Research Article

Dynamic Evaluation Method of the EW-AHP Attribute Identification Model for the Tunnel Gushing Water Disaster under Interval Conditions and Applications

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The gushing water disaster in tunnels is a kind of harmful and risky engineering disaster. It has become a key problem to evaluate the risk of tunnel gushing water accurately and objectively. A case study of a typical highway tunnel is performed for theory and practice analysis. For this reason, the risk identification is carried out on the assessed objects, and 10 evaluation indexes are determined. In turn, the risk evaluation index system and classification standard are established. Furthermore, the entropy weight method and the analytic hierarchy process are combined to assign the weight to each evaluation index. Therefore, a dynamic risk assessment system, including the pre-evaluation model and the postevaluation model, is constructed with the attribute identification model. As a result, the tunnel section with a high risk of water inrush is accurately assessed, which is consistent with the construction situation on site. Moreover, it is verified that the assessment results are reliable, which can provide a reference for the similar projects.

1. Introduction

China is the fastest developing country in tunneling construction [1]. However, the safety of tunneling construction is particularly prominent and has attracted much attention. In particular, the tunnel water inrush is a kind of engineering disaster which is difficult to predict. Therefore, the safety risk assessment of tunneling construction is widely practiced. By combining the interval analytic hierarchy process (I-AHP) with the technique for order preference by similarity to an ideal solution (TOPSIS), Lin et al. [2] proposed a novel fuzzy model which identified high-risk factors during excavations in urban karst geological environments. In addition, the theory of risk assessment has also developed rapidly. For example, Lin et al. [3] conducted research on the excavation system based on fuzzy set theory and machine learning methods. Furthermore, the development of assessment theory also promotes the application of safety assessment of

the tunneling water inrush. For instance, Li et al. [4] established a mechanical model of the minimum safe thickness of the rock burst prevention disk and carried out a series of model tests on the rock burst prevention disk in front of the tunnel face to find out the influence rules of various factors on the tunnel gushing water disaster. Additionally, Zhu et al. [5] focused on the study of the influence of the geological influencing factors on the tunnel gushing water risk and, based on this, established the risk assessment model of tunnel gushing water based on the weighted average method, etc.

At present, the lack of research on the systematic evaluation of the tunnel gushing water risk assessment theory has limited its popularization. Furthermore, many theories are static evaluation methods, which ignore that the evaluation index values are not always consistent with the previous ones during tunnel excavation. Therefore, a brand new risk assessment model is established, where the

subjective and objective weighting complex method are used to calculate the indexes' weight. Thus, the evaluation indexes can be assigned as interval or numerical values, which can change dynamically in real time according to the construction situation.

A case study of a typical highway tunnel in Fujian province is performed for theory and practice analysis. Through the analysis of its engineering characteristics and special geological conditions, a dynamic evaluation model of the highway tunnel water inrush risk is proposed based on the entropy weight method.

2. Methods

2.1. Improved Theoretical Model of Attribute Interval Identification. The problem of the system comprehensive evaluation is the measurement of the qualitative description. Attribute mathematics is a new branch of mathematics which appears to solve many systematic evaluation problems. The theoretical model of the attribute interval identification is developed on the basis of attribute mathematics. Suppose that evaluation objects' space $X = \{x_1, \dots, x_i, \dots, x_n\}$, where all the evaluation objects could be $x_i (i = 1, 2, \dots, n)$. I_{ij} is the j^{th} evaluation index of the

evaluation object x_i . F is the attribute interval space of X . $(R_1, R_2, \dots, R_k, \dots, R_K)$ is an ordered partition class of F , where $R_1 < R_2 < \dots < R_K$ [6].

2.1.1. Analysis of the Single-Index Attribute Measurement. It can be supposed that the value of the evaluation object x_i of the evaluation index I_{ij} is t_{ij} , and the attribute measure function represents the situation that the attribute measure μ_{ij} changes with the value t_{ij} of the evaluation index I_{ij} . The grading standards of the evaluation index are shown in Table 1. The main steps of the data processing are as follows:

$$b_{jk} = \frac{a_{j(k-1)} + a_{jk}}{2}, \quad (1)$$

$$d_{jk} = \min\{|b_{jk} - a_{jk}|, |b_{j(k+1)} - a_{jk}|\}, \quad (2)$$

where $k = 1, 2, \dots, K$ and $j = 1, 2, \dots, m$ in equation (1) and $k = 1, 2, \dots, (K-1)$ and $j = 1, 2, \dots, m$ in equation (2).

From [7–9], when $a_{j0} < a_{j1} < \dots < a_{jk} \dots < a_{jK}$, the single-index attribute measure function $\mu_{ijk}(t)$ can be expressed as follows:

$$\mu_{ij1}(t) = \begin{cases} 1, & t_j < a_{j1} - d_{j1}, \\ \frac{a_{j1} + d_{j1} - t_j}{2d_{j1}}, & a_{j1} - d_{j1} \leq t_j \leq a_{j1} + d_{j1}, \\ 0, & t_j > a_{j1} + d_{j1}, \end{cases} \quad (3)$$

$$\mu_{ij}(t) = \begin{cases} 0, & t_j < a_{j(k-1)} - d_{j(k-1)}, \\ \frac{t_j - a_{j(k-1)} + d_{j(k-1)}}{2d_{j(k-1)}}, & a_{j(k-1)} - d_{j(k-1)} \leq t_j \leq a_{j(k-1)} + d_{j(k-1)}, \\ 1, & a_{j(k-1)} + d_{j(k-1)} < t_j < a_{jk} - d_{jk}, \\ \frac{a_{jk} + d_{jk} - t_j}{2d_{jk}}, & a_{jk} - d_{jk} \leq t_j \leq a_{jk} + d_{jk}, \\ 0, & t_j > a_{j(K-1)} - d_{j(K-1)}, \end{cases} \quad (4)$$

$$\mu_{ijk}(t) = \begin{cases} 0, & t_j < a_{j(K-1)} - d_{j(K-1)}, \\ \frac{t_j - a_{j(K-1)} + d_{j(K-1)}}{2d_{j(K-1)}}, & a_{j(K-1)} - d_{j(K-1)} \leq t_j \leq a_{j(K-1)} + d_{j(K-1)}, \\ 1, & t_j > a_{j(K-1)} + d_{j(K-1)}. \end{cases} \quad (5)$$

TABLE 1: Grading standards for the evaluation index.

