

Research Article

Diagnosis of Critical Risk Sources in the Operation Safety of the Central Route Project of South-to-North Water Diversion Based on the Improved FMEA Method

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For the inaccurate description of the failure level in the traditional failure mode and effects analysis (FMEA) method, the research uses the fuzzy evidence reasoning theory to improve the traditional failure mode and effects analysis (FMEA) method. Based on the subjective weight determined by the analytic hierarchy process and the objective weight determined by the gray correlation degree method, we get the combined weight of risk factors through the principle of minimum discrimination information. Combined with the technique for order of preference by similarity to ideal solution (TOPSIS), an improved risk sequence number (IRPN) method was proposed to diagnose the key risk sources. In the case study on a canal section of the Central Route Project of South-to-North Water Diversion in Henan, the key risk factors for the operation safety of the project are identified as rainstorm and flood, geological conditions, geological disasters, and design safety coefficient, and the corresponding prevention measures are put forward to provide help for the safe operation of the Central Route Project of South-to-North Water Diversion.

1. Introduction

The Central Route Project of South-to-North Water Diversion is large in scale, has long-distance water diversion, and faces a complex geological environment. The Central Route Project is a typical series system in which there are a large number of cross buildings and control buildings such as water diversion gates and control gates. These buildings are vital to the safe operation of the whole water conveyance channel. Any accidents in a single building or canal section in the system will cause serious consequences to the safety of the project. Furthermore, superimposed risks of every single project will increase the difficulty of the operation safety management of the Central Route Project of South-to-North Water Diversion. A safety accident in the operation of the

Central Route Project will not only seriously affect people's lives but also cause huge economic losses and serious social problems. Therefore, it is necessary to comprehensively assess the risks that may happen in the operation of the Central Route Project to diagnose the key risk sources. Based on the assessment result, managers are able to take more targeted measures to guard the safety of the Central Route Project operation. FMEA is one of the important tools of quality management [1]. As a qualitative analysis methodology, FMEA quantifies the risk level through the analysis of potential or existing failure modes to determine the consequences that may happen or have happened [2]. According to the different failure modes that cause risks, managers can take targeted preventive and improvement measures to enhance product quality and ensure system reliability [3]. To identify

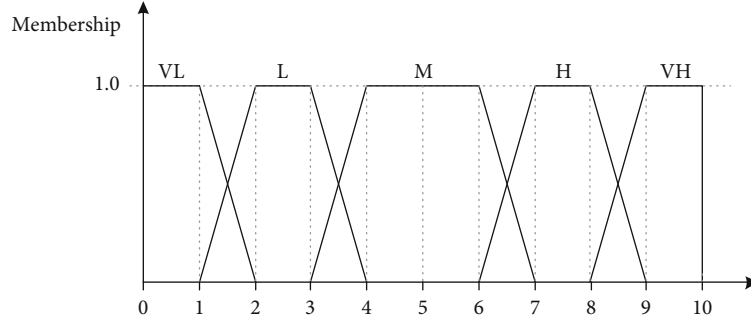


FIGURE 1: Fuzzy membership function of risk factor language variables.

TABLE 1: Evaluation criteria for the three factors of FMEA of the Central Route Project.

Rating	Frequency of occurrence (O)	Severity (S)	Difficulty to detect (D)	Fuzzy number
VL	Rarely happens	No impact	Very high probability of detection	(0, 0, 1, 2)
L	Less frequently	Minor impact	High probability of detection	(1, 2, 3, 4)
M	Occasionally	Moderate impact	Medium probability of detection	(3, 4, 6, 7)
H	Recurring	Serious impact	Low probability of detection	(6, 7, 8, 9)
VH	Inevitable	Bad impact	Very low probability of detection	(8, 9, 10, 10)

TABLE 2: The values of evaluation grades.

Rating	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}	H_{22}	H_{23}	H_{24}	H_{25}	H_{33}	H_{34}	H_{35}	H_{44}	H_{45}	H_{55}
h_{ii}	0.130	0.259	0.394	0.459	0.500	0.292	0.433	0.500	0.541	0.500	0.567	0.606	0.708	0.741	0.870

