

# Research Article

# **Risk Assessment of an Existing Metro Tunnel in Close Proximity to New Shield Tunnels following Construction**

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The construction of a new shield tunnel near an existing operating tunnel poses a great risk to the existing tunnel structure due to the continuous encryption of the rail transit network. This study investigated the safety status of an existing metro tunnel in close proximity to new shield tunnels following construction. A fuzzy comprehensive assessment model (hierarchical fuzzy comprehensive evaluation model) based on an analytic hierarchy process was proposed to assess the risks of the existing tunnel structure. The threshold of indicators in the existing tunnel structure risk assessment system was determined based on the tunnel function and structure security. Then, we described the membership vector determination method, weight vector determination method, and comprehensive evaluation vector processing method. Taking a project case in China as the research object, the quantitative analysis of the established evaluation system was carried out, and the intuitive risk assessment results were obtained. The hierarchical fuzzy comprehensive evaluation model can be employed as a decision-making tool for newly built shield tunnels passing through the existing tunnels, which can provide guidance for tunnel maintenance and guarantee.

## 1. Introduction

With the development of urban metro construction and commercialization in downtown areas, the crossing of metro tunnels is frequently encountered in geotechnical engineering practice. The construction of newly built tunnels will inevitably bring great risks to existing operating tunnels and even result in serious engineering accidents and economic losses [1, 2]. The influence of tunnel construction on the existing metro tunnel structure is mediated by the soil layer and groundwater during the process of the new metro tunnel passing through existing operational tunnels. The factors that influence the risk of existing track structure in the construction of a newly built tunnel underneath the existing tunnel project can be divided into three categories: condition of newly built tunnels (such as tunnel radius and net distance), existing tunnel structure condition (such as water seepage, structural cracking, and material deterioration), and hydrogeological condition. In order to ensure the safety

of the existing operating tunnels, it is necessary to conduct a risk assessment of the existing tunnel structure before beginning the construction of new tunnels [3].

Risk analysis is a tool designed to establish a proactive safety strategy by investigating potential risks [4-6]. In recent decades, risk analysis has also been adapted to tunnel safety [7, 8]. There are numerous methods for tunnel safety assessment, including failure modes and effects analysis (FMEA), criticality analysis (CA), fault tree analysis (FTA), event tree analysis (EAT), cause and consequence analysis (CCA), analytic hierarchy process (AHP), and fuzzy comprehension evaluation (FIE). Each method has its own characteristics and suitable conditions for application. The safety status of a metro tunnel structure is a multifaceted and vague concept [9]. On the one hand, the factors affecting the safety status of metro tunnel structures are very complex, and on the other hand, the relationship between these influencing factors and the safety status is ambiguous. First, some factors affecting the tunnel structure cannot be quantitatively analyzed using very accurate data but can only be analyzed qualitatively, so the analysis process will generate some fuzzy concepts [10, 11]. Second, there is no oneto-one functional relationship between the changes of various influencing factors and the safety state of the tunnel, and a very accurate mathematical model cannot be used for analysis and solution. In recent research, artificial intelligence methods have been gradually applied to risk assessment, including enhanced set pair analysis (SPA) [12], extended TODIM method [13], fuzzy decision-making model [14], fuzzy AHP incorporated into GIS [15], and IFN-SPA method [16].

Great achievements have been made in the risk assessment of tunnel engineering, which can be used to avoid a number of risks to a certain extent [17, 18]. Nonetheless, the following problems still exist: (1) currently, there are still few studies on the risk assessment of an existing metro tunnel in close proximity to new shield tunnels under construction. With the continuous densification of the urban metro network, there will be more and more such shield tunneling projects. (2) A set of risk assessment models and evaluation systems for the existing tunnel in shield tunneling project of water-rich and strongly differentiated argillaceous siltstone stratum is lacking. (3) Among all kinds of risk assessment models, there is a tendency to study the construction risk for newly built tunnels, and few include a special risk assessment for how the safety of existing tunnels is influenced by newly built tunnels.

When newly built tunnels pass under an existing operating rail transit tunnel, there are many factors that affect the structural safety of the existing rail transit tunnels, and it is usually impossible to intuitively make a pass definitive judgment on the risk of the existing tunnel structure [19-21]. The aim of a hierarchical fuzzy comprehensive evaluation is to comprehensively consider various factors affecting the evaluation object and then use the membership theory of fuzzy mathematics to transform a qualitative evaluation into a quantitative evaluation—that is, to use fuzzy mathematics to conduct an overall evaluation of the evaluation object restricted by many factors. Therefore, this paper introduces a hierarchical fuzzy comprehensive evaluation method to comprehensively evaluate the safety status of the metro structure. First, factors affecting the safety of the existing metro tunnel structure are studied. Then, the risk evaluation index is selected. Finally, a structural risk assessment system for the existing tunnel is established. Based on this framework, the hierarchical fuzzy comprehensive evaluation model was used for the quantitative analysis of the tunnel project connecting Nanchang Metro Line 4 from Dinggong Road South Station to Dinggong Road North Station.

## 2. The Hierarchical Fuzzy Comprehensive Evaluation Model

2.1. The Principle of Hierarchy Fuzzy Comprehensive Evaluation. The results and discussion may be presented separately, or in one combined section, and may optionally be divided into headed subsections.

A fuzzy comprehensive evaluation is a process of quantifying fuzzy relations by mathematical methods that are based on fuzzy theory. Through comprehensive evaluation, the fuzzy relations are quantified, and the results are approximated to increase accuracy. A hierarchical fuzzy comprehensive evaluation is based on fuzzy comprehensive evaluation and combined with an analytic hierarchy process. After hierarchical processing of complex problems, fuzzy comprehensive evaluation theory is used to analyze them layer by layer in order to improve the accuracy of the results.