Evaluation index I_i	Evaluation index value t_i	Order of evaluation			
		R_1	R_2	$\dots$	R_k
I_{i1}	t_{i1}	$a10 \sim a11$	$a11 \sim a12$	$\dots$	$a1(k-1) \sim a1k$
I_{i2}	t_{i2}	$a20 \sim a21$	$a21 \sim a22$	$\dots$	$a2(k-1) \sim a2k$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
I_{ij}	t_{ij}	$aj0 \sim aj1$	$aj1 \sim aj2$	$\dots$	$aj(k-1) \sim ajk$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
I_{im}	t_{im}	$am0 \sim am1$	$am1 \sim am2$	$\dots$	$am(k-1) \sim amk$

From [9, 10], when $a_{j0} < a_{j1} < \dots < a_{jk} < \dots < a_{jK}$, the single-index attribute measure function $\mu_{ijk}(t)$ can be expressed as follows:

$$\mu_{ij1}(t) = \begin{cases} 1, & t_j < a_{j1} - d_{j1}, \\ \frac{a_{j1} + d_{j1} + d_{j1}}{2d_{j1}}, & a_{j1} - d_{j1} \leq t_j \leq a_{j1} + d_{j1}, \\ 0, & t_j > a_{j1} + d_{j1}, \end{cases} \quad (6)$$

$$\mu_{ij}(t) = \begin{cases} 0, & t_j < a_{jk} - d_{jk}, \\ \frac{t_j < a_{j(k-1)} - d_{j(k-1)}}{2d_{j(k-1)}}, & a_{jk} - d_{jk} \leq t_j \leq a_{jk} + d_{jk}, \\ 1, & a_{jk} + d_{jk} < t_j < a_{j(k-1)} - d_{j(k-1)}, \\ \frac{a_{jk} + d_{jk} - t_j}{2d_j}, & a_{j(k-1)} - d_{j(k-1)} \leq t_j \leq a_{j(k-1)} + d_{j(k-1)}, \\ 0, & t_j > a_{j(k-1)} + d_{j(k-1)}, \end{cases} \quad (7)$$

$$\mu_{ijk}(t) = \begin{cases} 1, & t_j < a_{j(K-1)} - d_{j(K-1)}, \\ \frac{a_{j(K-1)} + d_{j(K-1)} - t_j}{2d_{j(K-1)}}, & a_{j(K-1)} - d_{j(K-1)} \leq t_j \leq a_{j(K-1)} + d_{j(K-1)}, \\ 0, & t_j > a_{j(K-1)} + d_{j(K-1)}, \end{cases} \quad (8)$$

where $i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$; and $k = 1, 2, \dots, K$.

2.1.2. Multi-Index Comprehensive Attribute Measurement Analysis. (1) The evaluation index value is an interval-type index: from [9], let $S_{ijk}(t)$ be the interval metric function of

the single-index attribute, and let t_j^+ and t_j^- be the upper and lower limits of the evaluation index, respectively. When $\alpha_{j0} > \alpha_{j1} > \dots > \alpha_{jk} > \dots > \alpha_{jK}$, the interval metric function $S_{ijk}(t)$ of the single-index attribute can be expressed as follows:

$$s_{ij1}(t) = \begin{cases} 0, & t_j^- \geq a_{j1} + d_{j1}, \\ \int_{t_j^-}^{a_{j1}+d_{j1}} \mu_{ij1}(t) dt, & t_j^- \leq a_{j1} + d_{j1} \leq t_j^+, \\ \int_{t_j^-}^{t_j^+} \mu_{ij1}(t) dt, & t_j^+ \leq a_{j1} + d_{j1}, \end{cases} \quad (9)$$

$$S_{ijk}(t) = \begin{cases} 0, & t_j^+ \leq a_{j(k-1)} - d_{j(k-1)}, \\ \int_{a_{j(k-1)}-d_{j(k-1)}}^{t_j^+} \mu_{ijk}(t) dt, & t_j^- \leq a_{j(k-1)} - d_{j(k-1)} \leq t_j^+ \leq a_{jk} + d_{jk}, \\ \int_{t_j^-}^{t_j^+} \mu_{ijk}(t) dt, & a_{j(k-1)} - d_{j(k-1)} \leq t_j^- \leq t_j^+ \leq a_{jk} + d_{jk}, \\ \int_{t_j^-}^{a_{jk}+d_{jk}} \mu_{ijk}(t) dt, & a_{j(k-1)} - d_{j(k-1)} \leq t_j^- \leq a_{jk} + d_{jk} \leq t_j^+, \\ 0, & t_j^- \geq a_{jk} + d_{jk}, \end{cases} \quad (10)$$

$$s_{ijK}(t) = \begin{cases} 0, & t_j^+ \leq a_{j(K-1)} - d_{j(K-1)}, \\ \int_{a_{j(K-1)}-d_{j(K-1)}}^{t_j^+} \mu_{ijK}(t) dt, & t_j^- \leq a_{j(K-1)} - d_{j(K-1)} \leq t_j^+, \\ \int_{t_j^-}^{t_j^+} \mu_{ijK}(t) dt, & t_j^- \geq a_{j(K-1)} - d_{j(K-1)}. \end{cases} \quad (11)$$

