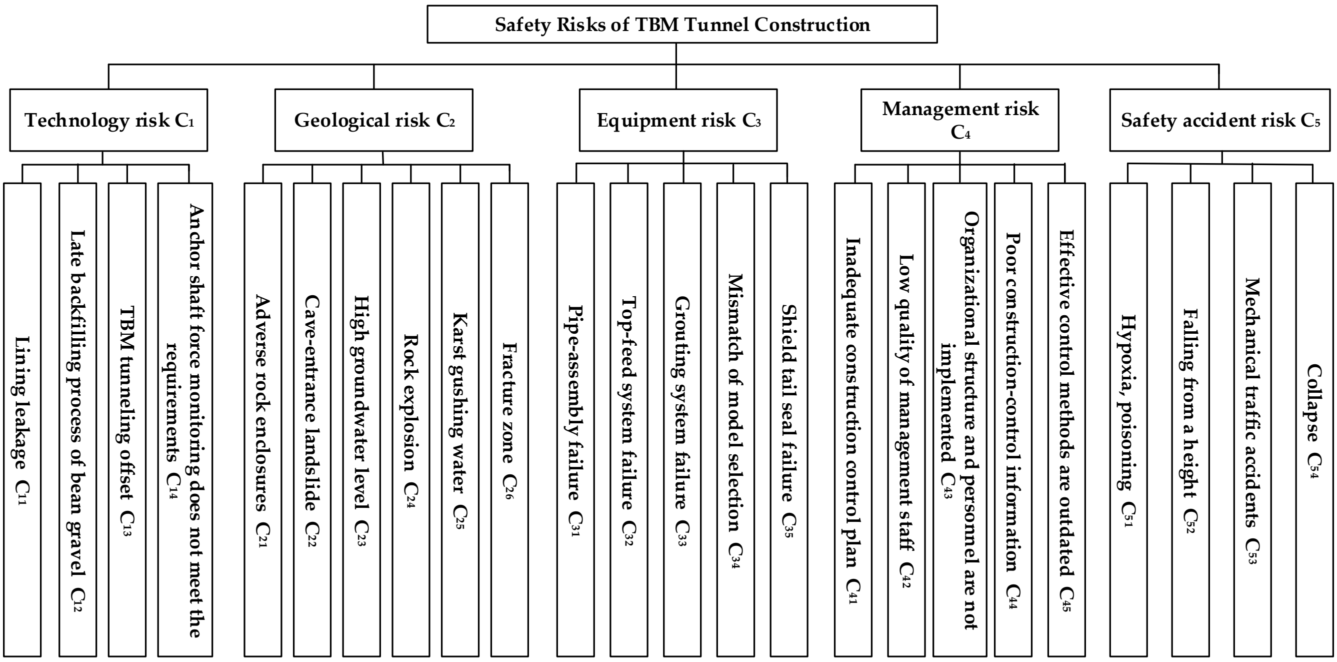

Figure 1. Safety risks of TBM tunnel construction.

3. Evaluation Model for Safety Risks of TBM Tunnel Construction

3.1. Determination of Indicator Weights

3.1.1. The Binary Semantic Judgment Matrix

Let the set of attributes be $C = \{C_i \mid i = 1, 2, 3, \ldots, i\}$, where C_i denotes the *i*th attribute; the decision group is set to be $D = \{D_m \mid m = 1, 2, 3, \ldots, m\}$, where D_m denotes the *m*th decision maker. The decision maker weight vector is $\lambda = \{\lambda_k \mid k = 1, 2, 3, \ldots, k\}$, and satisfies $\sum_{k=1}^{m} \lambda_k = 1, \lambda_k \in [0,1]$.

The linguistic evaluation set is $S = \{S_l \mid l = 0, 1, 2, \ldots, n\}$. $s_l^{D_m}$ is the decision maker D_m who selects an element from the set S defined in advance as a description of the importance of attribute C_i relative to attribute C_j, and obtains the linguistic judgment matrix S^m,

$$S^m = \begin{bmatrix} s_{11}^m & s_{12}^m & \cdots & s_{1i}^m \\ s_{21}^m & s_{22}^m & \cdots & s_{2i}^m \\ \vdots & \vdots & \cdots & \vdots \\ s_{11}^m & s_{i2}^m & \cdots & s_{ii}^m \end{bmatrix} \quad (1)$$

The matrix S^m satisfies $s_{ii}^m = s_{g/2}, i = 1, 2, 3, \cdots i$; $s_{ij} + s_{ji} = s_g$, that is, $s_{ji} = s_{g-u}$ when $s_{ij} = s_u$.

Multiple decision makers select appropriate semantic elements from the linguistic evaluation set to compare the safety risks of TBM tunnel construction with the same level and construct a relatively fuzzy linguistic decision matrix.

The corresponding binary semantics can be obtained from the function Δ, the inverse function Δ^{-1}, and the inverse operator "Neg" [40]. The binary semantic judgment matrix

R_m is obtained based on the initial linguistic judgment matrix S_m given by the decision maker. R_m is expressed as follows:

$$R^m = \begin{bmatrix} (r_{11}^m, \alpha_{11}^m) & (r_{12}^m, \alpha_{12}^m) & \cdots & (r_{1i}^m, \alpha_{1i}^m) \\ (r_{21}^m, \alpha_{21}^m) & (r_{22}^m, \alpha_{22}^m) & \cdots & (r_{2i}^m, \alpha_{2i}^m) \\ \vdots & \vdots & \cdots & \vdots \\ (r_{i1}^m, \alpha_{i1}^m) & (r_{i2}^m, \alpha_{i2}^m) & \cdots & (r_{ii}^m, \alpha_{ii}^m) \end{bmatrix} \quad (2)$$

$$r_{\mathrm{ij}}^m = s_{\mathrm{g}/2}, i = 1, 2, 3, \cdots i \quad (3)$$

$$r_{\mathrm{ij}}^m = (s_{\mathrm{i}}, 0), r_{\mathrm{ij}}^k = (s_{\mathrm{g-u}}, 0) \quad (4)$$

3.1.2. AHM Subjective Weights Based on Binary Semantics

An Attribute Hierarchical Model (AHM) can divide various factors of a complex problem into ordered levels with interrelations, and effectively combine the decision maker's opinion with the objective judgment results based on the subjective judgment structure of objective facts. There are many indicators of the same level in TBM tunnel construction safety-risk, and it is complicated to test the consistency of the judgment matrix one by one. Therefore, a HAM is used for the test to determine the subjective weights based on binary semantics as follows.