The process of a hierarchical fuzzy comprehensive evaluation is mainly as follows:

- (1) Determine the hierarchy of fuzzy comprehensive evaluation.
- (2) Establish an evaluation index set: the evaluation index set of the first level fuzzy comprehensive evaluation is  $C^1 = \{c_1^1, c_2^1, c_3^1, \dots, c_n^1\}$ . The evaluation index set of the second level fuzzy comprehensive evaluation is  $C^2 = \{c_1^2, c_2^2, c_3^2, \dots, c_m^2\}$ .
- (3) Determine the subordination degree vector of each evaluation index at the first level R<sub>n</sub><sup>1</sup>: determine the subordination degree vector of each index in the first-level fuzzy comprehensive evaluation R<sub>n</sub><sup>1</sup> = {r<sub>n1</sub><sup>1</sup>, r<sub>n2</sub><sup>1</sup>, r<sub>n3</sub><sup>1</sup>, ..., r<sub>nj</sub><sup>1</sup>}.
- (4) Determine the fuzzy weight vector w between the evaluation indexes in each level: the fuzzy weight vector w of evaluation indexes is determined for each level. In the first level fuzzy comprehensive evaluation, the fuzzy weight vector between the indexes is  $w_m^1 = \{w_1^1, w_2^1, w_3^1, \ldots, w_n^1\}$ ; the fuzzy weight vector between the indexes in the second level fuzzy comprehensive evaluation is  $w^1 = \{w_1^2, w_2^2, \dots, w_m^2\}$ .
- (5) Determine the first level fuzzy relation matrix  $R^1$ : by synthesizing the subordination degree vectors of each evaluation index of the first level, the fuzzy relation matrix  $R^1$  of the first level fuzzy comprehensive evaluation is determined as follows:

$$R^{1} = \begin{cases} R_{1}^{1} \\ R_{2}^{1} \\ R_{3}^{1} \\ \vdots \\ R_{n}^{1} \end{cases} \begin{cases} r_{11}^{1} & r_{12}^{1} & r_{13}^{1} & \cdots & r_{1j}^{1} \\ r_{21}^{1} & r_{22}^{1} & r_{23}^{1} & \cdots & r_{2j}^{1} \\ r_{31}^{1} & r_{32}^{1} & r_{33}^{1} & \cdots & r_{3j}^{1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_{n1}^{1} & r_{n2}^{1} & r_{n3}^{1} & \cdots & r_{nj}^{1} \end{bmatrix}.$$
(1)

(6) Determine the subordination vector  $R_m^2$ : based on the index fuzzy weight vector  $w_m^1$  and the fuzzy relation matrix  $R^1$  of the first-level fuzzy comprehensive evaluation, the subordination vector of each evaluation index of the second level can be obtained, that is, the first-level fuzzy comprehensive evaluation can be completed. The calculation formula is shown in the following formula:

$$R_m^2 = w_m^1 \times R^1 = \left\{ r_{m1}^2, r_{m2}^1, r_{m3}^1, \dots, r_{mj}^1 \right\}.$$
 (2)

(7) Determine the final comprehensive evaluation vector Z of the target layer: the steps are the same as for steps (5) and (6). First, the fuzzy relation matrix  $R^2$  is synthesized according to the subordination degree vectors of each index in the second level. Then, according to the index fuzzy weight vector  $w_m^2$  and the fuzzy relation matrix  $R^2$  in the second level, the second level fuzzy comprehensive evaluation can be completed. Finally, the comprehensive evaluation vector Z of the target evaluation object is obtained. The calculation formula is shown in the following formula:

$$Z = w_m^2 \times R^2 = \{z_1, z_2, z_3, \dots, z_j\}.$$
 (3)

(8) Determine evaluation results: the comprehensive evaluation vector Z is processed, and the final evaluation result is obtained.

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From the above description, it can be seen that in the process of the hierarchical-fuzzy comprehensive evaluation, the most important thing is the determination of the subordination degree vector of each index, the determination of the weight vector between indexes, and the treatment of comprehensive evaluation vector.

2.2. The Determination of Membership Degree Vector. In the process of the fuzzy comprehensive evaluation, it is very important to determine the membership vector, which is an important process to quantify fuzzy relations. According to the different indexes, the determination methods of membership degree vector can be roughly divided into two kinds. Some indicators cannot be quantitatively evaluated, and the expert evaluation method is used to determine the membership degree vector. Others can be quantitatively evaluated, the and membership function is used to determine membership degree vector.

2.2.1. Expert Evaluation Method. The expert evaluation method is a widely used mathematical statistics method. Its biggest advantage is that more accurate quantitative estimation values can be obtained through artificial scoring in the absence of statistical data and original data. The main process of using the expert evaluation method to determine the evaluation index is to determine the evaluation grade of each index and formulate the expert questionnaire according to the specific situation of the evaluation object. Then, the grade of the index will be judged by experts according to the actual situation. After statistical analysis of the results of the questionnaire, the membership degree vector of each index can be obtained after data normalization.

2.2.2. Membership Function. There are many kinds of membership functions suitable for a fuzzy comprehensive evaluation, including normal distribution function, triangular and semi-triangular distribution function, trapezoidal and semi-trapezoidal distribution function, Cauchy distribution function, and single-valued distribution

function. According to relevant studies, although the membership degree vector obtained by various membership functions is slightly different, the final fuzzy comprehensive evaluation result is the same. In this paper, the membership function  $u_n(x)$  of the normal distribution in Figure 1 is selected.

In Figure 1,  $u_n(x) = e^{-[(x-x_0)/c]^2}$ . Based on  $u(b_{n-1}) = 0.5$ and  $u(a_n) = 1$ , the coefficients c and  $x_0$  in the function of  $u_n(x)$  can be determined [22] as follows:

$$u_{1}(x) = \begin{cases} 1, & x \leq a_{0}, \\ e^{-\left[\sqrt{\ln 2} (x-a_{0})/b_{0}-a_{0}\right]^{2}}, & a_{0} < x \leq b_{0}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x-a_{1})/a_{1}-b_{0}\right]^{2}}, & b_{0} < x \leq a_{1}, \\ 0, & x > a_{1}. \end{cases}$$
(4)

$$u_{2}(x) = \begin{cases} 0, & x > a_{2}, x \le a_{0}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - a_{0})/b_{0} - a_{0}\right]^{2}}, & a_{0} < x \le b_{0}, \\ e^{-\left[\sqrt{\ln 2} (x - a_{1})/a_{1} - b_{0}\right]^{2}}, & b_{0} < x \le b_{1}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - a_{2})/a_{2} - b_{1}\right]^{2}}, & b_{1} < x < a_{2}. \end{cases}$$
(5)