When $\alpha_{j0} > \alpha_{j1} > \dots > \alpha_{jk} \dots > \alpha_{jK}$, the interval metric function $S_{ijk}(t)$ of the single-index attribute can be expressed as follows:

$$s_{ij1}(t) = \begin{cases} \int_{t_j^-}^{t_j^+} \mu_{ij1}(t) dt, & t_j^- \geq a_{j1} - d_{j1}, \\ \int_{a_{j1}-d_{j1}}^{t_j^+} \mu_{ij1}(t) dt, & t_j^- \leq a_{j1} - d_{j1} \leq t_j^+, \\ 0, & t_j^+ \leq a_{j1} + d_{j1}, \end{cases} \quad (12)$$

$$S_{ijk}(t) = \begin{cases} 0, & t_j^+ \leq a_{jk} - d_{jk}, \\ \int_{a_{jk}-d_{jk}}^{t_j^+} \mu_{ijk}(t) dt, & t_j^- \leq a_{jk} - d_{jk} \leq t_j^+ \leq a_{jk} + d_{jk}, \\ \int_{t_j^-}^{t_j^+} \mu_{ijk}(t) dt, & a_{jk} - d_{jk} \leq t_j^- \leq t_j^+ \leq a_{j(k-1)} + d_{j(k-1)}, \\ \int_{t_j^-}^{a_{j(k-1)}+d_{j(k-1)}} \mu_{ijk}(t) dt, & a_{jk} - d_{jk} \leq t_j^- \leq a_{j(k-1)} + d_{j(k-1)} \leq t_j^+, \\ 0, & t_j^- \geq a_{j(k-1)} + d_{j(k-1)}, \end{cases} \quad (13)$$

$$s_{ijk}(t) = \begin{cases} \int_{t_j^-}^{t_j^+} \mu_{ijk}(t) dt, & t_j^+ \leq a_{j(K-1)} - d_{j(K-1)}, \\ \int_{t_j^-}^{a_{j(K-1)} - d_{j(K-1)}} \mu_{ijk}(t) dt, & t_j^- \leq a_{j(K-1)} + d_{j(K-1)} \leq t_j^+, \\ 0, & t_j^- \geq a_{j(K-1)} + d_{j(K-1)}. \end{cases} \quad (14)$$

The weight of each index can be $\omega = \{\omega_1, \omega_2, \dots, \omega_m\}$, $0 \leq \omega_j \leq 1$, $\sum_{j=1}^m \omega_j = 1$. The attribute measure value μ_{ik} of the evaluation index I_{ij} belonging to the evaluation level R_k can be solved by the single-index attribute interval metric function $S_{ijk}(t)$, which can be expressed as follows:

$$\mu_{ik} = \sum_{j=1}^m \omega_j S'_{ijk}, \quad (15)$$

$$S'_{ijk} = \frac{S_{ijk}}{\sum_{k=1}^K S_{ijk}}. \quad (16)$$

(2) The evaluation index value is a noninterval-type index: as the weight of each index is $\omega = \{\omega_1, \omega_2, \dots, \omega_m\}$, $0 \leq \omega_j \leq 1$, $\sum_{j=1}^m \omega_j = 1$, the attribute measure value can be expressed as follows:

$$\mu_{ik} = \sum_{j=1}^m \omega_j \mu_{ijk}. \quad (17)$$

2.1.3. Attribute Identification Analysis. The attribute space F of a class on X is set, $R_1, R_2, \dots, R_k$ is the attribute interval set of X , and $F = \cup_{i=1}^k R_i$, $R_i \cap R_j = \emptyset$ ($i \neq j$) [6]. λ is the confidence level, and $0.5 < \lambda \leq 1$.

When $R_1 < R_2 < \dots < R_k < \dots < R_k$,

$$k = \min \left\{ l: \sum_{k=l}^l \mu_{ik} \geq \lambda, \quad 1 \leq l \leq K \right\}. \quad (18)$$

When $R_1 < R_2 < \dots < R_k < \dots < R_k$,

$$k = \max \left\{ l: \sum_{k=l}^l \mu_{ik} \geq \lambda, \quad 1 \leq l \leq K \right\}, \quad (19)$$

where x_i belongs to risk level R_k .

2.2. Combination Weighting. Different evaluation indexes have different influence proportions on the risk of the highway tunnel water inrush, so the scientific index weighting method should be adopted. The common methods include the subjective weighting method and the objective weighting method [11]. In order to avoid the result deviation caused by the single weighting method, the combined weighting method is adopted, which takes the subjective and objective factors into consideration.

2.2.1. Entropy Weight Method to Determine the Objective Weight. The entropy weight method [12–14] is an objective

method, which can determine the weight of the evaluation index objectively. It is according to the difference degree of the evaluation index value, and it can avoid the deviation caused by the human factors. So, it has higher accuracy. However, the disadvantage is that the importance of the evaluation index itself is ignored, and its function is limited if the difference of the evaluation index value is very small. In the risk assessment of the tunnel gushing water disaster, the sensitivity of the entropy weight method to the difference of the evaluation index value can be used. Thus, the difference degree of the same evaluation index value in different tunnel sections can be used as the danger signal of the tunnel gushing water disaster to some extent. Its main steps are shown as follows:

Step 1: the normalized matrix is constructed, and the normalized matrix is standardized. The normalized matrix $Z = (z_{ij})_{n \times m}$ can be obtained. Then, the proportion of the i^{th} sample value in the j^{th} index of the term is calculated as follows:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^n z_{ij}}. \quad (20)$$

Step 2: the information entropy of the evaluation index is calculated as follows:

$$e_j = \frac{\sum_{i=1}^m p_{ij} \ln(p_{ij})}{\ln n}. \quad (21)$$

Step 3: the evaluation index weight is assigned as follows:

$$\alpha_j = \frac{u_j}{\sum_{j=1}^n u_j}. \quad (22)$$

u_j is the difference coefficient of the calculated index, and $u_j = 1 - e_j$. The weight vector of the index is $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_n)$, and $\sum_{j=1}^n \alpha_j = 1$.

2.2.2. AHP Method to Determine the Subjective Weight. Analytic hierarchy process (AHP) [15–17] is a systematic analysis method, which can combine qualitative and quantitative methods organically to simplify complex system evaluation problems. It focuses on qualitative analysis and judgment. However, its shortcoming is that it is too subjective. As for too many indicators, the data statistics are large, and the weight is difficult to determine. The basic idea of the AHP is to compare the importance of multiple factors in pairs to judge each other, which improves the rationality of decision-making to some extent [18]. The main steps are as follows:

Step 1: the hierarchical relationship is determined among the influencing factors, and the system hierarchy is established.