the risk of each failure mode, the traditional FMEA method uses RPN to quantify the risk level [4]. The RPN is the product of the probability occurrence rate (O), severity (S), and the probability of not detecting the failure (D) mode [5]. In the application of the conventional FMEA method, managers may find it hard to evaluate the accurate value when assessing the grade number of each evaluation factor of failure modes [6]. When analyzing, an RPN value may correspond to different combinations that cannot be effectively distinguished. The RPN value of the risk is not a continuous sequence number. Besides, the calculation method of the RPN value does not have a sufficient scientific theory basis. The change in the grade value of a single evaluation factor may stimulate a sudden mutation of the RPN value and other defects [7]. Given the facts, scholars have proposed improved methods. Kumru and Kumru [8] used the fuzzy set theory to handle the information ambiguity and uncertainty in the FMEA evaluation process and solved the defect of the traditional FMEA model's incapability to describe the fault level accurately. Wang et al. [9] sorted the risk of failure modes with an improved FMEA method based on intuitive multiplicative preference relations and an improved TOPSIS method based on bidirectional projection distance, thus improving the accuracy of the risk ranking of failure modes. You et al. [10] leveraged the interval binary mixed weighted distance measure to improve the traditional FMEA model, which in turn solves the absence of the relative weight between the evaluation elements in the traditional FMEA model and the problem of different evaluation combinations

producing the same RPN value. Chang and Sun [11] used data envelopment analysis to enhance the FMEA evaluation capability using a value of 1 to 10 instead of fuzzy sets for parameters. Barends et al. [12] proposed a modified probabilistic FMEA that replaces the estimated proportional frequency to determine the rate of occurrence " O " and detection coefficient " D ," instead of the definite amounts used when calculating RPN. Dong [13] presented a cost-effective FMEA tool based on the fuzzy utility theory that used the utility theory and fuzzy membership functions for the assessment of severity, occurrence, and detection. Can [14] considered the intuitionistic fuzzy scale to be more practical and logical than the traditional FMEA evaluation scale and proposed the use of the intuition evaluation scale to determine the evaluation value of the factor. Based on the above research, we hereby propose an improved FMEA method based on the fuzzy evidence reasoning theory to diagnose the key risk sources of the operation safety of the Central Route Project of South-to-North Water Diversion.

2. Fuzzy Evidence Reasoning Theory

2.1. Fuzzy Confidence Structure. In the fuzzy evidence reasoning theory, accurate numerical values evaluate the level of each evaluation factor under the failure mode, and the confidence structure evaluates the level of risk elements. Suppose that the evaluation set of fuzzy language variables H_{ii} ($i = 1, 2, 3, \dots, 5$) is $H = (H_{11}, H_{22}, H_{33}, H_{44}, H_{55}) = \{VL, L, M, H, VH\}$, where VL is for very low, L for low, M for

TABLE 3: Standard values of random consistency index RI.

Matrix order n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

medium, H for high, and VH for very high. Assuming that the fuzzy evaluation levels are independent of each other and the adjacent fuzzy levels intersect, the five evaluation levels are represented by trapezoidal fuzzy numbers [15–18]. The fuzzy membership function of the linguistic variables of risk factors is shown in Figure 1.

Each fuzzy language variable evaluates the evaluation elements O (frequency of occurrence), S (severity), and D (difficulty to detect). The evaluation criteria for the three elements of FMEA for the Central Route Project are shown in Table 1.

Suppose that the FMEA evaluation team has k evaluators (EX_1, EX_2, \dots, EX_k), and the weight of each evaluator EX_k is λ_k ($\lambda_k > 0$), $\sum_{k=1}^K \lambda_k = 1$. Each evaluator evaluates the three evaluation elements of N risk factors ($F_1, F_2, \dots, F_n, \dots, F_N$), using $\{(H_{ij}, \alpha_{ij}^k(F_n, E_{FL}))\}$ to represent the confidence evaluation of the k th expert on the p th evaluation factor of the n th risk, whose grade is H_{ij} . Such representation of the result is called a fuzzy confidence structure in evidence reasoning, $\alpha_{ij}^k(F_n, E_{FL})$ is the corresponding confidence, H_{ij} indicates that the fuzzy grade of the evaluation set is between i and j , i and j indicate the fuzzy grade of the evaluation set, where $i \leq j$; $i = 1, 2, 3, 4, 5$; $j = 1, 2, 3, 4, 5$; $k = 1, 2, \dots, K$; $n = 1, 2, \dots, N$; and $L = 1, 2, 3$ [19–21]. Use $\tilde{x}_n = \{(H_{ij}, \alpha_{ij}^k(F_n, E_{FL}))\}$ to represent the result of the FMEA evaluation team's comprehensive evaluation on the risk factor F_n about the evaluation element E_{FL} . \tilde{x}_n is called the comprehensive confidence structure, and the confidence is

$$\alpha_{ij}(F_n, E_{FL}) = \sum_{k=1}^K \lambda_k \alpha_{ij}^k(F_n, E_{FL}). \quad (1)$$