$$u_{3}(x) = \begin{cases} 0, & x > a_{3}, x \le a_{1}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - a_{1})/a_{1} - b_{0}\right]^{2}}, & a_{1} < x \le b_{1}, \\ e^{-\left[\sqrt{\ln 2} (x - a_{2})/a_{2} - b_{1}\right]^{2}}, & b_{1} < x \le b_{2}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - a_{3})/a_{3} - b_{2}\right]^{2}}, & b_{2} < x < a_{3}. \end{cases}$$
(6)

$$u_{4}(x) = \begin{cases} 0, & x \leq a_{2}, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - a_{2})/a_{2} - b_{1}\right]^{2}}, & a_{2} < x \leq b_{2}, \\ e^{-\left[\sqrt{\ln 2} (x - a_{3})/a_{3} - b_{2}\right]^{2}}, & b_{2} < x \leq a_{3}, \\ 1, & x > a_{3}. \end{cases}$$
(7)

where  $b_0$ ,  $b_1$ , and  $b_2$  are the limits of each level of index evaluation grade. The x represents the measured value of indicator, where  $a_0 = b_0/2$ ,  $a_1 = (b_0 + b_1)/2$ , each  $a_2 = (b_1 + b_2)/2$ , and  $a_3 = 3b_2/2$ . The diagram of specific function distribution is shown in Figure 2.

2.3. The Determination of Weight Vector. Determining the weight of each index at the same level is a significantly important part of the hierarchical fuzzy comprehensive evaluation process, and the weight has a direct impact on the final analysis result. How to determine the weight of the evaluation index is, however, an extremely difficult problem because, in the process of assigning the weight of the index, people tend to have a certain degree of subjectivity and ignore some objective problems. In order to ensure that the fuzzy weight vector is as close as possible to the objective and reality, a variety of fuzzy weight vector determination methods have been gradually formed after a long period of research, among which the scale method is the most common. The existing scaling methods are mainly divided into conventional scaling and product scaling.









2.3.1. The Conventional Scaling Method. The conventional scaling method divides the comparison between indicators into five cases: of "same," "slightly larger," "obviously large," "strongly large," and "extremely large." Different scale values are assigned to each case. Since the 1–9 scale method was first put forward proposed by Saaty, the founder of Analytic Hierarchy Process (AHP), various scholars have since proposed put forward 9/9–9/1, 10/10–18/2, and the exponential scale method through continuous research and improvement, as shown in Table 1.

2.3.2. The Product Scaling Method. The biggest difference between the product scaling method and the conventional scaling method is that the product scaling method only sets two comparison levels, "same" and "slightly larger." If the comparison level of indicator A and indicator B is "same," the weight ratio defined is

$$W_A: W_B \approx 1: (0.9 \sim 1.1).$$
 (8)

If the comparison level of indicator *A* and indicator *B* is "slightly larger," the weight ratio defined is

$$W_A: W_B \approx (1.1 \sim 1.5): 1.$$
 (9)

The product scaling method is adopted in this paper. The weight ratio is determined according to the conventional scaling method, and the following scaling method is obtained:

- (1) Comparison grade: "same" and "slightly larger."
- (2) Combined with the weight ratio of "same" comparison grade in the conventional scaling method,

the weight ratio of index A and index B "same" is determined to be

$$W_A: W_B \approx 1: 1. \tag{10}$$

(3) In the conventional scaling method, except for the 1–9 scale method, which has a "slightly larger" weight ratio of 3, the weight ratios of 9/9–9/1 scaling method, 10/10–18/2 scaling method, and exponential scaling method are 1.286, 1.5, and 1.277, respectively, which all meet the range defined by the product scale method. Therefore, the average value of the "slightly larger" scale value of the three scaling methods is taken as the "slightly larger" scale value of the product scaling method; that is, its weight ratio is

$$W_A: W_B = \left(1.286 + 1.5 + \frac{1.277}{3}\right): 1 = 1.354: 1.$$
 (11)

(4) When index *A* is *n* "slightly larger" than index *B*, the defined weight ratio is

$$W_A: W_B = 1.354^n: 1.$$
 (12)

(5) Regardless of the number of indicators to be compared, the final weight vector  $w_m$  needs to be normalized, that is,

$$\sum_{i=1}^{m} w_i = 1.$$
(13)

(6) When the number of indicators m≥ 3, it is necessary to check the consistency of the obtained weight vector w<sub>m</sub>. Suppose the weight vector

TABLE 1: Four conventional scaling methods.

Comparison	1-9 scaling method	9/9-9/1 scaling method	10/10-18/2 scaling method	Index scaling method
Same	1	9/9 (1.000)	10/10 (1.000)	$9^0$ (1.000)
Slightly larger	3	9/7 (1.286)	12/8 (1.500)	$9^{1/9}$ (1.277)
Significantly larger	5	9/5 (1.800)	14/6 (2.333)	$9^{3/9}$ (2.080)
Strongly larger	7	9/3 (3.000)	16/4 (4.000)	$9^{6/9}$ (4.237)
Extremely larger	9	9/1 (9.000)	18/2 (9.000)	9 <sup>9/9</sup> (9.000)

 $w_m = \{w_1, w_2, w_3, \dots, w_m\}$ , then according to the construction of the judgment matrix *P*, it can be used as the basis for checking the consistency of the weight vector  $w_m$ .

$$P = \begin{cases} \frac{w_1}{w_1} & \frac{w_2}{w_1} & \cdots & \frac{w_m}{w_1} \\ \frac{w_1}{w_2} & \frac{w_2}{w_2} & \cdots & \frac{w_m}{w_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_1}{w_m} & \frac{w_2}{w_m} & \cdots & \frac{w_m}{w_m} \end{cases}.$$
(14)

Meanwhile, the consistency index CI of the judgment matrix is introduced to represent the strength of its consistency degree, and its calculation formula is shown as follows. The lower the CI value, the greater the consistency in the judgment matrix.

$$CI = \frac{\lambda_{\max} - m}{m - 1},$$
(15)

where  $\lambda_{\max}$  is the maximum eigenvalue of the judgment matrix *P* and *m* is the number of indicators in the same layer.

In order to judge whether the consistency intensity of the results is satisfactory, the average random consistency index RI (Table 2) is introduced. The ratio CR of them is used as the basis for judgment.