Step 2: combining with the importance level (Table 2), the evaluation indexes are compared in pairs, and the judgment matrix is constructed. The judgment matrix can be obtained as follows:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1K} \\ r_{21} & r_{22} & \cdots & r_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mK} \end{bmatrix}. \quad (23)$$

Step 3: the maximum eigenvalue $\lambda_{\max}$ of the judgment matrix R is calculated, the consistency index CI and consistency ratio CR are calculated, and the consistency test is conducted.

Step 4: the weight β_j of each evaluation index is calculated.

2.2.3. Combination Weighting of the Evaluation Index. From [19], the combined weights are calculated as follows:

$$\omega_j = \frac{\alpha_j \beta_j}{\sum_{i=1}^m \alpha_i \beta_i}. \quad (24)$$

3. The Dynamic Risk Assessment Model

3.1. The Index System and the Grading Standards. The risk factors of the gushing water disaster during highway tunneling present characteristics of fuzziness and uncertainty, which make the risk assessment become a complicated systematic evaluation problem. The adverse geological condition refers to the water-rich condition of the geological structure, which is an important influencing factor for the occurrence of tunnel water inrush. Thus, the water level refers to the elevation difference between the underground water level and tunnel floor, which represents the danger degree of water inrush in a way. Also, the length of the water-bearing layer reflects the spatial distribution of water bearing in the tunnel. Besides, the permeability coefficient of rock strata directly affects the groundwater activity. Moreover, the water inflow in the normal period reflects the water fluctuation of groundwater. Also, the negative topographic area ratio directly affects and reflects the development and occurrence characteristics of underground undesirable geology and groundwater. Except them, the dip angle of the rock stratum is an important factor affecting groundwater flow. Furthermore, the development degree of the layer and interlayer fissure affects the activity degree of groundwater, and it has an important influence on the tunnel water inrush. The situation of water dripping on the wall directly represents the current situation of water inrush after the formation of the tunnel initial support. To some extent, the buried depth of the tunnel represents the danger degree of tunnel water inrush.

As for the case of the highway tunneling project in Fujian province, the evaluation indexes are divided into four levels by combining with the geological prospecting, the geological survey data, and the analysis of statistical data [7, 20–23]. Furthermore, the gushing water disaster risk evaluation index system and the gushing water risk evaluation index grading standard have been established. Some are based on the expert scoring to determine the evaluation index classification, which include the influencing factors of the adverse geological conditions I_1 , the level and interlayer fissure I_8 , and the situation of drop water on the wall I_9 . The index system of the highway tunnel water inrush risk assessment is shown in Figure 1. The grading standards of the highway tunnel water inrush risk assessment index are shown in Table 3.

3.2. Attribute Measure Function. From equations (1)–(8), the single-index attribute measure can be calculated, and the calculation results are summarized as shown in Table 4.

3.3. Attribute Identification Analysis. Referring to the “Highway Bridge and Tunnel Engineering Construction Safety Risk Assessment System and Guide Analysis” [24], the highway tunnel gushing water risk is divided into four levels, so the evaluation set is $R = \{R_1, R_2, R_3, R_4\}$. The specific levels are described as shown in Table 5.

As the confidence value λ in attribute identification is generally $0.6 \sim 0.7$, $\lambda = 0.65$ is adopted in the calculation [10]. It can be seen from equation (18) that when $R_1 < R_2 < \cdots < R_k < \cdots < R_k$,

$$k = \min \left\{ l: \sum_{k=l}^l \mu_{ik} \geq 0.65, \quad 1 \leq l \leq 4 \right\}, \quad (25)$$

where x_i belongs to risk level R_k .

3.4. Dynamic Risk Assessment. The dynamic risk assessment system based on the attribute interval identification model is composed of two parts. One is the preassessment model, and the other one is the postassessment model. The research object of the pre-evaluation model is the unexcavated tunnel section. The evaluation index and the value of the evaluation index are determined. The weight of each evaluation index combination is calculated, and the corresponding interval risk assessment is carried out by the pre-evaluation model. The assessment results can provide guidance for construction safety. The research object of the postevaluation model is the tunnel section under construction. On the basis of the pre-evaluation model, it mainly monitors the sections with high risk of water inrush. The evaluation index value can be adjusted and corrected according to the construction and excavation situation on site. The specific flowchart is shown in Figure 2.

The specific steps are as follows:

Step 1: segment the similar terrain and the geological conditions of the unexcavated tunnel section.

Step 2: determine the evaluation index and its value.

TABLE 2: Importance level table.

Value	Difference in importance
1	Indicator i is as important as indicator j
3	Index i is slightly more important than index j
5	Indicator i is significantly more important than indicator j
7	Indicator i is strongly more important than indicator j
9	Indicator i is extremely important than indicator j
2, 4, 6, 8	Intermediate value between the above adjacent judgments
Explanation	When index j is over index i , its scale value is the reciprocal of index i over index j

FIGURE 1: The index system.

TABLE 3: The index grading standards.

Evaluation index	R_1	R_2	R_3	R_4
I_1	35 ~ 60	60 ~ 70	70 ~ 85	85 ~ 100
I_2 (m)	$h < 10$	$10 \leq h < 30$	$30 \leq h < 60$	$h > 60$
I_3 (m)	< 50	50 ~ 100	100 ~ 200	200 ~ 300
I_4 (10^{-5} cm/s)	< 1	1 ~ 1000	1000 ~ 100000	> 100000
I_5 (m^3/d)	< 100	100 ~ 500	500 ~ 1000	> 1000
I_6 (%)	< 20	20 ~ 40	40 ~ 60	> 60
I_7 (°)	0 ~ 10	10 ~ 25	25 ~ 45	45 ~ 65
I_8	35 ~ 60	60 ~ 70	70 ~ 85	85 ~ 100
I_9	35 ~ 60	60 ~ 70	70 ~ 85	85 ~ 100
I_{10} (m)	< 50	50 ~ 100	100 ~ 200	> 200

Step 3: the combined weighting method was used to assign weights to each evaluation index.