2.2. Explicit Confidence Matrix. The comprehensive confidence structure \tilde{x}_n defuzzification formula is [20]

$$h_{ij} = \frac{\sum_{p=0}^1 (b_p - c)}{\sum_{p=0}^1 (b_p - c) - \sum_{p=0}^1 (a_p - d)}. \quad (2)$$

Among them, h_{ij} is the unambiguous value of H_{ij} defuzzification, $c = 0$, and $d = 10$. When the membership function value of the language rating is 0, a_0 and b_0 are the critical values. When the membership function value of the language rating is 1, the critical value is a_1 and b_1 [22, 23]. The clear value of the evaluation level is shown in Table 2.

The risk factor F_n is obtained after the weighted average of the clear value of the evaluation factor E_{FL} :

$$x_n(L) = \sum_{i=1}^5 \sum_{j=1}^5 h_{ij} \alpha_{ij}(F_n, E_{FL}). \quad (3)$$

$x_n(L)$ constitutes a clear confidence matrix:

$$\mathbf{X} = \begin{matrix} F_1 \\ F_2 \\ \vdots \\ F_N \end{matrix} \begin{bmatrix} x_1(1) & x_1(2) & x_1(3) \\ x_2(1) & x_2(2) & x_2(3) \\ \vdots & \vdots & \vdots \\ x_N(1) & x_N(2) & x_N(3) \end{bmatrix}. \quad (4)$$

Use the vector normalization method to normalize the explicit confidence matrix:

$$R = (r_{nl})_{N \times 3}, \quad (5)$$

where $r_{nl} = x_n(L) / \sqrt{\sum_{n=1}^N x_n^2(L)}$, $n \in N$, $L = 1, 2, 3$.

3. Comprehensive Weight Calculation of Risk Factors

3.1. AHP Method to Determine the Subjective Weight of Risk Factors. Steps of using the analytic hierarchy process to determine the subjective weight of risk factors are as follows: (1) establish the hierarchical structure model; (2) construct the judgment matrix A ; (3) calculate the maximum eigenvalue λ_{\max} of matrix A and the eigenvector ω_A corresponding to the eigenvalue; and (4) use $(\lambda_{\max}(A) - n)$ that measures the degree of inconsistency of matrix A ; $CI = (\lambda_{\max} - n) / (n - 1)$ is the consistency index, and $RI = (CI_1 + CI_2 + \dots + CI_n) / n$ is the random consistency index of judgment matrix A . The standard value of random consistency index RI is shown in Table 3.

Usually, when the value of CR is less than 0.1, the judgment matrix A is considered passing the consistency test, otherwise restructuring the judgment matrix A until it passes the consistency test.

3.2. Gray Relational Analysis Method to Determine the Objective Weight of Risk Factors. By standardizing the original evaluation matrix X_{ij} , we get $x_{ij} = (X_{ij} - \bar{X}_j) / S_j$, the sample mean is $\bar{X}_j = (1/n) \sum_{i=1}^n X_{ij}$, and the sample mean square error is $S_j = \sqrt{(\sum_{i=1}^n (X_{ij} - \bar{X}_j)^2) / (n - 1)}$. Then, we take the maximum set x_0 of each risk factor as the reference sequence, where $\{x_0\} = \{x_0(i)\}$ ($i = 1, 2, \dots, n$), and the comparison sequence is x_i ($i = 1, \dots, n$), so the correlation coefficient calculation formula is

$$y_{ij}(k) = \frac{m + \xi M}{\Delta_{ij}(k) + \xi M} \quad (k = 1, 2, \dots, n; i = 1, 2, \dots, m). \quad (6)$$

Among them, $m = \min \min |x_0(k) - x_i(k)|$ is the minimum difference between the comparison sequence and the reference sequence element, $M = \max \max |x_0(k) - x_i(k)|$ is the maximum difference between the comparison sequence and the reference sequence element, $\Delta_{ij}(k) = |x_0(k) - x_i(k)|$ represents the absolute value of the difference between the

reference sequence and the comparison sequence element. The gray correlation degree judgment matrix is

$$\Lambda = \begin{bmatrix} y_{11}(1) & y_{12}(2) & \cdots & y_{1m}(k) \\ y_{21}(1) & y_{22}(2) & \cdots & y_{2m}(k) \\ \vdots & \vdots & \vdots & \vdots \\ y_{n1}(1) & y_{n2}(2) & \cdots & y_{nm}(k) \end{bmatrix}. \quad (7)$$

The correlation degree Y_{ij} between the evaluation sequence of risk factor i and the reference sequence is

$$Y_{ij} = \frac{1}{n} \sum_{k=1}^n y_{ij}(k). \quad (8)$$

The weight assigned according to the degree of correlation of the risk factor i is

$$\omega_y = \frac{Y_{ij}}{\sum_{i=1}^m Y_{ij}}. \quad (9)$$

$\omega_y(\omega_1, \omega_2, \dots, \omega_m)$ is the objective weight of the risk factor determined by the gray correlation degree.