(1) Construction of the AHM attribute judgment matrix. The elements of the AHM attribute judgment matrix Q_m can be obtained by the conversion of the scale b_{ij} in the HAP [40,41]. Table 1 shows the meanings of scales 1 to 9 in AHP, and the conversion formula is presented by Formula (5).

$$L_{\mathrm{ij}} = \begin{cases} \frac{\beta k}{\beta k+1} & b_{\mathrm{ij}} = k \\ \frac{1}{\beta k+1} & b_{\mathrm{ij}} = \frac{1}{k} \\ 0.5 & b_{\mathrm{ij}} = 1, i \neq j \\ 0 & b_{\mathrm{ij}} = 1, i = j \end{cases} \quad (5)$$

where $k \in Z$ and $k > 2$; $\beta \geq 1$, usually $\beta = 1$ or 2. When $\beta \to \infty$, $u_{ij} = 1$ if $a_{ij} = k > 1$, $u_{ij} = 0.5$ if $a_{ij} = 1$, and $u_{ij} = 0$ if $a_{ij} < 1$.

Table 1. Meanings of scales 1 to 9 in the AHP.

Scale	Meaning
1	q_i q_j equally important
3	q_i is a little more important than q_j
5	q_i is more important than q_j
7	q_i is much more important than q_j
9	q_i is exceedingly more important than q_j
2, 4, 6, 8	Represents the median value of the above adjacent judgments
reciprocal	If the ratio of the importance of element q_i to element q_j is b_{ij}, then the ratio of element q_j to element q_i is $b_{ji} = 1/b_{ij}$

The attribute judgment matrix $Q_{\mathrm{ij}}^{D_m}$ can be obtained from the conversion Formula (5):

$$Q_{ij}^{D_m}=\begin{bmatrix}(q_{11}^{D_m},\alpha_{11}^{D_m}) & (q_{12}^{D_m},\alpha_{12}^{D_m}) & \cdots & (q_{1i}^{D_m},\alpha_{1i}^{D_m})\\ (q_{21}^{D_m},\alpha_{21}^{D_m}) & (q_{22}^{D_m},\alpha_{22}^{D_m}) & \cdots & (q_{2i}^{D_m},\alpha_{2i}^{D_m})\\ \vdots & \vdots & \cdots & \vdots\\ (q_{i1}^{D_m},\alpha_{i1}^{D_m}) & (q_{i2}^{D_m},\alpha_{i2}^{D_m}) & \cdots & (q_{ii}^{D_m},\alpha_{ii}^{D_m})\end{bmatrix} \tag{6}$$

(2) Calculate the subjective weights. Let

$$\lambda_{\mathrm{i}}^{1}(i)=\frac{2}{n(n-1)}\sum_{j=1}^{n}Q_{\mathrm{ij}}^{D_m} \tag{7}$$

The relative attribute weights are

$$\lambda_{\mathrm{i}}^{1}=\left(\lambda_{\mathrm{i}}^{1}(1),\lambda_{\mathrm{i}}^{1}(2),\cdots,\lambda_{\mathrm{i}}^{1}(n)\right)^{T} \tag{8}$$

where T denotes transpose,

$$\sum_{i=1}^{i}\lambda_{\mathrm{i}}^{1}=1,\lambda_{\mathrm{i}}^{1}\in[0,1] \tag{9}$$

3.1.3. The Objective Weights Based on the Binary Semantics of Deviation Maximization

The objective weights based on the binary semantics of deviation maximization are calculated as follows:

(1) The judgment deviation on indicator C_{i} made by decision maker $D_{\mathrm{m}}{}'$ and by other decision makers is ρ_i^m,

$$(d,\alpha)=\Delta\left[\left|\Delta^{-1}(s_{\mathrm{i}},\alpha_{\mathrm{i}})-\Delta^{-1}(s_{\mathrm{j}},\alpha_{\mathrm{j}})\right|\right] \tag{10}$$

$$\rho_{\mathrm{i}}^{m}=\frac{1}{i}\sum_{i=1}^{i}\sum_{m=1}^{m}\left|\Delta^{-1}\left(r_{\mathrm{ij}}^{m},\alpha_{\mathrm{ij}}^{m}\right)-\Delta^{-1}\left(r_{\mathrm{ij}}^{n},\alpha_{\mathrm{ij}}^{n}\right)\right| \tag{11}$$

where $d\in S,\alpha\in[-0.5,0.5]$.

(2) The total deviation of judgment made by the decision makers on the evaluation indicator C_{i} is η_{i}:

$$\eta_{\mathrm{i}}=\sum_{m=1}^{m}\lambda_{\mathrm{m}}\rho_{\mathrm{i}}^{m} \tag{12}$$

(3) According to the criterion of deviation maximization, larger weights are put on the indicators with larger deviations. The objective weights λ_{i}^{2} of indicator C_{i} based on binary semantics of maximization deviation can be obtained as follows:

$$\lambda_{\mathrm{i}}^{2}=\frac{\rho_{\mathrm{i}}^{m}}{\sum\limits_{i=1}^{i}\eta_{\mathrm{i}}^{m}} \tag{13}$$

where $\sum\limits_{i=1}^{i}\lambda_{\mathrm{i}}^{2}=1,\lambda_{\mathrm{i}}^{2}\in[0,1]$.