Step 4: pre-evaluate the tunnel interval. Combined with equations (1)–(8), the single-index attribute measure analysis is carried out for each evaluation index, and the single-index attribute measure function is calculated. Determine whether the evaluation index is an interval-type index. If it is an interval-type index, the multi-index comprehensive attribute measurement analysis is conducted according to equations (9)–(16). Otherwise, the multi-index comprehensive attribute measurement analysis is conducted according to equation (17). Finally, the attribute identification analysis combined with the confidence degree is conducted to determine the hazard level of the tunnel water inrush.

Step 5: dynamically revise the evaluation index value according to the construction and excavation situation, and repeat Step 4 to redetermine the hazard level of the tunnel water inrush after the evaluation of the tunnel section.

Step 6: construct and excavate, and at the same time, take preventive measures for risk control, and perform a good record of emergency.

4. Engineering Applications

4.1. Engineering Background. A highway tunneling case of the Puyan highway is a double-line separated tunnel in Sanming, Fujian Province. It is designed as a two-way six-lane tunnel. The main structure of the tunnel area is intrusive contact structure. The surrounding rock of the tunnel is mainly medium-weathered rock. Under the influence of the intrusive contact structure, the joints and fissures in rock mass at the tunnel site are developed, and the integrity of the rock mass is poor. The vault is prone to drop blocks, and accidents such as collapse, water gushing, and mud gushing are easy to occur in the construction. Similarly, with the influence of the stratum, lithological and geological structure, topography, and geomorphology, water in the tunnel area is mainly bedrock fissure water. Bedrock fissure water mainly occurs in strongly and moderately weathered bedrock, among which strongly weathered bedrock mass has developed joint fissure and relatively good water enrichment. According to the analysis of exploration and disclosure of the water level, groundwater in most sections of the tunnel is well developed, and the groundwater level in the tunnel area is higher than the designed elevation. The lining of the tunnel adopts the separated structure, in which the open-cut section adopts the integral lining, and the underground section adopts the composite lining. The initial support mainly consists of steel arch, steel mesh, radial anchor, and sprayed concrete. After the formation of the initial support, the water outlet of the tunnel vault at the construction site is relatively obvious, as shown in Figure 3. Therefore, there is a high risk of the water inrush in this section of the tunnel, and the preventive measures should be strengthened during construction. According to the detailed geological survey reports and the design documents, the right line of the tunnel is divided into 5 sections based on the level of the surrounding rock, as shown in Table 6.

TABLE 4: The single-index attribute measure function.

R_1	R_2	R_3	R_4
$\mu_{111}(t) = \begin{cases} 1, & t \leq 55, \\ (65-t)/10, & 55 \leq t \leq 65, \\ 0, & t \geq 65, \end{cases}$	$\mu_{112}(t) = \begin{cases} 0, & t \leq 55, \\ (t-55)/10, & 55 \leq t \leq 65, \\ (75-t)/10, & 65 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{113}(t) = \begin{cases} 0, & t \leq 65, \\ (t-65)/10, & 65 \leq t \leq 75, \\ 1, & 75 \leq t \leq 77.5, \\ (92.5-t)/15, & 77.5 \leq t \leq 92.5, \\ 0, & t \geq 92.5, \end{cases}$	$\mu_{114}(t) = \begin{cases} 0, & t \leq 77.5, \\ (t-77.5)/15, & 77.5 \leq t \leq 92.5, \\ 1, & t \geq 92.5, \end{cases}$
$\mu_{121}(t) = \begin{cases} 1, & t \leq 5, \\ (15-t)/10, & 5 \leq t \leq 15, \\ 0, & t \geq 15, \end{cases}$	$\mu_{122}(t) = \begin{cases} 0, & t \leq 5, \\ (t-5)/10, & 5 \leq t \leq 15, \\ 1, & 15 \leq t \leq 20, \\ (40-t)/20, & 20 \leq t \leq 40, \\ 0, & t \geq 40, \end{cases}$	$\mu_{123}(t) = \begin{cases} 0, & t \leq 20, \\ (t-20)/20, & 20 \leq t \leq 40, \\ 1, & 40 \leq t \leq 45, \\ (75-t)/30, & 40 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{124}(t) = \begin{cases} 0, & t \leq 45, \\ (t-45)/30, & 45 \leq t \leq 75, \\ t, & t \geq 75, \end{cases}$
$\mu_{131}(t) = \begin{cases} 1, & t \leq 25, \\ (75-t)/50, & 25 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{132}(t) = \begin{cases} 0, & t \leq 25, \\ (t-25)/50, & 25 \leq t \leq 75, \\ (125-t)/50, & 75 \leq t \leq 125, \\ 0, & t \geq 125, \end{cases}$	$\mu_{133}(t) = \begin{cases} 0, & t \leq 75, \\ (t-75)/50, & 75 \leq t \leq 125, \\ 1, & 125 \leq t \leq 150, \\ (250-t)/100, & 150 \leq t \leq 250, \\ 0, & t \geq 250, \end{cases}$	$\mu_{134}(t) = \begin{cases} 0, & t \leq 150, \\ (t-150)/100, & 150 \leq t \leq 250, \\ 1, & t \geq 250, \end{cases}$
$\mu_{141}(t) = \begin{cases} 1, & t \leq 0.5, \\ 1.5-t, & 0.5 \leq t \leq 1.5, \\ 0, & t \geq 1.5, \end{cases}$	$\mu_{142}(t) = \begin{cases} 0, & t \leq 0.5, \\ t-0.5, & 0.5 \leq t \leq 1.5, \\ 1, & 1.5 \leq t \leq 500.5, \\ (1499.5-t)/999, & 500.5 \leq t \leq 1499.5, \\ 0, & t \geq 1499.5, \end{cases}$	$\mu_{143}(t) = \begin{cases} 0, & t \leq 500.5, \\ (t-500.5)/999, & 500.5 \leq t \leq 1499.5, \\ 1, & 1499.5 \leq t \leq 50500, \\ (149500-t)/99000, & 50500 \leq t \leq 149500, \\ 0, & t \geq 149500, \end{cases}$	$\mu_{144}(t) = \begin{cases} 0, & t \leq 50500, \\ (t-50500)/99000, & 50500 \leq t \leq 149500, \\ 1, & t \geq 149500, \end{cases}$
$\mu_{151}(t) = \begin{cases} 1, & t \leq 50, \\ (150-t)/100, & 50 \leq t \leq 150, \\ 0, & t \geq 150, \end{cases}$	$\mu_{152}(t) = \begin{cases} 0, & t \leq 50, \\ (t-50)/100, & 50 \leq t \leq 150, \\ 1, & 150 \leq t \leq 300, \\ (700-t)/400, & 300 \leq t \leq 700, \\ 0, & t \geq 700, \end{cases}$	$\mu_{153}(t) = \begin{cases} 0, & t \leq 300, \\ (t-300)/400, & 300 \leq t \leq 700, \\ 1, & 700 \leq t \leq 750, \\ (1250-t)/500, & 750 \leq t \leq 1250, \\ 0, & t \geq 1250, \end{cases}$	$\mu_{154}(t) = \begin{cases} 0, & t \leq 750, \\ (t-750)/500, & 750 \leq t \leq 1250, \\ 1, & t \geq 1250, \end{cases}$
$\mu_{161}(t) = \begin{cases} 1, & t \leq 10, \\ (30-t)/20, & 10 \leq t \leq 30, \\ 0, & t \geq 30, \end{cases}$	$\mu_{162}(t) = \begin{cases} 0, & t \leq 10, \\ (t-10)/20, & 10 \leq t \leq 30, \\ (50-t)/20, & 30 \leq t \leq 50, \\ 0, & t \geq 50, \end{cases}$	$\mu_{163}(t) = \begin{cases} 0, & t \leq 30, \\ (t-30)/20, & 30 \leq t \leq 70, \\ (70-t)/20, & 50 \leq t \leq 70, \\ 0, & t \geq 70, \end{cases}$	$\mu_{164}(t) = \begin{cases} 0, & t \leq 50, \\ (t-50)/20, & 50 \leq t \leq 70, \\ 1, & t \geq 70, \end{cases}$
$\mu_{171}(t) = \begin{cases} 1, & t \leq 5, \\ (15-t)/10, & 5 \leq t \leq 15, \\ 0, & t \geq 15, \end{cases}$	$\mu_{172}(t) = \begin{cases} 0, & t \leq 5, \\ (t-5)/10, & 5 \leq t \leq 15, \\ 1, & 15 \leq t \leq 32.5, \\ (32.5-t)/15, & 17.5 \leq t \leq 32.5, \\ 0, & t \geq 32.5, \end{cases}$	$\mu_{173}(t) = \begin{cases} 0, & t \geq 17.5, \\ (t-17.5)/15, & 17.5 \leq t \leq 32.5, \\ 1, & 32.5 \leq t \leq 35, \\ (55-t)/20, & 35 \leq t \leq 55, \\ 0, & t \geq 55, \end{cases}$	$\mu_{174}(t) = \begin{cases} 0, & t \leq 35, \\ (t-35)/25, & 35 \leq t \leq 55, \\ 1, & t \geq 55, \end{cases}$