3.3. The Principle of Minimum Discriminative Information Determines the Weight of Risk Factor Combinations. The subjective weight $\omega_A(\omega_1, \omega_2, \dots, \omega_m)$ determined by the analytic hierarchy process and the objective weight $\omega_y(\omega_1, \omega_2, \dots, \omega_m)$ determined by the gray relational analysis method are used to determine the comprehensive weight $\omega_z(\omega_1, \omega_2, \dots, \omega_m)$ which has the highest similarity to the subjective and objective weights by the smallest discriminating information. When the sum of the two discriminating information reaches the smallest level, the comprehensive weight is similar to the subjective and objective weights, and establish the objective function:

$$\min F = I(\omega_z, \omega_A) + I(\omega_z, \omega_y) = \sum_{j=1}^m \omega_z \left[\ln \frac{\omega_z}{\omega_A} \right] + \sum_{j=1}^m \omega_z \left[\ln \frac{\omega_z}{\omega_y} \right]. \quad (10)$$

Among them, the comprehensive weight is ω_z , which satisfies $\omega_1 + \omega_2 + \dots + \omega_m = 1$, and $\omega_1, \omega_2, \dots, \omega_m > 0$.

Use the Lagrange function to get the value of minimum discriminative information:

$$L(\omega_z, \lambda) = \sum_{j=1}^m \omega_z \left[\ln \frac{\omega_z}{\omega_A} \right] + \sum_{j=1}^m \omega_z \left[\ln \frac{\omega_z}{\omega_y} \right] - \lambda \left(\sum_{j=1}^m \omega_z - 1 \right). \quad (11)$$

When there is an extreme value, the solution is

$$\omega_z = \frac{\sqrt{\omega_A \omega_y}}{\sum_{i=1}^m \sqrt{\omega_A \omega_y}}. \quad (12)$$

4. Key Risk Source Diagnosis Based on the TOPSIS Analysis Method

Based on determining the normalized matrix, the TOPSIS method is used to calculate the distance between the risk factor and its ideal solution to judge the priority of the risk factor.

- (1) Determine the positive ideal solution S^+ and the negative ideal solution S^-

$$S^+ = (R_1^+, R_2^+, R_3^+), \quad (13)$$

$$S^- = (R_1^-, R_2^-, R_3^-). \quad (14)$$

Among them, $r_L^+ = \max \{r_{nL}\}$ and $r_L^- = \min \{r_{nL}\}$ represent the maximum and minimum values of elements in the explicit confidence matrix R , respectively.

- (2) Use the Euclidean distance formula to calculate the distance between the risk factor and the positive ideal solution or the negative ideal solution

$$d_n^+ = \|R_{nL} - S^+\| = \sqrt{\sum_{L=1}^3 (r_{nL} - r_L^+)^2}, \quad (15)$$

$$d_n^- = \|R_{nL} - S^-\| = \sqrt{\sum_{L=1}^3 (r_{nL} - r_L^-)^2}. \quad (16)$$

- (3) Calculate the relative closeness C_n of each risk factor and the improvement risk sequence number. The calculation formula for the relative closeness is

$$C_n = \frac{d_n^-}{d_n^+ + d_n^-}. \quad (17)$$

The greater the relative closeness, the longer the distance between the risk factor and the negative ideal solution, but the shorter the distance to the positive ideal solution, the larger the impact on the system. Meanwhile, the combination of the relative closeness and the comprehensive weights of risk factors generates the value of the importance risk priority number (IRPN). The larger the IRPN value, the higher the priority of the representative risk factor, and the more significant the risk factor, thus translating into the basis for the diagnosis of key risk sources [24, 25]. The IRPN value calculation formula is

$$\text{IRPN} = C_n \times \omega_z. \quad (18)$$

5. Case Analysis

In a section of the Central Route Project of South-to-North Water Diversion in Henan, the pile no. starts from

TABLE 4: The ranking of d_i^+ , d_i^- , C_i , ω_Z , and the final RPN values of each risk factor.