When the obtained CR < 0.1, the consistency can be considered satisfactory.

2.4. The Processing Method of Comprehensive Evaluation Vector. The final comprehensive evaluation vector is essentially the membership vector of the evaluation object to each evaluation grade. It is a fuzzy vector rather than a definite value. Therefore, in order to know the final result of the evaluation more clearly, it is necessary to process the fuzzy vector. In this paper, the single-value principle is selected as the processing method for the comprehensive evaluation vector is a single value, it is necessary to assign values for each evaluation grade, and the assigned values should be equal to the score value. Suppose the values assigned to j levels are  $(x_1, x_2, x_3, \ldots, x_j)$ , for the comprehensive evaluation vector  $Z = \{z_1, z_2, z_3, \ldots, z_j\}$ , the result after evaluation unitization is as follows:

TABLE 2: Average random consistency index RI value.

т	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

$$F = \frac{x_1 z_1 + x_2 z_2 + x_3 z_3 + \dots + x_j z_j}{z_1 + z_2 + z_3 + \dots + z_j}.$$
 (16)

Meanwhile, the evaluation grade quantization table can be established according to the values assigned to j grades. Combined with the obtained comprehensive evaluation vector quantization single value, the final evaluation grade is obtained by comparing the evaluation grade quantization table.

In this study, four grades are assigned equal score values (1, 2, 3, 4). Then, according to formula (16), the single-value calculation formula to obtain the evaluation result (see Table 3) is shown in the following formula:

$$F = \frac{z_1 + 2z_2 + 3z_3 + 4z_4}{z_1 + z_2 + z_3 + z_4}.$$
 (17)

### 3. Case Analysis

3.1. Project Overview. The tunnel between Dinggong Road South Station and Dinggong Road North Station of Nanchang Metro Line 4 is located in the Xihu District of Nanchang city (see Figure 3). After exiting Dinggong Road South Station, the line between this area passes under the tunnel of Metro Line 2 and connects to Dinggong Road North Station. The new tunnel of Line 4 is constructed using the shield tunneling method. The outer diameter of the shield tunnel segment is 6 m, and the thickness is 0.3 m. The buried depth of the tunnel ranges from 19.44 to 25.73 m. The tunnel structure is mainly located in the bedrock of the stratum, and part of the tunnel passes through the coarse sand layer. The minimum net distance between the new tunnel structure and the existing tunnel structure is 4.06 m, and the line intersection angle is about 80° (see Figure 4).

Geological survey shows that the regional strata are mainly argillaceous siltstone and calcareous mudstone, with a flat occurrence and an inclination of less than 10°. The geological structure of the site is mainly controlled by the Ganjiang fault, and no obvious fault structure passes through the tunnel line within the survey scope. The Quaternary strata along the project are relatively stable, and there has been no strong fault activity since Quaternary, so the influence of surface dislocation caused by fault seismic activity can be ignored.

TABLE 3: The quantification of the risk level.

Risk level	Ι	II	III	IV
Security status	Unsafe	Relatively unsafe	Relatively safe	Safe
Quantitative values	$1 \le F < 1.5$	$1.5 \le F < 2.5$	$2.5 \le F < 3.5$	$3.5 \le F < 4$



FIGURE 3: Planned layout of the metro line.

Relying on the hierarchical fuzzy comprehensive evaluation model, combined with the engineering situation of Nanchang Rail Transit Line 4 passing under the existing tunnel of Line 2, the risk assessment study of the existing tunnel of Line 2 was carried out.

3.2. Selection of Risk Assessment Indicators. The evaluation index constituting the evaluation system is the basis of the quantitative risk evaluation of existing tunnel structures, and the rationality of the selected evaluation index usually determines the reliability of the evaluation. The obtained evaluation system is shown in Figure 5. The evaluation system is divided into three layers: the first is the target layer, the second is the criterion layer, and the third is the scheme layer.

#### 3.3. The Risk Classification

3.3.1. Risk Classification of Existing Tunnel Structures. The risk classification of the existing tunnel structure is divided to define the degree of risk to the existing tunnel structure in the process of newly built tunnel penetration. The partition results are shown in Table 4.

3.3.2. Classification of Impact Degree of Evaluation Indexes. In order to allow comparison to the results of risk classification for the target layer, the impact degree of evaluation indexes of scheme level is also divided into four degrees: I, II, III, and IV. The higher the number, the lower the degree of influence. The influence of evaluation indexes "tunnel construction method," "soil properties," and "groundwater"



FIGURE 4: 3D view of crossing tunnels of line 2 undercrossed by line 4 and the soil profile.



FIGURE 5: Risk assessment system diagram.

TABLE 4: Risk grade classification table of existing tunnel structure.

Risk grade	Security status	Structural state of the existing tunnel
Ι	Unsafe	The structural deformation of the existing tunnel exceeds the deformation control standards and is considered serious; therefore, the metro cannot operate normally.
II	Relatively unsafe	The degree of structural deformation of the existing tunnel is large and exceeds the prewarning value of deformation. The tunnel structure should be comprehensively monitored and the metro should be operated slowly or at a limited speed.
III	Relatively safe	The structural deformation of the existing tunnel is normal, but there are certain factors that have a great influence on the structural deformation. It is necessary to monitor the structural deformation, and the metro can operate normally.
IV	Safe	Tunnel structure deformation is normal and the metro can operate normally.

on the "existing tunnel risk situation" in the target layer can only be qualitatively evaluated, while the influence degree of the evaluation indexes "ratio *B*," "structural water seepage," "structural cracking," and "structural deterioration" on the "existing tunnel structural risk" of the target layer can be quantitatively analyzed. The impact of "ratio *B*," "structural seepage," "structural cracking," and "structural deterioration" on the structural safety of existing tunnels can be quantitatively classified (see Tables 5–8) by consulting technical specifications such as Technical code for protection structures of urban rail transit (CJJ/T 202–2013) [23], Code for acceptance of construction quality of underground waterproof (GB 50208–2011) [24], Code for design of metro (GB 50157–2013) [25], and Code for Design of Concrete Structures (GB50010-2010) [26].

3.4. Determination of Risk Assessment Indicators. Based on the risk assessment system for the existing rail transit tunnel structure established, the situation of each evaluation index in the risk assessment system was confirmed through field investigation and tunnel engineering design data.