TABLE 4: Continued.

R_1	R_2	R_3	R_4
$\mu_{f81}(t) = \begin{cases} 1, & t \leq 55, \\ (65 - t)/10, & 55 \leq t \leq 65, \\ 0, & t \geq 65, \end{cases}$	$\mu_{f82}(t) = \begin{cases} 0, & t \leq 55, \\ (t - 55)/10, & 55 \leq t \leq 65, \\ (75 - t)/10, & 65 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{f83}(t) = \begin{cases} 0, & t \leq 65, \\ (t - 65)/10, & 65 \leq t \leq 75, \\ 1, & 75 \leq t \leq 77.5, \\ (92.5 - t)/15, & 77.5 \leq t \leq 92.5, \\ 0, & t \geq 92.5, \end{cases}$	$\mu_{f84}(t) = \begin{cases} 0, & t \leq 77.5, \\ (t - 77.5)/15, & 77.5 \leq t \leq 92.5, \\ 1, & t \geq 92.5, \end{cases}$
$\mu_{f91}(t) = \begin{cases} 1, & t \leq 55, \\ (65 - t)/10, & 55 \leq t \leq 65, \\ 0, & t \geq 65, \end{cases}$	$\mu_{f92}(t) = \begin{cases} 0, & t \leq 55, \\ (t - 55)/10, & 55 \leq t \leq 65, \\ (75 - t)/10, & 65 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{f93}(t) = \begin{cases} 0, & t \leq 65, \\ (t - 65)/10, & 65 \leq t \leq 75, \\ 1, & 75 \leq t \leq 77.5, \\ (92.5 - t)/15, & 77.5 \leq t \leq 92.5, \\ 0, & t \geq 92.5, \end{cases}$	$\mu_{f94}(t) = \begin{cases} 0, & t \leq 77.5, \\ (t - 77.5)/15, & 77.5 \leq t \leq 92.5, \\ 1, & t \geq 92.5, \end{cases}$
$\mu_{f101}(t) = \begin{cases} 1, & t \leq 25, \\ (75 - t)/50, & 25 \leq t \leq 75, \\ 0, & t \geq 75, \end{cases}$	$\mu_{f102}(t) = \begin{cases} 0, & t \leq 25, \\ (t - 25)/50, & 25 \leq t \leq 75, \\ (125 - t)/50, & 75 \leq t \leq 125, \\ 0, & t \geq 125, \end{cases}$	$\mu_{f103}(t) = \begin{cases} 0, & t \leq 75, \\ (t - 75)/50, & 75 \leq t \leq 125, \\ 1, & 125 \leq t \leq 150, \\ (250 - t)/100, & 150 \leq t \leq 250, \\ 0, & t \geq 250, \end{cases}$	$\mu_{f104}(t) = \begin{cases} 0, & t \leq 150, \\ (t - 150)/100, & 150 \leq t \leq 250, \\ 1, & t \geq 250, \end{cases}$

FIGURE 2: The highway tunnel gushing water dynamic risk assessment.

