Research on Risk Assessment of Complex Mountain Tunnels Based on AHP-FCE

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Abstract. Complex geological environment and difficulties in operation and maintenance of mountain tunnels result in a lot of damage during the operation period of mountain tunnels. Therefore, the risk assessment and reinforcement technologies for complex mountain tunnels during the operation period need to be developed and improved. As a result, in this paper, the research on safety influence factors and their weights during the operation period of complex mountain tunnels was conducted based on Fuzzy Comprehensive Evaluation (FCE) and Analytic Hierarchy Process (AHP), the fuzzy set of weights for risk influencing factors during the operation period of complex mountain tunnels was established, the membership functions of factors at the index level were determined, the comprehensive evaluation matrix of tunnel risks was obtained, and the fuzzy comprehensive evaluation method for risks of complex mountain tunnels was proposed. This method has been verified in the Jinjishan Tunnel, and its analysis results are credible. In addition, corresponding risk prevention and control measures were put forward based on the evaluation results, and they provided guidance and reference for similar projects.

1. Introduction
The construction of mountain tunnels features the complexity of construction and the uncertainty of stratum conditions and surrounding environment, as well as higher construction difficulties and risks. In addition, during the operation period of mountain tunnels, due to material aging, tunnel structures are prone to damage at different levels [1]. As a result, domestic and foreign researchers have done a lot of research on tunnel risk assessment.

In order to control the risk of water inrush and mud outburst from karst tunnels, Li Shucai et al[2] researched the controlling factors and their weight values of water inrush and mud outburst from karst tunnels based on the statistical and theoretical analysis as well as AHP, and proposed a three-stage assessment and control method for the risk of water inrush and mud outburst from karst tunnels; Huang Hongwei et al[3] used the expert investigation method and AHP to identify and evaluate the engineering example of Shanghai Metro Line 11, and finally put forward corresponding
suggestions for risk control of key nodes; Zhang Dingli et al[4] used the fuzzy mathematical comprehensive evaluation method to establish membership functions and select different weights for different influencing factors of undercut tunnels for support works, and applied the fuzzy language to evaluate different degrees of building risks, and finally determined five risk levels; Yu Yongyan[5] determined the risk factors based on the statistical analysis of the causes of tunnel collapse accidents in China and the tunnel conditions, used the relative scale method to determine the weight values of factors, established a risk assessment model, and obtained the possibility of tunnel collapse accidents in different mileage sections of the Chonganjiang Tunnel; Song Pingyuan[6], based on the potential risk sources at the tunnel portal, used an extension model and AHP to evaluate the risks at the tunnel portal; Shen Hongyun et al[7] established a construction risk evaluation index system for tunnels with gently inclined strata, applied the entropy method and fuzzy comprehensive evaluation method to risk assessment, determined the stability of surrounding rock and supporting system based on the discrete element numerical simulation software and put forward corresponding risk avoidance countermeasures according to the risk assessment results; Li Dechang et al[8] introduced the basic principles and steps of using the improved fuzzy comprehensive method based on AHP (Analytic Hierarchy Process) to evaluate the construction risks of shallow tunnels, established a hierarchical analysis model of the construction risks of shallow tunnels, and developed a risk possibility judgment matrix with the improved fuzzy numbers; Chen Jiejian et al[9] used the fuzzy hierarchy comprehensive evaluation method to evaluate the risk of collapse during tunnel construction, and established a fuzzy hierarchy evaluation model of collapse risks, which has been verified in the Qingshangang Tunnel. According to the current research status at home and abroad, scholars at home and abroad have conducted in-depth research on risk analysis and evaluation of mountain tunnels and achieved a lot of results. However, the existing research mostly focuses on the tunnel construction period, and scarcely evaluates the tunnel risks during the operation period. As a result, in this paper, a comprehensive risk evaluation model for the operation period of complex mountain tunnels has been established based on FCE and AHP for evaluating the risks of the Jinjishan Tunnel during the operation period so as to provide reference for similar projects.

2. Establishment of Risk Assessment Model for Complex Mountain Tunnels

2.1. Steps of Model Establishment
• Establish a hierarchical structure model. The relevant factors are classified into several levels according to different attributes.
  • Establish a factor set and a risk index system. The influence degree of each factor on the object to be evaluated has been taken into account.
  • Determine the relative weight values of risk factors;
  • Determine membership functions. The membership evaluation of each factor in terms of the object to be evaluated has been taken into account, and the evaluation results of each single factor have been incorporated into the matrix;
  • Conduct the fuzzy estimate of risk probability. The risk probability has been calculated according to the matrix formed by the relative weight and membership.
  • Perform the comprehensive evaluation. The evaluation results have been processed according to the probability obtained.