Risk factor	d_i^+	d_i^-	C_i	ω_A	ω_y	ω_Z	IRPN	Sort
Storm flood F1	0.0076	0.3229	0.9770	0.2095	0.0744	0.1249	0.1220	1
Geological disaster F2	0.2156	0.1151	0.3481	0.0799	0.0718	0.0758	0.0264	3
Extreme weather F3	0.2885	0.0365	0.1123	0.0305	0.0412	0.0355	0.0040	10
Design safety factor F4	0.2626	0.0857	0.2461	0.1215	0.0637	0.0880	0.0217	4
Building reliability F5	0.3110	0.0653	0.1735	0.0811	0.0569	0.0680	0.0118	5
Equipment reliability F6	0.3138	0.0157	0.0477	0.0664	0.0391	0.0509	0.0024	14
Geological conditions F7	0.2914	0.1055	0.2657	0.2202	0.0734	0.1271	0.0338	2
Engineering construction quality F8	0.2429	0.0934	0.2777	0.0165	0.0608	0.0316	0.0088	6
Personnel management quality F9	0.3108	0.0332	0.0966	0.0455	0.0406	0.0430	0.0042	9
Engineering maintenance management level F10	0.3056	0.0317	0.0940	0.0228	0.0409	0.0305	0.0029	12
Management system perfection level F11	0.3139	0.0156	0.0473	0.0228	0.0382	0.0295	0.0014	18
Human activity impact F12	0.3024	0.0523	0.1474	0.0203	0.0472	0.0309	0.0046	8
Operation and maintenance construction management level F13	0.3204	0.0170	0.0503	0.0040	0.0391	0.0125	0.0006	19
Protection scope violation activity F14	0.3075	0.0469	0.1323	0.0116	0.0457	0.0230	0.0030	11
Illegal operation F15	0.3220	0.0034	0.0104	0.0059	0.0366	0.0147	0.0002	20
Man-made sabotage F16	0.2993	0.0453	0.1316	0.0026	0.0457	0.0109	0.0014	17
Fire F17	0.2985	0.0385	0.1143	0.0127	0.0437	0.0236	0.0027	13
Sudden water pollution F18	0.3030	0.0548	0.1531	0.0199	0.0500	0.0315	0.0048	7
Traffic accident F19	0.2990	0.0381	0.1131	0.0043	0.0438	0.0138	0.0016	16
Social dispute F20	0.2817	0.0563	0.1667	0.0020	0.0473	0.0096	0.0016	15

IV28+500 to IV66+960. The canal is 38.46 km long, of which the length of the building is 3.68 km and the length of the open channel is 34.78 km. In the beginning, the designed flow rates and the increased flow rates are 265 m³/s and 320 m³/s, respectively, while the statistics at the end of the canal are 260 m³/s and 310 m³/s. The designed lift is 2.955 m, and the designed water depth is 7 m. Channel engineering covers the three forms of full excavation, half-excavation half-filling, and full filling. The length of the excavated canal section is 20.19 km, the maximum digging depth is 40 m, the cumulative length of the high-filled canal section is 6.5 km, the maximum filling height is 13 m, and the cumulative length of the half-cut and half-filled sections is 7.39 km. The channel passes through several special geological canal sections, including high-groundwater level canal sections, weak expansive soil canal sections, and collapsible loess canal sections. The section of the high-groundwater level is about 16.58 km long, and the weak expansive soil canal section is about 2.93 km long. The total length of the collapsible loess canal section is 4.3 km, and the length of the stone canal section is 2.5 km. Geological problems are significant in these sections—all the projects where the main canal crossing rivers, irrigation canals, railways, and highways adopt the interchange layouts. There are 69 buildings of different types along the line, including 2 control gates, 3 exit gates, 3 water diversion gates, and 8 river canal crossing buildings. Among them, the Baimamen River inverted siphon, Lihe inverted siphon, and Shanmen River culvert are all facing relatively great flood risk. There are 3 drainage buildings on the left bank, 48 bridges (27 highway bridges, 10 production bridges, and 11 railway brid-

ges), and 2 sewage corridors. Besides, this section is the only project that passes through the main urban area of the entire Central Route Project. The surrounding environment of the project is extremely complex. It involves 4 districts, 1 county, and 30 administrative villages along the line. Adjacent to the South-to-North Water Diversion, there are all kinds of crossing projects which are facing great dangers and high emergent accident possibilities. It is one of the most special engineering sections in the Central Route Project of South-to-North Water Diversion.