TABLE 5: Accident probability grading standards.

Risk level	Risk level description
R_1	Basically no risk
R_2	Low risk
R_3	Moderate risk
R_4	High risk

4.2. Risk before Assessment

4.2.1. Determine the Evaluation Index and Its Value. Based on the geological exploration, the geological survey data, the advanced geological forecast, and the relevant reference, the evaluation index values of the target section X_i ($i = 1, 2, 3, 4, 5$) can be determined, which are combined with the grading standard of the highway tunnel water inrush risk assessment index in Table 2. It is shown in Table 7.

4.2.2. Weight Calculation. The combined weighting method is used to assign weights to each evaluation index. In the

FIGURE 3: The tunnel water inrush of the arch roof after the initial support.

middle-long highway tunnel, the difference of the same evaluation index in different sections is large due to the topographic and geological conditions and other factors,

TABLE 6: Tunnel sections.

Target segment	Sectional mileage range	Length (m)
X_1	K242 + 555 ~ K242 + 635	80
X_2	K242 + 635 ~ K242 + 815	180
X_3	K242 + 815 ~ K242 + 875	60
X_4	K242 + 875 ~ K243 + 150	275
X_5	K243 + 150 ~ K243 + 337	187

TABLE 7: Pre-evaluation evaluation index value.

Target segment	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}
X_1	83	16	85	1.62	[40, 50]	[35, 42]	[10, 20]	83	80	[1, 52.13]
X_2	72	25	180	1.62	[300, 330]	[26, 38]	[30, 40]	85	82	[77.625, 340.05]
X_3	85	23	60	1.16	[150, 180]	[41, 53]	[30, 45]	81	85	[38.245, 74.16]
X_4	78	35	275	1.62	[1000, 1300]	[55, 62]	[45, 55]	90	92	[57.37, 131]
X_5	84	21	188	1.27	[170, 200]	[32, 41]	[15, 25]	82	81	[1, 131]

which is a danger signal for the tunnel gushing water disaster. The entropy weight method is one way to determine the index weight according to the difference between the data. Therefore, the objective weight calculation uses the entropy weight method, which takes the pre-evaluation

evaluation index value as the evaluation object to study the weight of the tunnel gushing water evaluation index.

The objective weight of each evaluation index can be calculated as follows:

$$\alpha = \{0.002 \ 0.034 \ 0.130 \ 0.010 \ 0.489 \ 0.024 \ 0.085 \ 0.001 \ 0.001 \ 0.224\}. \quad (26)$$

The subjective weight is calculated by the analytic hierarchy process, and the subjective weight of each evaluation index can be calculated as follows:

$$\beta = \{0.061 \ 0.132 \ 0.121 \ 0.235 \ 0.091 \ 0.048 \ 0.111 \ 0.133 \ 0.034 \ 0.035\}. \quad (27)$$

According to the objective weight and subjective weight calculated above and equation (24), the weight of each evaluation index can be obtained as follows:

$$\omega = \{0.001 \ 0.052 \ 0.0182 \ 0.028 \ 0.520 \ 0.014 \ 0.110 \ 0.001 \ 0.001 \ 0.091\}. \quad (28)$$

4.2.3. Preassessment. Combined with the single-index attribute measure function in Table 4, the pre-evaluation evaluation index value in Table 7, and combination weight ω , the comprehensive attribute measure μ_{ik} of multiple indexes can be obtained by calculating from equations (3) to (16). The calculation results are shown in Table 8. And it can be known from equation (25) as follows:

$$k = \min \left\{ l: \sum_{k=1}^l \mu_{ik} \geq 0.5, \quad 1 \leq l \leq 5 \right\}. \quad (29)$$

For the tunnel section X_1 , the pre-evaluation results are shown as follows:

$$\begin{aligned} \sum_{k=1}^1 \mu_{1k} &= 0.6120 < 0.65, \\ \sum_{k=1}^2 \mu_{1k} &= 0.6120 + 0.3405 = 0.9525 > 0.65, \\ \sum_{k=1}^3 \mu_{1k} &= 0.6120 + 0.3405 + 0.0465 = 0.999 > 0.65, \\ \sum_{k=1}^4 \mu_{1k} &= 0.6120 + 0.3405 + 0.0465 + 0.0010 = 1 > 0.65. \end{aligned} \quad (30)$$

TABLE 8: Calculation table of attribute measure values.

Target segment	Attribute measure values				Risk level
	R_1	R_2	R_3	R_4	
X_1	0.6120	0.3405	0.0465	0.0010	R_2
X_2	0.0005	0.5869	0.2903	0.1224	R_3
X_3	0.0983	0.7707	0.1114	0.0196	R_3
X_4	0.0038	0.0895	0.2224	0.6842	R_4
X_5	0.0423	0.7264	0.1610	0.0703	R_2

TABLE 9: Tunnel sections.

Tunnel section X_4	Sectional mileage range
X_{41}	$K242 + 890 \sim K242 + 900$
X_{42}	$K243 + 010 \sim K243 + 020$
X_{43}	$K243 + 130 \sim K243 + 140$

TABLE 10: Postevaluation evaluation index value.

Tunnel section X_4	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}
X_{41}	70	2.085	10	1.62	[700, 800]	[35, 42]	[40, 42]	83	80	[62.805, 65.655]
X_{42}	72	5.205	10	1.62	[500, 600]	[30, 38]	[30, 40]	85	82	[96.105, 101.965]
X_{43}	80	3.625	10	1.62	[1000, 1300]	[55, 62]	[45, 55]	92	91	[78.485, 83.18]

Obviously, when k is 2, 3, or 4, all inequalities are true, so k is 2. The hazard risk level of the water inrush of the tunnel section X_1 is R_2 . Similarly, the water gushing risks of tunnel intervals X_2 , X_3 , X_4 , and X_5 are, respectively, R_3 , R_3 , R_4 , and R_2 . The final evaluation results are shown in Table 8.