3.1.4. The Combined Weights Determined by Combination Weighting Based on the Principle of Minimum Deviation

When conducting multi-attribute studies to determine index weights, some scholars have used methods such as linear weighting and product weighting to collectively obtain the combined weights [27–30]. However, no full investigation has been conducted on the reasonably assignment of subjective and objective weights in the field of TBM tunnel construction safety-risk evaluation. In this paper, combination weighting based on the principle of minimum deviation is used to determine the index weights.

For a given decision problem, the decision maker uses N methods to assign weights to attributes, denoted as $N = (n_1, n_2, n_3, \ldots, n_n)$. The indicator weights calculated by each assignment method are denoted as $\lambda_{N_n C_i} = (\lambda_{n_1 c_1}, \lambda_{n_1 c_2}, \lambda_{n_1 c_3}, \cdots \lambda_{n_n c_i})$, where $n = (1, 2, 3, \ldots, n)$, $i = (1, 2, 3, \ldots, i)$.

The weight vector of each assignment method is calculated with the following procedure.

(1) To construct the indicator layer weight matrix T.

$$T = \begin{pmatrix} \lambda_{n_1 c_1} & t_{n_2 c_1} & \cdots & t_{n_n c_1} \\ t_{n_1 c_2} & t_{n_2 c_2} & \cdots & t_{n_n c_2} \\ \vdots & \vdots & \vdots & \vdots \\ t_{n_1 c_i} & t_{n_2 c_i} & \cdots & t_{n_n c_i} \end{pmatrix} \tag{14}$$

where $N = (n_1, n_2, n_3, \ldots, n_n)$ is the total of N methods for attribute assignment used by the decision maker; $\lambda_{N_n C_i} = (\lambda_{n_1 c_1}, \lambda_{n_1 c_2}, \lambda_{n_1 c_3}, \cdots \lambda_{n_n c_i})$ is the weight of the attribute calculated by each assignment method.

(2) To calculate the optimal weight vector for each assignment method.

(a) Constructing a single-objective optimization model based on the principle of minimum deviation:

$$\min P = \sum_{k=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{i} (a_{N_k} \lambda_{N_k C_i} - a_{N_j} \lambda_{N_j C_i})^2 \tag{15}$$

where a_{N_k} is the weight of the N_kth method, and $\sum_{k=1}^{n} a_{N_k} = 1, a_{N_k} > 0$; a_{N_j} is the weight of the N_jth method, and $\sum_{j=1}^{n} a_{N_j} = 1, a_{N_j} > 0$; $\lambda_{N_k C_i}$ is the weight of the attribute C_i calculated by the N_kth method, and $\sum_{i=1}^{i} \lambda_{N_k C_i} = 1, \lambda_{N_k C_i} > 0$; $\lambda_{N_j C_i}$ is the weight of the attribute C_i calculated by the N_jth method, and $\sum_{i=1}^{i} \lambda_{N_j C_i} = 1, \lambda_{N_j C_i} > 0$;

(b) Constructing Lagrangian functions based on a single-objective optimization model, as expressed as follows:

$$L(a, \tau) = \sum_{k=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{i} (a_{N_k} \lambda_{N_k C_i} - a_{N_j} \lambda_{N_j C_i})^2 + \tau(\sum_{t=1}^{n} a_{N_t} - 1) \tag{16}$$

Formula (17) can be obtained by the derivation of Formula (16) to a_{N_k} and τ:

$$n a_{N_k} \sum_{i=1}^{i} \lambda_{N_k C_i}^2 - a_1 \sum_{i=1}^{i} \lambda_{1 C_i} \lambda_{N_k C_i} + a_2 \sum_{i=1}^{i} \lambda_{2 C_i} \lambda_{N_k C_i} - a_n \sum_{i=1}^{i} \lambda_{n C_i} \lambda_{N_k C_i}) + \frac{\tau}{2} = 0 \tag{17}$$

$$\sum_{t=1}^{n} a_t - 1 = 0 \tag{18}$$

(3) To solve the weight of each assignment method a_N according to the joint equation of Formulas (17) and (18).

3.1.5. Determination of the Combined Weight of Indicators

Linear weighting is used to obtain the combined weight of indicators λ:

$$\lambda_{\mathrm{i}} = \sum_{n=1}^{n} a_{N_{\mathrm{n}}} \lambda_{\mathrm{i}}^{n} \tag{19}$$

3.2. A Comprehensive Evaluation Model Based on Fuzzy Evidence Reasoning

3.2.1. Fuzzy Confidence Structure Model

For the multi-index evaluation problem, it is assumed that there are L evaluation indexes e_{i} (i = 1, 2, 3, ... , L), and the weight of the index L is ω_{i} (i = 1, 2, 3, ... , L), which satisfies $0 \leq \omega_{\mathrm{i}} \leq 1$, $\Sigma\omega_{\mathrm{i}} = 1$ [30]. The fuzzy evaluation level set is RL = {RL_{n}, n = 1, 2, 3, ... , n), and RL_{n} is the qualitative evaluation level described in the language. The affiliation function of the qualitative evaluation level RL_{n} is expressed by the fuzzy normal distribution. Figure 2 shows the affiliation-degree comparison of the fuzzy normal distribution and the triangular distribution. Figure 3 shows the fuzzy evaluation level. The corresponding affiliation function of the fuzzy evaluation level is:

$$r(u) = \begin{cases} 0 & u < \mu - 3\sigma \text{ or } u > \mu + 3\sigma \\ e^{-\frac{(u-\mu)^2}{2\sigma^2}} & \mu - 3\sigma \leq u \leq \mu + 3\sigma \end{cases} \tag{20}$$