5.1. Constructing a Clear Confidence Matrix. To obtain comprehensive evaluation information, five experts from universities and construction management institutes were invited to team up with an FMEA expert group. The five experts participated in the construction, management, and scientific research work during the construction and operation periods of the Central Route Project of South-to-North Water Diversion. Considering the difference in the experience and knowledge level of these evaluation experts, the weight λ_k is assigned to each expert at values of 0.1, 0.3, 0.25, 0.15, and 0.2. The 20 risk factors in this segment are as follows: rainstorm and flood F1, geological disasters F2, extreme weather F3, design safety factor F4, building reliability F5, equipment reliability F6, geological conditions F7, engineering construction quality F8, personnel management quality F9, engineering maintenance management level F10, management system perfection level F11, human activity impact F12, operation and maintenance construction management level F13, protection scope violation activity F14, illegal operation F15,

man-made sabotage F16, fire F17, sudden water pollution F18, traffic accident F19, and social dispute F20. The fuzzy confidence structure is used to express 20 risk factors evaluated by the five experts from the three evaluation factors. Taking Table 2 into consideration together with formulas (1) and (3), a clear confidence matrix is obtained after defuzzification. After performing vector normalization to formula (5), we get

$$\begin{aligned}
 X = & \begin{bmatrix} 0.6977 & 0.8020 & 0.1790 \\ 0.2881 & 0.6491 & 0.6909 \\ 0.2215 & 0.2467 & 0.3331 \\ 0.2503 & 0.7974 & 0.4357 \\ 0.2183 & 0.7910 & 0.1764 \\ 0.1997 & 0.3025 & 0.1899 \\ 0.7483 & 0.7035 & 0.2256 \\ 0.2157 & 0.6780 & 0.5566 \\ 0.3760 & 0.2011 & 0.1850 \\ 0.2614 & 0.3366 & 0.2064 \\ 0.2377 & 0.2135 & 0.1856 \\ 0.4425 & 0.4587 & 0.1972 \\ 0.2026 & 0.3340 & 0.1494 \\ 0.4073 & 0.4490 & 0.1747 \\ 0.1772 & 0.1850 & 0.1622 \\ 0.3784 & 0.4479 & 0.2235 \\ 0.3472 & 0.3750 & 0.2390 \\ 0.1616 & 0.6762 & 0.2352 \\ 0.3384 & 0.3884 & 0.2365 \\ 0.4438 & 0.3614 & 0.3170 \end{bmatrix}, \\
 R = & \begin{bmatrix} 0.1055 & 0.0853 & 0.3338 \\ 0.0436 & 0.0691 & 0.1304 \\ 0.0335 & 0.0263 & 0.0629 \\ 0.0378 & 0.0849 & 0.0822 \\ 0.0330 & 0.0842 & 0.0333 \\ 0.0302 & 0.0322 & 0.0358 \\ 0.1131 & 0.0749 & 0.0426 \\ 0.0326 & 0.0722 & 0.1050 \\ 0.0569 & 0.0214 & 0.0349 \\ 0.0495 & 0.0358 & 0.0390 \\ 0.0359 & 0.0227 & 0.0350 \\ 0.0669 & 0.0488 & 0.0372 \\ 0.0306 & 0.0355 & 0.0282 \\ 0.0616 & 0.0478 & 0.0330 \\ 0.0268 & 0.0197 & 0.0306 \\ 0.0572 & 0.0477 & 0.0422 \\ 0.0525 & 0.0399 & 0.0451 \\ 0.0244 & 0.0720 & 0.0444 \\ 0.0512 & 0.0413 & 0.0446 \\ 0.0671 & 0.0385 & 0.0598 \end{bmatrix},
 \end{aligned} \tag{19}$$

5.2. Calculation of Risk Factor Weights

5.2.1. Calculation of Subjective Weights of Risk Factors Based on the Analytic Hierarchy Process

(1) *Determination of the Weights of Secondary Risk Indicators.* According to our communication with the management of the Central Route Project of South-to-North Water Diversion, together with the recommendations of the FMEA evaluation expert group, we figured out the relative importance of the secondary indicators of the operational safety assessment of the Central Route Project. The five indicators are natural environmental risks, engineering risks, operation management risks, man-made risks, and urgent public safety incident risks. The judgment matrix of the relative importance is

$$A_E = \begin{bmatrix} 1 & \frac{1}{3} & 6 & 8 & 9 \\ 3 & 1 & 3 & 6 & 7 \\ \frac{1}{6} & \frac{1}{3} & 1 & 2 & 3 \\ \frac{1}{8} & \frac{1}{6} & \frac{1}{2} & 1 & 1 \\ \frac{1}{9} & \frac{1}{7} & \frac{1}{3} & 1 & 1 \end{bmatrix}. \tag{20}$$