*3.4.1. Conditions of the Newly Built Tunnel.* Tunnel construction method: According to the shield structure selection above, the newly built tunnel adopts the shield tunneling method for construction and excavation.

The ratio of proximity distance to tunnel diameter: According to the design data of the newly built shield tunnel, the cross section size of shield tunnel is D = 6m. The distance from the top of the newly built shield tunnel to the bottom of the existing tunnel is H = 4.06m. Namely, B = H/D = 0.677.

*3.4.2. Hydrogeological Conditions.* Soil layer properties: According to geological survey data, the stratum in the tunnel traversing area is complex, mainly including plain fill soil, clay, fine sand, medium sand, coarse sand, and argillaceous siltstone. The existing tunnel is mainly located in the coarse sand stratum, while the newly built tunnel is mainly located in the argillaceous siltstone stratum.

Groundwater conditions: According to geological prospecting data, this area is close to the Ganjiang River and is rich in underground water resources. The underground water buried in the underpass area was shown to be 4 m below the surface.

3.4.3. Conditions of Existing Tunnels. In order to understand the condition of the existing tunnel structure, a nonmetallic ultrasonic detector and concrete rebound tester, shown inFigures 6-8, were used to measure the evaluation indexes such as structural cracking, concrete deterioration, and structural seepage. Through the inspection of the existing structural segments, the crack width of the existing tunnel segment is taken as 0.2 mm. The strength of the existing tunnel segment was determined to be 45.53 MPa, while the design strength is 50 MPa. Therefore, the ratio K is 0.91. Through the inspection of the whole tunnel, it is found that the interior of the existing tunnel is relatively dry and there is no obvious water flow, but there are still some minor seepage points. In order to ensure the safety of the existing tunnel and make the evaluation results more conservative, the maximum structural seepage rate in the operation and maintenance records of tunnels is chosen as the final structural seepage rate. The optimal structural seepage rate is determined as 35 drops/min.

#### 3.5. The First Level of Fuzzy Comprehensive Evaluation

3.5.1. Determination of the First Level of Membership Vector. According to the introduction above, the membership degree vectors of the first-level indicators were determined using the expert evaluation method and membership function, respectively. The membership vectors of "tunnel construction method," "groundwater conditions," and "soil properties" are determined using the expert evaluation method, and the membership vectors of "ratio *B*," "structural seepage," "structural cracking," and "structural deterioration" are determined according to the membership functions.

(1) The Expert Evaluation Method. A total of 35 questionnaires were sent out and 34 valid questionnaires were retrieved following the "expert evaluation method." The units participating in this survey include Nanchang Rail Transit Group Co. LTD, China Railway No.5 Engineering Bureau Co. Ltd, China Railway No.4 Survey and Design Institute Co, Ltd, and the Department of Tunnel, School of Civil Engineering, Southwest Jiaotong University. The main personnel was professors, associate professors, senior engineers, lecturers, engineers, and doctors.

Through the statistics of the questionnaire and normalized processing, the membership vectors  $R_{11}^1$ ,  $R_{21}^1$ , and  $R_{22}^1$  of "tunnel construction method," "groundwater conditions," and "soil properties," respectively, were obtained.

$$R_{11}^{1} = (0, 0, 0.382, 0.618),$$

$$R_{21}^{1} = (0.029, 0.5, 0.412, 0.059),$$

$$R_{22}^{1} = (0, 0.323, 0.588, 0.089).$$
(18)

(2) *The Membership Function*. The evaluation indexes "ratio *B*," "structural seepage," "structural cracking," and "structure deterioration" and results determined through field investigation are shown in Table 9.

According to Table 5 and the membership function selected in Section 2.2, namely, formulas  $(4)\sim(7)$ , the membership function formulas of ratio *B* are established as follows:

$$u_{1}(x) = \begin{cases} 1 & x \le 0.15 \\ e^{-[\sqrt{\ln 2} (x - 0.15)/0.15]^{2}}, & 0.15 < x \le 0.3, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.5)/0.2]^{2}}, & 0.3 < x \le 0.5, \\ 0, & x > 0.5. \end{cases}$$
(19)  
$$u_{2}(x) = \begin{cases} 0, & x > 0.85, x \le 0.15, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.15)/0.15]^{2}}, & 0.15 < x \le 0.3, \\ e^{-[\sqrt{\ln 2} (x - 0.5)/0.2]^{2}}, & 0.3 < x \le 0.7, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.85)/0.15]^{2}}, & 0.7 < x < 0.85. \end{cases}$$
(20)

TABLE 5. Classification of failo D.				
Impact degree	The ratio of proximity distance to tunnel diameter	Structural state of existing tunnel		
Ι	$B \leq 0.3$	Unsafe		
II	$0.3 < B \le 0.7$	Relatively unsafe		
III	$0.7 < B \le 1.0$	Relatively safe		
IV	1.0 < B	Safe		

TABLE 5: Classification of ratio B

TABLE 6: Classification of seepage water.

Impact degree	Seepage velocity V (drops/minute)	Safety status of existing tunnel structures
Ι	V > 300	Unsafe
II	$60 < V \le 300$	Relatively unsafe
III	$5 < V \le 60$	Relatively safe
IV	$V \leq 5$	Safe

TABLE 7: Classification of structural cracking.

Impact degree	Maximum width of cracks $w_{\text{max}}$ (mm)	Safety status of existing tunnel structures
Ι	$w_{\rm max} > 0.4$	Unsafe
II	$0.2 < w_{\rm max} \le 0.4$	Relatively unsafe
III	$0.1 < w_{\rm max} \le 0.2$	Relatively safe
IV	$w_{ m max}$ $\leq$ 0.1	Safe

TABLE 8: Classification of structural deterioration grades.