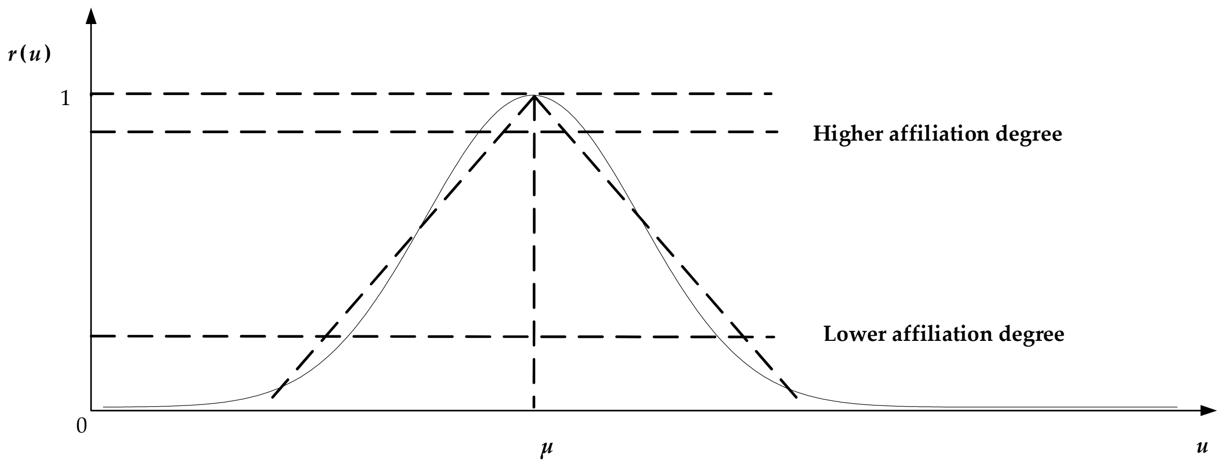

Figure 2. Affiliation-degree comparison of the fuzzy normal distribution and the triangular distribution.

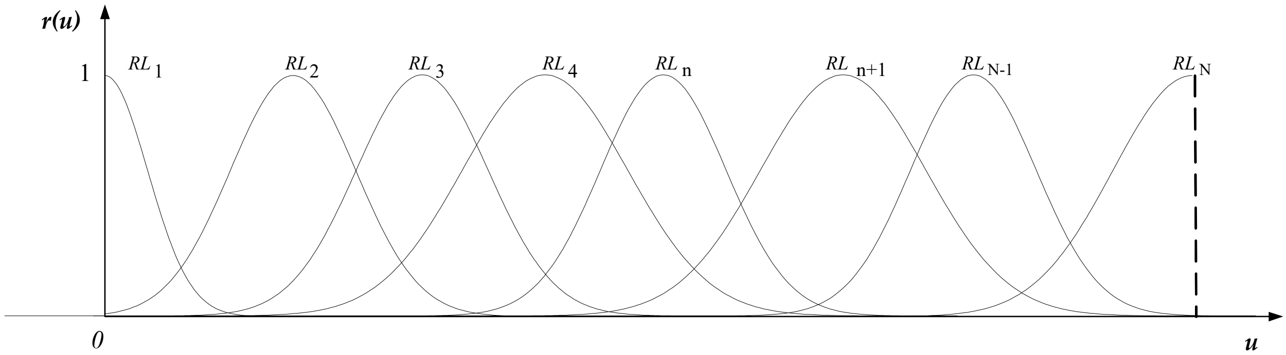

Figure 3. Fuzzy evaluation level.

The fuzzy confidence structure FCS can be expressed as

$$FCS(e_{\mathrm{i}}) = \{(RL_{\mathrm{n}}, \beta_{\mathrm{n}}), n = 1, 2, \cdots, N\} \tag{21}$$

where N is the number of levels; β_n is the confidence of evaluation index e_i on fuzzy evaluation level RL_n. $\beta_n \geq 0$, $\sum_{n=1}^{N} \beta_n \leq 1$. β_n is the description of uncertainty. The information is complete if $\sum_{n=1}^{N} \beta_n = 1$, the information is insufficient if $\sum_{n=1}^{N} \beta_n < 1$, and the information is completely unknown if $\sum_{n=1}^{N} \beta_n = 0$.

3.2.2. Algorithm of Fuzzy Evidence Inference

The basic confidence assignment function $m_i\{H_n\}$ of the evaluation index e_i on the evaluation level RL_n, and the unassigned confidence $m_i\{H\}$, are expressed as:

$$m_i\{H_n\} = \omega\beta_n \tag{22}$$

$$m_i\{H\} = 1 - \sum_{n=1}^{N} m_i\{H_n\} \tag{23}$$

Meanwhile, $m_i\{H\}$ indicates the degree to which all evidence is integrated but not assigned. Let

$$\overline{m}_i\{H\} = 1 - \omega_i \tag{24}$$

Evidence fusion is performed on the L evaluation indicators included in the evaluation object, and the specific algorithm is as follows:

$$m_{1-L}\{H_n\} = k\{\prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H\}] - \prod_{i=1}^{L} m_i\{H\}\},\ n = 1, 2, \ldots, N \tag{25}$$

$$m_{1-L}\{H\} = k\{\prod_{i=1}^{L}[m_i\{H\}\} \tag{26}$$

$$\overline{m}_{1-L}\{H\} = k\{\prod_{i=1}^{L}[\overline{m}_i\{H\}\} \tag{27}$$

$$\begin{aligned} m_{1-L}\{\overline{H}_{n(n+t)}\} = k\mu_{H_{n(n+t)}}^{max}\{\prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H_{n+t}\} + m_i\{H\}] \\ -\prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H\}] - \prod_{i=1}^{L} m_i\{H_{n+t}\} + m_i\{H\}] + \prod_{i=1}^{L} m_i\{H\}\} \\ n = 1, 2, \cdots, N-1; t = 1, 2, \cdots, N-1, \text{ and } n + t \leq N \end{aligned} \tag{28}$$