2.2. Establishment of Hierarchical Model for Tunnel Risk Assessment
The safety evaluation model of tunnel structure shall be established before the evaluation on the safety of tunnel structure. According to the levels and fuzziness of the identified risk factors, the evaluation indexes affecting the soundness status of the main tunnel structure are classified into three levels:
  • Target level: soundness status of the main structure of the mountain tunnel;
  • Criterion level: it is composed of factors that affect the safety of tunnel structure, including the risk inducing environment, structure defects and load effect;
- Index level: it is composed of indexes that have influence on the factors at the criterion level, including quantitative and qualitative indexes.

The specific hierarchical model for risk assessment is shown in Table 1.

| Target level | Criterion level | Index level |
|--------------|-----------------|-------------|
| Soundness status of the main structure of the mountain tunnel | Risk inducing environment | Fault and fracture zone |
| | | Flow rate of leakage water |
| | | Area of leakage water |
| | | Range of surrounding rock cavity |
| | | Length of surrounding rock cavity |
| | | Depth of surrounding rock cavity |
| | Structure defects | Defects in lining thickness |
| | | Effective thickness ratio of lining |
| | Load effect | Crack length of lining structure |
| | | Crack width of lining structure |
| | | Degree of degradation of initial support strength |
| | | Axial force on main structure |
| | | Bending moment on main structure |

2.3. Determination of Weight

The relative importance is determined and the relative weight is obtained through the pairwise analysis and comparison of the elements on the same level, and the scale value is used to represent the relative weight, so as to obtain the judgment matrix [10]. The scale values are expressed by 1~9 and their reciprocals, and the meanings are shown in Table 2.

| Scale | Meaning |
|-------|---------|
| 1     | For the two elements compared, they are equally important. |
| 3     | For the two elements compared, one is slightly more important than the other. |
| 5     | For the two elements compared, one is obviously more important than the other. |
| 7     | For the two elements compared, one is particularly more important than the other. |
| 9     | For the two elements compared, one is extremely more important than the other. |
| 2,4,6,8 | The importance is between the above two adjacent numbers. |

The judgment matrix formed is as follows:

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}$$

(1)

where: $$b_{ji} = 1/b_{ij}$$.

The characteristic root method shall be adopted for calculating the weight values of influencing factors. The maximum characteristic root of the judgment matrix shall be obtained through calculation, and its corresponding characteristic vector shall be normalized to serve as the result of the single
hierarchical arrangement. Namely, the weight vectors of influencing factors are obtained; and then, a weight set is formed, and it is expressed as follows:

\[ A = \{a_1, a_2, a_3, \ldots, a_m\} \]  

Finally, the consistency tests on the obtained results shall be carried out to ensure the correctness of numerical selection.

2.4. Determination of Membership Functions

For calculating the memberships of influencing factors, the membership functions must be determined first. The so-called membership function is a mathematical expression used to represent the quantitative relationship between influencing factors and evaluation grades. When the influencing factor is in a certain state, the membership of the influencing factor in terms of the target at this time can be obtained based on the membership function. In this paper, the soundness evaluation of the tunnel structure refers to a fuzzy evaluation [11]. The membership function established based on the fuzzy set is called the fuzzy distribution function. Since the fuzzy statistics method is simple and convenient, and it is in line with the actual condition of the tunnel structure soundness evaluation, such method is adopted in this paper to determine membership functions.

2.5. Fuzzy Estimate of Risk Probability

Before the fuzzy estimate of risk probability, hypotheses shall be made for the results of various evaluations, corresponding sets shall be established, and a comprehensive evaluation matrix shall be established based on the membership functions. The comprehensive evaluation matrix is expressed as follows:

\[
R_i = \begin{bmatrix}
  r_{i1} & r_{i2} & \cdots & r_{ip} \\
  r_{i1} & r_{i2} & \cdots & r_{ip} \\
  \vdots & \vdots & \ddots & \vdots \\
  b_{ni} & b_{n2} & \cdots & b_{np}
\end{bmatrix}
\]  

In the above comprehensive evaluation matrix, \( r_{ij} \) reflects the importance of the \( i \)th influencing factor to the \( j \)th comment in the comment set.