Impact degree	Intensity ratio K	Safety status of existing tunnel structures
Ι	$K \leq 2/3$	Unsafe
II	$2/3 < K \le 4/5$	Relatively unsafe
III	$4/5 < K \le 7/8$	Relatively safe
IV	K > 7/8	Safe

$$u_{3}(x) = \begin{cases} 0, & x > 1.5, x \le 0.5, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.5)/0.2]^{2}}, & 0.5 < x \le 0.7, \\ e^{-[\sqrt{\ln 2} (x - 0.85)/0.15]^{2}}, & 0.7 < x \le 1.0, \\ 1 - e^{-[\sqrt{\ln 2} (x - 1.5)/0.5]^{2}}, & 1.0 < x < 1.5. \end{cases}$$
(21)  
$$u_{4}(x) = \begin{cases} 0, & x \le 0.85, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.85)/0.15]^{2}}, & 0.85 < x \le 1.0, \\ e^{-[\sqrt{\ln 2} (x - 1.5)/0.5]^{2}}, & 1.0 < x \le 1.5, \\ 1, & x > 1.5. \end{cases}$$
(22)

By substituting measured values of ratio *B* in Table 9 into formulas (19)~(22), the membership degree vector representing the degree of ratio *B* is obtained:

$$R_{12}^{1} = (u_1(0.677), u_2(0.677), u_3(0.677), u_4(0.677))$$
  
= (0, 0.581, 0.419, 0). (23)

Based on the classification standards of tunnel structural seepage in Table 6 and the membership function selected in Section 2.2, the membership function formulas of tunnel structural seepage are established as follows:

$$u_{1}(x) = \begin{cases} 1, & x \le 2.5, \\ e^{-[\sqrt{\ln 2} (x-2.5)/2.5]^{2}}, & 2.5 < x \le 5, \\ 1 - e^{-[\sqrt{\ln 2} (x-32.5)/27.5]^{2}}, & 5 < x \le 32.5, \\ 0, & x > 32.5. \end{cases}$$
(24)

$$u_{2}(x) = \begin{cases} 0, & x > 180, x \le 2.5, \\ 1 - e^{-[\sqrt{\ln 2} (x - 2.5)/2.5]^{2}}, & 2.5 < x \le 5, \\ e^{-[\sqrt{\ln 2} (x - 32.5)/27.5]^{2}}, & 5 < x \le 60, \\ 1 - e^{-[\sqrt{\ln 2} (x - 180)/120]^{2}}, & 60 < x < 180. \end{cases}$$
(25)

$$u_{3}(x) = \begin{cases} 0, & x > 450, x \le 32.5, \\ 1 - e^{-[\sqrt{\ln 2} (x - 32.5)/27.5]^{2}}, & 32.5 < x \le 60, \\ e^{-[\sqrt{\ln 2} (x - 180)/120]^{2}}, & 60 < x \le 300, \\ 1 - e^{-[\sqrt{\ln 2} (x - 450)/150]^{2}}, & 300 < x < 450. \end{cases}$$
(26)

$$u_{4}(x) = \begin{cases} 0, & x \le 180, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - 180)/120\right]^{2}}, & 180 < x \le 300, \\ e^{-\left[\sqrt{\ln 2} (x - 450)/150\right]^{2}}, & 300 < x \le 450, \\ 1, & x > 450. \end{cases}$$
(27)



(a)



(b)

FIGURE 6: Instruments for measuring evaluation indexes.

By substituting measured values of tunnel structural seepage in Table 9 into formulas  $(24)\sim(27)$ , the membership degree vector representing the water seepage degree of tunnel structure is obtained:

$$R_{31}^{1} = (u_{4}(35), u_{3}(35), u_{2}(35), u_{1}(35)) = (0, 0.01, 0.99, 0).$$
(28)

According to classification standards of tunnel structural cracking in Table 7 and the membership function selected in

Section 2.2, the membership function formulas of tunnel structure cracking are established as follows:

$$u_{1}(x) = \begin{cases} 1, & x \le 0.05, \\ e^{-[\sqrt{ln^{2}} (x - 0.05)/0.05]^{2}}, & 0.05 < x \le 0.1, \\ 1 - e^{-[\sqrt{ln^{2}} (x - 0.15)/0.05]^{2}}, & 0.1 < x \le 0.15, \\ 0, & x > 0.15. \end{cases}$$
(29)

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FIGURE 7: Segment ultrasonic pulse velocity test.



FIGURE 8: Segment rebound hammer test.

$$u_{2}(x) = \begin{cases} 0, & x > 0.3, x \le 0.05, \\ 1 - e^{-[\sqrt{ln2}(x - 0.05)/0.05]^{2}}, & 0.05 < x \le 0.1, \\ e^{-[\sqrt{ln2}(x - 0.15)/0.05]^{2}}, & 0.1 < x \le 0.2, \\ 1 - e^{-[\sqrt{ln2}(x - 0.3)/0.1]^{2}}, & 0.2 < x < 0.3. \end{cases}$$
(30)  
$$u_{3}(x) = \begin{cases} 0, & x > 0.6, x \le 0.15, \\ 1 - e^{-[\sqrt{ln2}(x - 0.3)/0.1]^{2}}, & 0.15 < x \le 0.2, \\ e^{-[\sqrt{ln2}(x - 0.3)/0.1]^{2}}, & 0.2 < x \le 0.4, \\ 1 - e^{-[\sqrt{ln2}(x - 0.6)/0.2]^{2}}, & 0.4 < x < 0.6. \end{cases}$$
(31)  
$$u_{4}(x) = \begin{cases} 0, & x \le 0.3, \\ 1 - e^{-[\sqrt{ln2}(x - 0.3)/0.1]^{2}}, & 0.3 < x \le 0.4, \\ e^{-[\sqrt{ln2}(x - 0.6)/0.2]^{2}}, & 0.4 < x \le 0.6, \\ 1, & x > 0.6. \end{cases}$$
(32)

By substituting measured values of tunnel structural cracking in Table 9 into formulas  $(29)\sim(32)$ , the membership degree vector representing the cracking degree of tunnel structure is obtained:

$$R_{32}^{1} = (u_{4}(0.2), u_{3}(0.2), u_{2}(0.2), u_{1}(0.2)) = (0, 0.5, 0.5, 0).$$
(33)