$$\begin{aligned} k = \{\sum_{n=1}^{N}\{\prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H\}] - \prod_{i=1}^{L} m_i\{H\}\} + \sum_{t=1}^{N-1}\sum_{n=1}^{N-t}\mu_{H_{n(n+t)}}^{max}\{\prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H_{n+t}\} + m_i\{H\}] \\ - \prod_{i=1}^{L}[m_i\{H_n\} + m_i\{H\}] - \prod_{i=1}^{L}[m_i\{H_{n+t}\} + m_i\{H\}] + \prod_{i=1}^{L} m_i\{H\}\} + \prod_{i=1}^{L} m_i\{H\}\}^{-1} \end{aligned} \tag{29}$$

According to the fusion operation of Formulas (25)–(29), the total risk evaluation mass value $m_{1-L}\{H\}$ of the evaluation object, the mass value $m_{1-L}\{\overline{H}_{n(n+t)}\}$ on the intersection of fuzzy evaluation levels $RL_{n,n+t}$, and the normalized coefficient k are obtained. Here, $\mu_{H_{n(n+t)}}^{max}$ is the maximum ordinate of the intersection of evaluation levels RL_n and RL_{n+t}.

3.2.3. Assignment of Fuzzy Intersection Confidence

When L evaluation indicators are integrated, the combined reliability β_n and $\beta_{n(n+t)}$ of the evaluation object can be obtained as:

$$\beta_n = \frac{m_{1-L}\{H_n\}}{1 - \overline{m}_{1-L}\{H\}}, n = 1, 2, \cdots, N \tag{30}$$

$$\beta_{\mathrm{n(n+t)}} = \frac{m_{1-\mathrm{L}}\{\overline{H}_{\mathrm{n(n+t)}}\}}{1-\overline{m}_{1-\mathrm{L}}\{H\}} \quad n = 1,\ 2,\ \cdots,\ N-1 \quad t = 1,\ 2,\ \cdots,\ N-1, \text{and } n+t \le N \tag{31}$$

Reliability $\beta_{\mathrm{n(n+t)}}$ on $RL_{\mathrm{n,n+t}}$ is assigned to reliability $\beta_{\mathrm{n}}^{n(n+t)}$ on RL_{n} and reliability $\beta_{\mathrm{(n+t)}}^{n(n+t)}$ on $RL_{\mathrm{n+t}}$. They are, respectively, expressed as:

$$\beta_{\mathrm{n}}^{n(n+t)} = \frac{S_{\mathrm{n}} + AF_{\mathrm{n}}^{n(n+t)} S_{\mathrm{n(n+t)}}}{S_{\mathrm{n}} + S_{\mathrm{n(n+t)}} + S_{\mathrm{(n+t)}}} \beta_{\mathrm{n(n+t)}} \tag{32}$$

$$\beta_{\mathrm{n+t}}^{n(n+t)} = \frac{S_{\mathrm{n+t}} + AF_{\mathrm{n+t}}^{n(n+t)} S_{\mathrm{n(n+t)}}}{S_{\mathrm{n}} + S_{\mathrm{n(n+t)}} + S_{\mathrm{(n+t)}}} \beta_{\mathrm{n(n+t)}} \tag{33}$$

$$AF_{\mathrm{n}}^{n(n+t)} = \frac{1}{2}\left[(1 - \frac{d_{\mathrm{n}}}{d_{\mathrm{n}} + d_{\mathrm{n+t}}}) + \frac{S_{\mathrm{n}}}{S_{\mathrm{n}} + S_{\mathrm{n+t}}}\right] \tag{34}$$

$$AF_{\mathrm{n+t}}^{n(n+t)} = \frac{1}{2}\left[(1 - \frac{d_{\mathrm{n+t}}}{d_{\mathrm{n}} + d_{\mathrm{n+t}}}) + \frac{S_{\mathrm{n+t}}}{S_{\mathrm{n}} + S_{\mathrm{n+t}}}\right] \tag{35}$$

where d_{n} and $d_{\mathrm{n+t}}$ are the minimum distances between the horizontal coordinates corresponding to the maximum affiliation of evaluation level $RL_{\mathrm{n(n+t)}}$ and evaluation levels RL_{n} and $RL_{\mathrm{n+t}}$, respectively. S_{n} + $S_{\mathrm{n(n+t)}}$ and $S_{\mathrm{n+t}}$ + $S_{\mathrm{n(n+t)}}$ denote the area of the intersection of $RL_{\mathrm{n(n+t)}}$ and the evaluation levels RL_{n} and $RL_{\mathrm{n+t}}$, respectively. $\beta_{\mathrm{n}}^{n(n+t)}$ and $\beta_{\mathrm{n+t}}^{n(n+t)}$ are the redistribution confidence; $AF_{\mathrm{n}}^{n(n+t)}$ and $AF_{\mathrm{n+t}}^{n(n+t)}$ are the confidence subfactors.

The assignment of fuzzy intersection confidence is shown in Figure 4.