Use MATLAB to obtain the maximum eigenvalue $\lambda_E = 5.3369$ of the judgment matrix A_E of the secondary risk index, and the maximum eigenvector $\omega_E = (0.6038, 0.7706, 0.1718, 0.0837, 0.0734)$. Then, normalize the matrix to get the weight vector $\omega_{AE} = (0.3545, 0.4524, 0.1009, 0.0491, 0.0431)$ of the secondary index, and perform the consistency test. The maximum eigenvalue $\lambda_E = 5.3369$, and $CI = 0.0842$ is a fifth-order matrix. By searching the table, we find $RI = 1.12$ and $CR = CI/RI = 0.0752 < 0.1$, thus the judgment matrix passing the consistency test. The weights of the second-level risk factors are as follows: natural environmental risk, engineering risk, operation management risk, man-made risk, and public safety incident risk are 0.3545, 0.4524, 0.1009, 0.0491, and 0.0431, respectively.

(2) Determining the Three-Level Risk Factor Index Weight.

Take the natural environmental risk of the secondary risk index as an example. The weights of heavy rain and flood, geological disasters, and extreme weather compared to the secondary risk indicators are calculated as 0.6458, 0.2498, and 0.0953, and the weight vector of the third-level indicator is $\omega_A = (0.2321, 0.0886, 0.0338)$.

5.2.2. Calculation of Objective Weights of Risk Factors Based on Gray Relational Analysis.

Normalize the original evaluation matrix X to obtain the matrix Z . The reference sequence is $Z_0 = (2.6004, 1.5662, 3.0043)$, and each row of sequence in Z is a comparison sequence. Formula (6) calculated the correlation coefficient of each item in the matrix Z , based on which forms the correlation matrix Λ .

$$\begin{aligned}
 Z = & \begin{bmatrix} 2.2849 & 1.5662 & -0.6061 \\ -0.2653 & 0.8453 & 3.0043 \\ -0.6800 & -1.0517 & 0.4811 \\ -0.5005 & 1.5446 & 1.2047 \\ -0.6996 & 1.5141 & -0.6243 \\ -0.8156 & -0.7887 & -0.5293 \\ 2.6004 & 1.1021 & -0.2769 \\ -0.7164 & 0.9817 & 2.0572 \\ 0.2823 & -1.2671 & -0.5637 \\ -0.4316 & -0.6279 & -0.4124 \\ -0.5791 & -1.2086 & -0.5595 \\ 0.6960 & -0.0523 & -0.4772 \\ -0.7978 & -0.6403 & -0.8149 \\ 0.4771 & -0.0981 & -0.6361 \\ -0.9557 & -1.3429 & -0.7243 \\ 0.2970 & -0.1034 & -0.2921 \\ 0.1027 & -0.4470 & -0.1825 \\ -1.0528 & 0.9733 & -0.2098 \\ 0.0481 & -0.3838 & -0.2000 \\ 0.7039 & -0.5112 & 0.3673 \end{bmatrix}, \\
 \Lambda = & \begin{bmatrix} 0.8582 & 1.0000 & 0.3459 \\ 0.3999 & 0.7209 & 1.0000 \\ 0.3679 & 0.4218 & 0.4308 \\ 0.3811 & 0.9888 & 0.5148 \\ 0.3666 & 0.9735 & 0.3448 \\ 0.3586 & 0.4478 & 0.3508 \\ 1.0000 & 0.8045 & 0.3679 \\ 0.3654 & 0.7656 & 0.6685 \\ 0.4571 & 0.4026 & 0.3486 \\ 0.3864 & 0.4653 & 0.3585 \\ 0.3752 & 0.4077 & 0.3489 \\ 0.5007 & 0.5413 & 0.3542 \\ 0.3598 & 0.4639 & 0.3333 \\ 0.4735 & 0.5343 & 0.3441 \\ 0.3494 & 0.3963 & 0.3387 \\ 0.4533 & 0.5335 & 0.3668 \\ 0.4333 & 0.4868 & 0.3747 \\ 0.3433 & 0.7631 & 0.3727 \\ 0.4280 & 0.4948 & 0.3734 \\ 0.5017 & 0.4790 & 0.4200 \end{bmatrix}.
 \end{aligned} \tag{21}$$

We collected the scattered information based on formula (8) to find the correlation degree of each risk factor.

Formula (9) generates the objective weight ω_y of the risk factor.