Based on the classification standards for tunnel structural deterioration in Table 8 and the membership function selected in Section 2.2, the membership function formulas of tunnel structural deterioration are established as follows:

$$u_{1}(x) = \begin{cases} 1, & x \le 0.34, \\ e^{-[\sqrt{ln^{2}} (x - 0.34)/0.34]^{2}}, & 0.34 < x \le 0.68, \\ 1 - e^{-[\sqrt{ln^{2}} (x - 0.74)/0.06]^{2}}, & 0.68 < x \le 0.74, \\ 0, & x > 0.74. \end{cases}$$
(34)

$$u_{2}(x) = \begin{cases} 0, & x > 0.84, x \le 0.34, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - 0.34)/0.34\right]^{2}}, & 0.34 < x \le 0.68, \\ e^{-\left[\sqrt{\ln 2} (x - 0.74)/0.06\right]^{2}}, & 0.68 < x \le 0.8, \\ 1 - e^{-\left[\sqrt{\ln 2} (x - 0.84)/0.04\right]^{2}}, & 0.8 < x < 0.84, \end{cases}$$
(35)

$$u_{3}(x) = \begin{cases} 0, & x > 1.0, x \le 0.74, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.74)/0.06]^{2}}, & 0.74 < x \le 0.8, \\ e^{-[\sqrt{\ln 2} (x - 0.84)/0.04]^{2}}, & 0.8 < x \le 0.88, \\ 1 - e^{-[\sqrt{\ln 2} (x - 1.0)/0.12]^{2}}, & 0.88 < x < 1.0. \end{cases}$$
(36)

$$u_{4}(x) = \begin{cases} 0, & x \le 0.84, \\ 1 - e^{-[\sqrt{\ln 2} (x - 0.84)/0.04]^{2}}, & 0.84 < x \le 0.88, \\ e^{-[\sqrt{\ln 2} (x - 1.0)/0.12]^{2}}, & 0.88 < x \le 1.0, \\ 1, & x > 1.0. \end{cases}$$
(37)

By substituting measured values of tunnel structural deterioration in Table 9 into formulas  $(34)\sim(37)$ , the membership degree vector representing the deterioration degree of tunnel structure is obtained:

TABLE 9: The measured values of evaluation indexes.

Evaluation index	Feature	Measured value
The ratio of proximity distance to tunnel diameter	B = H/D	0.677
Structural cracking	Maximum crack width $w_{max}$ (mm)	0.2
Structural seepage	Seepage rate V (drops/minute)	35
Structural deterioration	K = actual strength/design strength	0.91

$$R_{33}^{I} = (u_1(0.91), u_2(0.91), u_3(0.91), u_4(0.91))$$
  
= (0, 0, 0.677, 0.323). (38)

3.5.2. Determination of the First Level of Weight Vectors. The weight vectors of the first level are scaled using the product scaling method. The first level is mainly divided into three parts: condition of newly built tunnels, hydrogeological conditions, and condition of existing tunnels, which need to be scaled separately.

(1) The Condition of Newly Built Tunnels. The condition of newly built tunnels includes two evaluation indexes: tunnel construction method and ratio *B*. By searching information and combining the results from the expert evaluation table, it is judged that "ratio *B*" is too "slightly larger" than "tunnel construction method," then

$$W_A: W_B = 1.354^2: 1 = 1.833: 1.$$
 (39)

After normalization, the weight vector is

$$w_1^1 = (0.353, 0.647).$$
 (40)

There are only two evaluation indexes in this section. Therefore, its judgment matrix must satisfy the requirement for consistency.

(2) Hydrogeological Conditions. Hydrogeological conditions include two evaluation indexes: groundwater conditions and soil properties. Groundwater and soil layers, as the filling medium between the new structure and the existing structure, mainly play a role in transmitting influence. After the disturbance caused by the newly built tunnels, the influence is gradually transmitted to the existing structure through groundwater and soil layer. In this process, there is little difference between the effect of groundwater and soil layer. Therefore, it is considered that "groundwater conditions" are the "same" as "soil properties," then

$$W_A: W_B = 1: 1.$$
 (41)

After normalization, the weight vector is

$$w_2^1 = (0.5, 0.5).$$
 (42)

There are only two evaluation indexes in this part. Therefore, its judgment matrix must satisfy the requirement for consistency.

(3) The Condition of Existing Tunnels The condition of existing tunnels includes three evaluation indexes: structural seepage, structural cracking, and structural deterioration. The existing tunnel structure is in the sand

stratum characterized by strong permeability; therefore, when the existing structure is deformed due to the disturbance of newly built tunnel excavation, water seepage is likely to further expand under the action of water pressure, resulting in the destruction of the structure. Structural cracking and structural deterioration both represent the influence on the bearing capacity of the structure. Therefore, it is considered that "structural seepage" is "slightly larger" compared with "structural cracking," and "structural deterioration" is "same" compared with "structural cracking," then

$$W_A: W_B: W_C = 1.354: 1: 1.$$
 (43)

After normalization, the weight vector is:

$$w_3^1 = (0.404, 0.298, 0.298).$$
 (44)

There are three evaluation indexes in this part, which are needed to judge consistency. The judgment matrix  $P_3$  is constructed:

$$P_{3} = \left\{ \begin{array}{rrr} 1 & 0.739 & 0.739 \\ 1.354 & 1 & 1 \\ 1.354 & 1 & 1 \end{array} \right\}.$$
 (45)

According to the calculation, the maximum eigenvalue of the judgment matrix is 3.0004, and m = 3, then the consistency index *CI* value of the judgment matrix is

$$CI = \frac{\lambda_{max} - m}{m - 1} = \frac{3.0004 - 3}{3 - 1} = 0.0002.$$
(46)

Table 7 shows that if RI value of average random consistency index is 0.58, then CR = 0.00034 < 0.1. Namely, the consistency is judged as satisfactory.

3.5.3. Determination of the second level of membership vector. Through the above calculation of the first level of membership vector and weight vector of each indicator, the second level of membership vector of each indicator can be obtained.