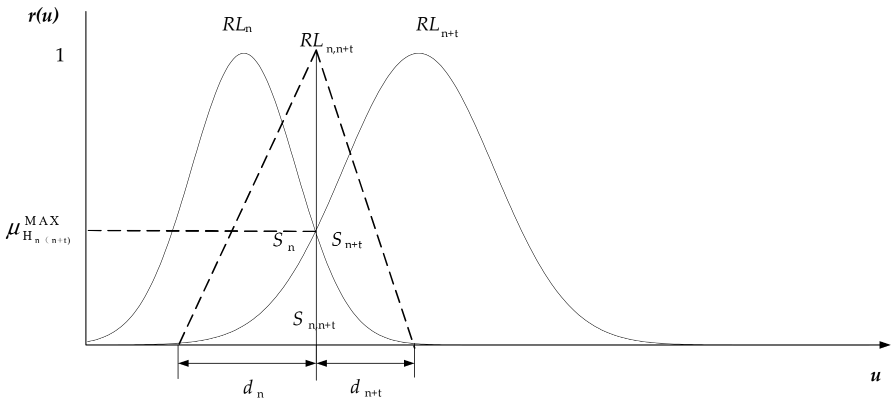

Figure 4. Assignment of fuzzy intersection confidence.

4. Verification of the Evaluation Model Applied in the Engineering Project

4.1. Project Overview

To develop the economic and environmental benefits of the Central South to North Water Convey Project, a tunnel with a total length of 13.18 km is being constructed in the western part of Anyang City through the hilly area. This is a branch line distributing water in the main channel to the region of Anyang City, Henan province of China. The tunnel project mainly includes a TBM starting site, TBM boring section, TBM receiving site, and drilling and blasting section. Except for the drilling and blasting section, TBM tunneling is 11,822 m in length from the TBM start section to TBM exit section. The tunnel is designed with a diameter of 3.5 m, which is bored by double-shield TBM with an excavation diameter of 4.33 m. The longitudinal sloping is 0.01%. The horizontal curve is designed with a radius of 1500 m.

Based on the hydrogeological exploration [42], the tunnel passes through several kinds of geological conditions with hard and integrated rocks, fractured and earthy rocks, weak and earthy rocks, and soil layers. Part of the tunnel needs to pass through the coal bed, including a waste mine roadway. No underground water exists at the boring elevation.

4.2. Determination of the Combined Weight of Risk Indicators

4.2.1. Binary Semantic Judgment Matrix

Two experts from category I (D_1, D_2) and one expert from category II, III, and IV (D_3, D_4, D_5) were invited, respectively, according to the expert classification in Table 2.

Table 2. Expert-classification table.

Category	Category I	Category II	Category III	Category IV
Description of specialist classification	Expert in the field of tunnel engineering	Construction technicians with senior professional titles or above	Construction technicians with intermediate titles or above	Construction technicians with junior professional titles or above
	Project manager of construction unit	Scientific research personnel with senior professional titles or above	Scientific research personnel with intermediate titles or above	Scientific research personnel with junior professional titles or above
	Senior resident supervising engineer	Supervisors with senior professional titles or above	Supervisors with intermediate titles or above	Supervisors with junior professional titles or above
	Design person in charge	Designers with senior professional titles or above	Designers with intermediate titles or above	Designers with junior professional titles or above

Let the expert weight vector W = (0.3, 0.3, 0.2, 0.15, 0.05). The construction safety-risk index of the water transfer TBM tunnel of Anyang is evaluated in five aspects, namely, technical risk (C_1), geological risk (C_2), equipment risk (C_3), management risk (C_4), and safety-accident risk (C_5), to be used as the original data for index weight calculation. Considering the language evaluation set S = {very unimportant (FBI), unimportant (HBI), relatively unimportant (JBI), slightly unimportant (LBI), generally important (I), slightly important (LI), relatively important (TI), and very important (HI)}, with granularity of 7, experts made a qualitative evaluation on the safety-risk indicators of the water transfer TBM tunnel of Anyang, as presented in Table 3.

Table 3. Language evaluation of first-level indicators of the expert group.

First-Level Indicator	Expert Language Evaluation				
	D_1	D_2	D_3	D_4	D_5
Technical risk C_1	JI	HI	JI	JI	HI
Geological risk C_2	HI	JI	HI	JI	TI
Equipment risk C_3	TI	HI	HI	HI	I
Management risk C_4	I	TI	TI	TI	JBI
Safety accident risk C_5	JBI	I	JBI	I	JBI

According to the evaluation information of the first-level risk indicators by experts, a binary semantic judgment matrix is constructed. The binary semantic judgment matrix established by expert D_1 for the first-level risk indicators is presented as follows:

$$R^{D_1} = \begin{bmatrix} (S_4,0) & (S_5,0.1) & (S_6,0) & (S_7,0) & (S_8,0) \\ (S_3,-0.1) & (S_4,0) & (S_5,0) & (S_6,0) & (S_7,0) \\ (S_2,0) & (S_3,0) & (S_4,0) & (S_5,0) & (S_6,0.2) \\ (S_1,0) & (S_2,0) & (S_3,0) & (S_4,0) & (S_5,0) \\ (S_0,0) & (S_1,0) & (S_2,-0.2) & (S_3,0) & (S_4,0) \end{bmatrix}$$

4.2.2. Subjective Weight

According to the scale in Table 1, by comparing and judging the experts' evaluation on the importance of indicators, the attribute judgment matrix of experts on all levels of indicators can be derived with the conversion Formula (11), taking $\beta = 2$.

Based on Formulas (5) and (6), the attribute judgment matrix and weight of expert D^1 for risk indicators at all levels can be calculated, as presented in Table 4. The subjective weights of other indicators of each expert can be obtained by the same token.

Table 4. Attribute judgment matrix and weight λ_{D_1} of expert D^1 for the first-level indicators.

D^1 Indicator	C_1	C_2	C_3	C_4	C_5	Weights
C_1	0	0.400	0.857	0.909	0.923	0.309
C_2	0.600	0	0.857	0.923	0.933	0.331
C_3	0.143	0.143	0	0.909	0.933	0.213
C_4	0.091	0.077	0.091	0	0.909	0.117
C_5	0.077	0.067	0.067	0.091	0	0.030

4.2.3. Objective Weight

Step 1: calculate the deviation between an expert's judgment and other experts' judgments on the evaluation index. The expert-deviation degree of the first-class index is shown in Table 5. Similarly, the deviation degrees of other experts can be obtained.