4.3. Risk after Assessment

4.3.1. Determine the Evaluation Index and Its Value. According to the pre-evaluation model, the highway tunnel water inrush risk in the tunnel section X_1 , X_2 , X_3 , X_4 , and X_5 is, respectively, R_2 , R_3 , R_3 , R_4 , and R_2 . Tunnel sections X_2 and X_3 are of moderate risk in terms of water inrush, and tunnel section X_4 is of high risk in terms of water inrush. Therefore, tunnel sections X_2 , X_3 , and X_4 need to be segmented into smaller sections.

According to the on-site construction, the evaluation index value was modified in real time, and dynamically, the tunnel gushing water risk was evaluated in a more detailed way. Tunnel interval X_4 was taken as an example. So, it takes every 10 m as the section, and 3 sections of the tunnel are selected as the research object of postevaluation, as shown in Table 9.

Based on the topographic and geological conditions and the grading standards in Table 3, the evaluation index value of the target section of the tunnel can be determined as shown in Table 10.

4.3.2. Postassessment. Considering the single-index attribute measure function in Table 4, the postevaluation evaluation index value in Table 10, and the combination weight, the comprehensive attribute measure of multiple indexes

can be obtained by calculating from equations (3) to (16). The calculation results are shown in Table 11. And it can be known from equation (25) as follows:

$$k = \min \left\{ l: \sum_{k=l}^l \mu_{ik} \geq 0.65, \quad 1 \leq l \leq 5 \right\}. \quad (31)$$

For tunnel section X_{41} , the postevaluation results are shown:

$$\begin{aligned} \sum_{k=1}^1 \mu_{4k} &= 0.2538 < 0.65, \\ \sum_{k=1}^2 \mu_{4k} &= 0.2538 + 0.1075 = 0.3613 < 0.65, \\ \sum_{k=1}^3 \mu_{4k} &= 0.2538 + 0.1075 + 0.5921 = 0.9534 > 0.65, \\ \sum_{k=1}^4 \mu_{4k} &= 0.2538 + 0.1075 + 0.5921 + 0.0466 = 1 > 0.65. \end{aligned} \quad (32)$$

Obviously, when k is equal to 3 or 4, all inequalities are true, so k is 3. The hazard risk level of the water inrush of tunnel section X_{41} is R_3 . Similarly, the water gushing risks of tunnel intervals X_{42} and X_{43} are, respectively, R_3 and R_4 . The water inrush hazard of tunnel intervals $K242 + 890 \sim K242 + 900$ and $K243 + 010 \sim K243 + 020$ is of moderate risk, while the water inrush hazard of tunnel interval $K243 + 130 \sim K243 + 140$ is of high risk. The final assessment results are shown in Table 11.

TABLE 11: Calculation table of attribute measure values.

Tunnel section X_4	Attribute measure values				Risk level
	R_1	R_2	R_3	R_4	
X_{41}	0.2538	0.1075	0.5921	0.0466	R_3
X_{42}	0.2332	0.2845	0.4748	0.0075	R_3
X_{43}	0.2342	0.1080	0.1556	0.5022	R_4

FIGURE 4: Verification of excavation results. (a) The lower steps were partially submerged by a surge of water. (b) Multiple jets of water spurted from the tunnel face.

TABLE 12: Comparison of risk assessment results before and after excavation.

Tunnel section X_4	Attribute measure values				Risk level
	R_1	R_2	R_3	R_4	
X_{43}	0.2342	0.1080	0.1556	0.5022	R_4
X'_{43}	0.2342	0.1080	0.1385	0.5192	R_4

5. Verification of Evaluation Results

At about 7:20 a.m. on July 28, 2020, when the right line of the tunnel is excavated up to K243 + 132, the water inrush occurred. Gushing water appeared in the gun holes at several positions of the tunnel surface with a certain pressure, and the jetting distance was about 3–5 m. The water column on the right side of the tunnel surface was large, and some of it carried yellow mud, as shown in Figure 4.

After the accident occurred, the evaluation index values were modified according to the site construction conditions. The tunnel water inrush risk assessment was carried out again for the same section. Thus, it was concluded that tunnel section K243 + 130 ~ K243 + 140 was still of high risk. The evaluation results are in good agreement with the site construction. The comparison of risk assessment results before and after excavation is shown in Table 12.

In this risk accident, the construction company has formulated emergency risk control measures for the gushing water disaster in the tunnel in advance and convened expert meetings in time to discuss the corresponding measures after the occurrence of danger. Therefore, no casualties were caused in this risk accident, and the construction loss was reduced to the minimum.

6. Conclusion

In this paper, a dynamic risk assessment based on the EW-AHP attribute evaluation model is carried out for the highway tunnel water inrush under interval conditions.

- (1) The index system and the index grading standards of the highway tunnel water inrush risk assessment have been established based on a highway tunnel case of the geological prospecting, geological survey data, and reference. Furthermore, a set of dynamic highway tunnel water inrush risk assessment models with preassessment model and postassessment model is established, which has combined with the combination of empowerment and the attribute identification theoretical model.
- (2) The highway tunnel water gushing risk assessment model is set as a dynamic risk assessment model, which is based on the EW-AHP attribute evaluation model and composed of the pre-evaluation model and postevaluation model. The preassessment model is to control the water inrush risk of each tunnel section as a whole. Thus, the postassessment model is to carry out the risk assessment of the water inrush

risk of the tunnel in time and dynamically according to the construction needs.

- (3) The evaluation index values of the dynamic risk assessment model can be a certain value or range. So, it makes the evaluation index values more flexible, less restricted, and more in line with the engineering practice. Moreover, the weight calculation of each evaluation index only needs to be determined in the pre-evaluation model, and there is no need to change frequently in the postevaluation model due to the change of the evaluation index value.
- (4) A case study of tunneling gushing water risk assessment was performed with the dynamic risk assessment model based on the attribute interval identification model. The water gushing risk of tunnel section $K243 + 130 \sim K243 + 140$ is R_4 , which is of high risk. The evaluation results are consistent with the situation on the construction site, which verifies the rationality and feasibility of the evaluation model.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

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