(1) The Condition of Newly Built Tunnels. According to the two indicators in the condition of newly built tunnels, the membership vector of tunnel construction method and the membership vector of ratio *B*, the fuzzy relationship matrix between the condition of newly built tunnels and indicators can be obtained as follows:

$$R_{1}^{1} = \left\{ \begin{array}{c} R_{11}^{1} \\ R_{12}^{1} \end{array} \right\} = \left[ \begin{array}{ccc} 0 & 0 & 0.382 & 0.618 \\ 0 & 0.581 & 0.419 & 0 \end{array} \right].$$
(47)

The membership vector of the condition of newly built tunnels is

$$R_1^2 = w_1^1 \times R_1^1 = \begin{bmatrix} 0 & 0.376 & 0.406 & 0.218 \end{bmatrix}.$$
 (48)

(2) Hydrogeological Conditions. According to the two indicators of the hydrogeological conditions, the membership vector of groundwater and soil geology, the fuzzy relationship matrix between the hydrogeological conditions and indicators is obtained as follows:

$$R_{2}^{1} = \left\{ \begin{array}{c} R_{21}^{1} \\ R_{22}^{1} \end{array} \right\} = \left[ \begin{array}{ccc} 0.029 & 0.5 & 0.412 & 0.059 \\ 0 & 0.323 & 0.588 & 0.089 \end{array} \right].$$
(49)

Namely, the membership vector of hydrogeological conditions is

$$R_2^2 = w_2^1 \times R_2^1 = \begin{bmatrix} 0.014 & 0.412 & 0.5 & 0.074 \end{bmatrix}.$$
 (50)

(3) The Condition of Existing Tunnels. According to the three indicators in the condition of existing tunnels, the membership vectors of structural seepage, structural cracking, and structural deterioration, the fuzzy relationship matrix between the condition of existing tunnels and indicators is obtained as follows:

$$R_{3}^{1} = \left\{ \begin{array}{c} R_{31}^{1} \\ R_{32}^{1} \\ R_{33}^{1} \end{array} \right\} = \left\{ \begin{array}{ccc} 0 & 0.01 & 0.99 & 0 \\ 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0.677 & 0.323 \end{array} \right\}.$$
 (51)

The membership vector of the condition of existing tunnels is

$$R_3^2 = w_3^1 \times R_3^1 = \begin{bmatrix} 0 & 0.153 & 0.751 & 0.096 \end{bmatrix}.$$
 (52)

#### 3.6. The Second Level of Fuzzy Comprehensive Evaluation

3.6.1. Determination of the Second Level of Weight Vector. The evaluation indexes of the second level are the condition of newly built tunnels, condition of hydrogeology, and existing tunnels. When there is no new construction around the existing tunnel, the condition of existing tunnels is generally sufficient to ensure the safety of the tunnel structure; that is, the safety risk of the existing tunnel is very low. When a newly built tunnel is being constructed, the formation disturbance generated by the new tunnel is transmitted to the existing tunnel through the groundwater and soil layer, which in turn creates new safety risks for the existing tunnel. Therefore, it is considered that "the condition of newly built tunnels" is "same" compared with "hydrogeological conditions," and that of "condition of newly built tunnels" is "slightly larger" compared with "condition of existing tunnels." Then,

$$W_A: W_B: W_C = 1.354: 1.354: 1.$$
 (53)

After normalization, the weight vector is

$$w^2 = (0.365, 0.365, 0.270).$$
 (54)

There are three evaluation indexes in this part, which need to be judged as consistent. The judgment matrix  $P_3$  is constructed as follows:

$$P_{3} = \left\{ \begin{array}{ccc} 1 & 1 & 0.739 \\ 1 & 1 & 0.739 \\ 1.354 & 1.354 & 1 \end{array} \right\}.$$
 (55)

According to the calculation, the maximum eigenvalue of the judgment matrix is 3.0004 and m = 3. Therefore, the consistency index CI value of the judgment matrix is

$$CI = \frac{\lambda_{\max} - m}{m - 1} = \frac{3.0004 - 3}{3 - 1} = 0.0002.$$
 (56)

It is shown in Table 7 that RI value of average random consistency index is 0.58. Therefore, CR = 0.00034 < 0.1, and the consistency is judged as satisfactory.

3.6.2. The vector of the comprehensive evaluation result. According to the three indicators of the second level: the membership vectors of the condition of newly built tunnels, hydrogeology conditions, and the condition of existing tunnels, the fuzzy relationship matrix between the risk from the newly built tunnel passing through the underground of the existing tunnel structure and second-level indicators is obtained as follows:

$$R^{2} = \begin{cases} R_{1}^{2} \\ R_{2}^{2} \\ R_{3}^{2} \end{cases} = \begin{cases} 0 & 0.376 & 0.406 & 0.218 \\ 0.014 & 0.412 & 0.5 & 0.074 \\ 0 & 0.153 & 0.751 & 0.096 \end{cases}.$$
 (57)

Namely, the vector of comprehensive evaluation result (the membership vector of the risk of that newly built tunnel passes through the underground of an existing tunnel structure) is as follows:

$$Z = w^2 \times R^2 = \begin{bmatrix} 0.005 & 0.329 & 0.533 & 0.133 \end{bmatrix}.$$
 (58)

3.7. The Processing of Evaluation Results. In this paper, the principle of a single value is adopted to process the comprehensive evaluation vector. According to the single-value calculation formula determined above, the single-value result is obtained as follows:

$$F = \frac{0.005 + 2 \times 0.329 + 3 \times 0.533 + 4 \times 0.133}{0.005 + 0.329 + 0.533 + 0.133} = 2.794.$$
 (59)

According to the table of risk grade quantification (Table 3),  $2.5 \le F < 3.5$ , the results of the risk assessment in this paper show that the risk level of the existing tunnel is III (relatively safe). Under this risk level, the tunnel deformation is normal and the metro can operate normally. However, some factors have a great influence on structural deformation, which means that it is necessary to monitor structural deformation.

## 4. Conclusions

In this paper, an existing tunnel structure risk assessment system was established for the evaluation of a newly built tunnel passing through an existing tunnel underground. The main conclusions are as follows:

- According to the principle of the hierarchical fuzzy comprehensive evaluation model, the determination methods of membership vector, weight vector, and comprehensive evaluation vector for existing tunnel risk assessment were determined.
- (2) The risk assessment system for the existing tunnel structure composed of a target layer, criterion layer, and scheme layer was established by analyzing the structural risk factors of an existing metro tunnel. The influence degree of each index in the scheme layer was graded by referring to the relevant technical specifications and scientific research results.
- (3) The methods of membership vector determination, weight vector determination, and comprehensive evaluation vector processing, which are suitable for the risk assessment of existing tunnels, were determined according to the characteristics of the risk assessment system used for existing tunnel structures.

### **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

### **Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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