Table 5. The expert-deviation degree of the first-class index.

Indicators	Expert				
	D_1	D_2	D_3	D_4	D_5
C_1	32.200	28.100	22.800	25.500	23.000
C_2	13.500	10.100	9.850	9.454	9.245
C_3	7.467	6.487	6.302	6.204	6.114
C_4	5.300	5.700	5.400	4.300	5.300
C_5	3.800	2.200	2.600	2.200	2.000

Step 2: calculate the total deviation of experts' judgment on evaluation indicators according to Formula (12). The total deviation of first-level indicators is shown in Table 6.

Table 6. Total deviation of experts on the first-level indicators.

Indicators	C_1	C_2	C_3	C_4	C_5
Total deviation	29.508	13.458	6.984	5.143	2.147

Step 3: calculate the objective weight of TBM tunnel construction risk based on maximum deviation according to Formula (13). The first-level index weight λ_{1i} is shown in Table 7.

Table 7. Expert's objective weight λ_i^1 for the first-level indicators.

Indicators	C_1	C_2	C_3	C_4	C_5
Weight	0.534	0.238	0.124	0.098	0.006

4.2.4. Comprehensive Weight

Step 1: The weight of the first-level index calculated by the objective weighting method based on the maximizing deviation of binary semantics is $\lambda_{C_1}^2 = 0.534$, $\lambda_{C_2}^2 = 0.238$, $\lambda_{C_3}^2 = 0.124$, $\lambda_{C_4}^2 = 0.098$, $\lambda_{C_5}^2 = 0.006$.

According to Formula (14), the index layer weight matrix is constructed. The index layer weight matrix for the first-level index is as follows:

$$T^1 = \begin{bmatrix} 0.310 & 0.324\ 0.211\ 0.124\ 0.031 \\ 0.534 & 0.238\ 0.124\ 0.098\ 0.006 \end{bmatrix}$$

Step 2: Based on the principle of minimum deviation, a single-objective optimization model is constructed. By Formula (16) and the single-objective optimization model, the Lagrange function of the first-level index C_1 is:

$$L(a,\tau) = \sum_{j=1}^{6}\sum_{i=1}^{6}\left(a_{N_1}\lambda_{N_1C_i} - a_{N_2}\lambda_{N_2C_i}\right)^2 + \tau(a_{N_2} - 1)$$

Step 3: By using the Formulas (15)–(18), the equations are constructed with first-class indexes:

$$2a_{N_1}\sum_{i=1}^{6}{\lambda_{N_1C_i}}^2 - a_{N_1}\sum_{i=1}^{6}\lambda_{N_1C_i}\lambda_{N_1C_i} + a_{N_2}\sum_{i=1}^{6}\lambda_{N_2C_i}\lambda_{1C_i} + \frac{\tau}{2} = 0$$

$$2a_{N_2}\sum_{i=1}^{6}{\lambda_{N_2C_i}}^2 - a_{N_1}\sum_{i=1}^{6}\lambda_{N_1C_i}\lambda_{N_2C_i} + a_{N_2}\sum_{i=1}^{6}\lambda_{N_2C_i}\lambda_{N_2C_i} + \frac{\tau}{2} = 0$$

$$a_{N_1} + a_{N_2} - 1 = 0$$

It can be derived that $a_{N_1} = 0.601, a_{N_2} = 0.399$.

With the linear weighting of Formula (19), the comprehensive weight of the first-level indicators can be obtained as shown in Table 8. Similarly, the weights of the second-level indicators can be obtained:

Table 8. Weights of first-level indicators of safety risks in TBM tunnel construction.

First-Level Indicator	C_1	C_2	C_3	C_4	C_5
Weight	0.399	0.290	0.176	0.114	0.021

4.3. Comprehensive Risk Evaluation

By analyzing the risk indicators and their impacts in TBM tunnel construction, risk was classified into five levels by referring to the conventional classification of risk assessment and management of railway tunnels [43,44]. The five levels are named RL = {RL_1, RL_2, RL_3, RL_4, RL_5} = {'low risk', 'somewhat low risk', 'medium risk', 'somewhat high risk', 'high risk'}. The risk value and membership function of this project are shown in Table 9, and the fuzzy evaluation level of TBM tunnel construction emergency risk is shown in Figure 5.

Table 9. Value at risk and membership function.

Risk Level	The Range of Risk Value u	Membership Function μ and σ
Low risk	$0 < u \leq 45$	μ = 0, σ = 15
Somewhat low risk	$0 < u \leq 60$	μ = 30, σ = 10
Medium risk	$5 < u \leq 95$	μ = 50, σ = 15
Somewhat high risk	$30 < u \leq 100$	μ = 75, σ = 15
High risk	$70 < u \leq 100$	μ = 100, σ = 10

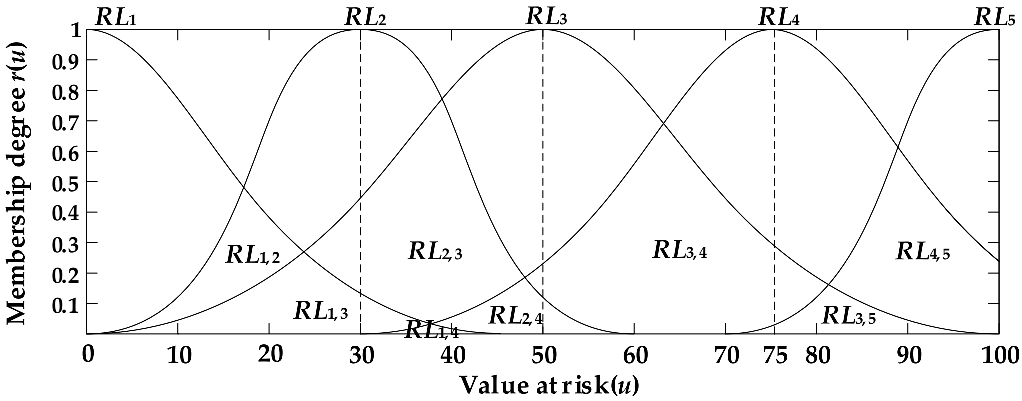

Figure 5. Fuzzy evaluation level of emergency risk in TBM tunnel construction.