5.2.3. Calculation of Comprehensive Weights of Risk Factors Based on the Principle of Minimum Discriminative Information. Integrate the subjective weight ω_A of the risk factor with the objective weight ω_y , and obtain the comprehensive weight ω_Z through formulas (10)–(12). When the objective function takes the smallest value, the comprehensive weight is ω_Z , and the authentication information value is the smallest subject to the constraints of the subjective weight ω_A and the objective weight ω_y . The comprehensive weight ω_Z is similar to the subjective and objective weights ω_A and ω_y . The subjective weight, objective weight, and comprehensive weight of risk factors are shown in columns 5-7 in Table 4.

5.3. Ranking of TOPSIS Risk Factors. Identify the positive ideal solution S^+ and the negative ideal solution S^- , and combined with the clear confidence matrix R , according to formulas (13) and (14), we get $S^+ = (0.0409 \ 0.0393 \ 0.0233)$ and $S^- = (0.0088 \ 0.0091 \ 0.0050)$. Based on formulas (15) and (16), the distance between each risk factor and the positive ideal solution S^+ is d_i^+ and the distance between each risk factor and the negative ideal solution S^- is d_i^- . Then, we obtain the relative closeness C_i of each risk factor based on the two distances, thus gaining the comprehensive weight of the risk factor ω_Z . We then use formula (18) to obtain the improvement risk sequence number. The arrangement of d_i^+ , d_i^- , C_i , weight, and the final IRPN value of each risk factor is shown in Table 4.

According to the IRPN ranking, the key risk factors of this section of the South-to-North Water Diversion Project include storm floods, geological conditions, geological disasters, and safety factors in designing. From the field investigation, there are areas with poor geological conditions such as expansive soil and coal mine goaf in this section of the project. Due to the terrain conditions, there are also a large number of high-filled and deep excavation projects. In addition, some problems in the engineering design stage were not considered enough. Therefore, geological disasters such as landslides are extremely prone to occur in this engineering section during continuous heavy rainstorms during the flood season. Once the disaster occurs, not only will it cause a lot of economic losses, but also the safety of life and property of the people along the route will be greatly threatened. The risk events occurred mainly in the flood season from late July to early August every year. Storm floods, geological conditions, geological disasters, and design safety factors are indeed the risk factors with a high-risk level in this section. In addition, as the only section of the middle line that passes through the main urban area, this section is greatly influenced by daily human activities and has many emergencies. Compared with other sections, the risk level of risk factors such as human activity impact and illegal operation within the protection scope is also higher. For key risk factors, this paper proposes specific countermeasures:

- (1) During the flood season, the weather forecast should be continuously paid attention to, and the flood discharge channel should be checked and cleared
- (2) Strengthen patrol inspections in areas with poor geological conditions, and remove hidden dangers in time
- (3) The operation management unit shall formulate disaster emergency plans and organize drills
- (4) Reinforce and strengthen the projects with high-risk factors due to design problems
- (5) Post signs along the channel and report contact information to reduce illegal activities on both sides of the channel

6. Summary

This essay improves the FMEA according to the fuzzy confidence theory and further overcomes the shortcomings of the traditional FMEA model that fails to depict the fault accurately. The TOPSIS method is used to diagnose key risk sources, which improves the accuracy of risk ranking. In the example selected from one of the project sections of the Central Route Project of South-to-North Water Diversion, the paper calculated the weights of risk factors and the number of risk sequences. The importance of the risk is determined according to the risk sequence number, which includes storm floods, geological conditions, geological disasters, design safety factors, building reliability, engineering construction quality, sudden water pollution, human activity impact, personnel management quality, extreme weather, protection scope of illegal activities, project maintenance management level, fire, equipment reliability, social disputes, traffic accidents, man-made sabotage, management system perfection, operation and maintenance construction management level, and illegal operation. The key risks are storm floods, geological conditions, geological disasters, and design safety factors. The diagnosis results are consistent with the actual situation in the field, indicating that the improved method is reasonable and effective. Finally, specific countermeasures are put forward for key risks, which provides help for improving the risk management level of project operation management units.

However, the improved FMEA method is still insufficient in the selection of elements and only takes the frequency of occurrence, severity, and difficulty of inspection as the three evaluation elements. In a large-scale project such as the South-to-North Water Diversion Project, there are still some limitations in using only these three evaluation elements as the evaluation basis.

For example, in the process of engineering operation, maintenance cost and the difference of the impact on the project after risk correction and improvement and before risk occurrence are important evaluation factors of risk factors. It should also be taken into account in the application of the method, and the diagnostic results of key risk sources obtained by measuring the importance of risk factors with multiple evaluation factors are more accurate and scientific. This will be the direction of further research.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

It is declared by the authors that this article is free of conflict of interest.

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