According to Figure 5, the maximum affiliation degree $\mu^{\max}_{n(n+1)}$ of the intersection of each evaluation level is obtained as shown in Table 10.

Table 10. List of maximum membership degree of intersection of evaluation grades.

$\mu^{\max}_{n(n+1)}$	RL_1	RL_2	RL_3	RL_4	RL_5
RL_1	1	0.487	0.249	0.044	0
RL_2		1	0.726	0.198	0
RL_3			1	0.707	0.135
RL_4				1	0.607
RL_5					1

By using the summary table of risk index weight and the confidence structure of risk level, the risk of TBM tunnel construction is evaluated. The confidence structure of each risk level of technical risk (C_1) is shown in Table 11.

Table 11. Confidence Structure of Technical Risk Indicators.

Criterion Layer	Standard Floor	Confidence Structure				
		RL_1	RL_2	RL_3	RL_4	RL_5
Technical risk C_1	C_{11}	0.0776	0.1254	0.3428	0.2344	0.2198
	C_{12}	0.0464	0.2021	0.2484	0.3578	0.1453
	C_{13}	0.1864	0.3262	0.2646	0.1543	0.0685
	C_{14}	0.0820	0.2130	0.2839	0.3251	0.0950

The basic confidence $m_i\{H_n\}$ and unassigned confidence $m_i\{H\}$ on all risk re-identification frameworks are calculated according to Formulas (22) and (23). The integrated assignment function for all risk evaluations is calculated with Formulas (24)–(29), and the integrated risk assignment function for technical risk evaluations is shown in Table 12.

Table 12. Portfolio probability distribution function for technical risk evaluation.

n	$m\{H_n\}$	$m\{H_{1n}\}$	$m\{H_{2n}\}$	$m\{H_{3n}\}$	$m\{H_{4n}\}$
1	0.0447				
2	0.0947	0.0033			
3	0.2095	0.0028	0.0206		
4	0.1711	0.0005	0.0049	0.0316	
5	0.1200	0.0000	0.0000	0.0034	0.0154

$k = 1.12$; $m\{H\} = 0.28$; $\overline{m}\{H\} = 0.28$.

The combined confidences of risk β_{n} and $\beta_{\mathrm{n(n+t)}}$ are calculated by Formulas (30) and (31), and $\beta_{\mathrm{n(n+t)}}$ is redistributed with Formulas (30)–(35) to finally obtain the confidence structure of each risk level as shown in Table 13.

Table 13. Results of fuzzy intersection reliability assignment of risk indicators.

	RL_1	RL_2	RL_3	RL_4	RL_5
β_{C_1}	0.076	0.153	0.331	0.263	0.177
β_{C_2}	0.074	0.163	0.258	0.363	0.142
β_{C_3}	0.120	0.294	0.361	0.162	0.061
β_{C_4}	0.128	0.254	0.363	0.185	0.066
β_{C_5}	0.167	0.439	0.208	0.139	0.045
β_C	0.081	0.194	0.318	0.259	0.145

According to the calculation results, the fuzzy intersection reliability structure of the construction risk is β_C = {(RL_1, 0.076), (RL_2, 0.153), (RL_3, 0.331), (RL_4, 0.263), (RL_5, 0.177)}. The results show that the construction safety-risk level of the TBM tunnel is at the middle- and high-risk levels, and the safety-accident risk level belongs to the fuzzy evaluation level RL_2, which is at low risk. The technical risk level, equipment risk level, and management risk level belong to the fuzzy evaluation level RL_3, which is medium risk. The geological risk level belongs to the fuzzy evaluation level RL_4, which is a relatively high risk and should be controlled with emphasis.

4.4. Implement Achievement

Based on this study of the risk evaluation in this TBM tunnel project, partners of the project effectively control the risk sources. In particular, a special construction scheme has been formulated and implemented in view of the geological complex conditions. After TBM tunneling construction for about eighteen months, this tunnel has been successfully completed.

5. Conclusions

Based on the study in this paper, conclusions can be made as follows:

(1) According to the characteristics of TBM tunnel construction, five categories of technical risk, geological risk, equipment risk, management risk, and safety-accident risk are identified and analyzed, with a total of 24 indicators.

(2) Based on binary semantic theory, and aiming at the limitation of determining the subjective and objective weights, a combined weighting with the principle of minimum deviation is introduced, and a weight determination model of risk indicators is established. Aiming at the uncertainty existing in the comprehensive evaluation process, the decision-makers' evidence theory and fuzzy theory are applied, and a fuzzy normal distribution is introduced as the affiliation function distribution of fuzzy evaluation levels.

(3) Based on the two-by-two intersection of fuzzy evaluation rank functions, a safety-risk evaluation model for TBM tunnel construction is established by collecting evidence and revising the affiliation function for the first time. The rationality of this model is verified with a case study on TBM construction of a water conveyance tunnel. Under the guidance of the analytical results for the risk assessment and management of TBM construction, the water conveyance tunnel has been safely penetrated.

(4) Although part of the uncertainty problem can be effectively solved by using the fuzzy evidence reasoning method, the risk magnitude still cannot be accurately determined. This should be improved in the risk evaluation model considering other factors.

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