In order to reflect the comprehensive influence of all factors, the weight fuzzy sets of factors and the comprehensive evaluation matrixes are used for corresponding calculations so as to perform the fuzzy estimate of risk probability.

\[
C = A \ast R = \{a_1, a_2, a_3, \ldots, a_m\} \ast \begin{bmatrix}
  r_{i1} & r_{i2} & \cdots & r_{ip} \\
  r_{i1} & r_{i2} & \cdots & r_{ip} \\
  \vdots & \vdots & \ddots & \vdots \\
  b_{ni} & b_{n2} & \cdots & b_{np}
\end{bmatrix} = (C_1, C_2, C_3, \ldots, C_p)
\]  

Where, \( C \) represents the comprehensive evaluation result of risk probability, and \( C_j \) represents the importance of the comprehensive evaluation result to the \( j \)th comment in the comment set.

For the calculation of \( \ast \), there are a lot of calculation models available. This paper deals with the comprehensive influence of influencing factors on the structure soundness of mountain tunnels. Therefore, the weighted average evaluation model \( M(\ast, \oplus) \) shall be adopted for the calculation for comprehensive evaluation [12]. The model indicates that the degrees of influences of factors on the target are fully characterized and comprehensively considered, and it is expressed as follows:

\[
C_j = \sum_{i=1}^{m} (a_i \cdot r_{ij})(j = 1, 2, \ldots, p)
\]  

2.6. Comprehensive Evaluation

At present, there are two most commonly used evaluation methods, namely the maximum membership degree method and the average value method. In this paper, the maximum membership degree method
has been selected to conduct the result evaluation on the tunnel safety risk probability. The so-called maximum membership degree method refers to selecting the comment set corresponding to the largest evaluation index $C_j$ in matrix $C$ as the final evaluation result \cite{13}, and such comment set is expressed as follows:

$$V = \{v_i|v_i \leftarrow \text{The largest element in } C\}$$ (6)

In order to elaborate the soundness status of the complex mountain tunnel structures, the four-grade division method has been adopted in this paper to classify the soundness status of the main structures of the complex mountain tunnels, and the specific safety grades are shown in Table 3.

| Grade | Description of soundness status of tunnel structures |
|-------|-----------------------------------------------------|
| Grade I | Grade I represents that the structure is safe, intact or basically intact, and free from any observable damage, and meets the service requirements. |
| Grade II | Grade II represents that the structure is basically safe and slightly damaged, but the bearing capacity and rigidity of the structure will not be affected. Observation shall be made as far as possible during use as such damage may affect the safety of the structure. |
| Grade III | Grade III represents that the structure is potentially unsafe and subject to general damage, which reduces the safety performance of the structure and causes some observable tunnel damage. If such damage becomes more severe, risks may occur. Monitoring shall be strengthened and corresponding countermeasures shall be taken during use. |
| Grade IV | Grade IV represents that the structure is unsafe and subject to destructive damage. The structure can no longer meet the service requirements, and reinforcement measures shall be taken immediately. |

The comprehensive comment set established based on information in the table is as follows:

$$V = \{v_1,v_2,v_3,v_4\}$$ (7)

3. Case Study

3.1. Project Overview

The Jinjishan Tunnel is a key project of the second ring road in Fuzhou, and it is a two-tunnel and two-lane mountain tunnel with separated up and down traffic, and a single tunnel is 578m long. The construction commenced on October 31, 1994. The main section of the tunnel is designed according to the Grade I standard of the urban main road. For the inner contour of the tunnel, the holocentric circular and curved wall section is adopted. The clear width for travelling in the tunnel is 8m, the height limit is 5m, and the clearance is 7.05m. The tunnel is designed according to the principle of the New Austrian Tunnelling Method and it is provided with the composite lining. The plan of tunnel site is shown in Figure 1.
The Jinjishan Tunnel has a history of 24 years since its completion. Due to the aging of materials and the low design and construction levels at that time, the secondary lining in some sections has been subject to damage such as severe cracks, as shown in Figure 2 ~ Figure 5. In order to identify the actual condition of the damage and determine the current safety status of the tunnel, the damage detection and safety risk assessment must be carried out for the tunnel. The on-site inspection is shown in Figure 6.
During the tunnel risk assessment, the typical section with the surrounding rock at Grade V shall be selected for analysis. The monitoring data on each evaluation index of the analysis section obtained through the concrete crack and secondary lining concrete strength monitoring and the on-site monitoring and measurement are shown in Table 4.

### Table 4. On-site Inspection of the Jinjishan Tunnel.

| Influencing factors               | Values at the index level                                                                 |
|-----------------------------------|------------------------------------------------------------------------------------------|
| Fault and fracture zone           | The tectonic fracture zone is relatively narrow and has been subject to extrusion transmission, with developed joints and fissures, broken rock mass and poor integrity. The value is 0.4. |
| Flow rate of leakage water        | Flow rate of leakage water: 1.6 L/d                                                      |
| Area of leakage water             | Area of leakage water: 32 cm²                                                             |
| Range of surrounding rock cavity  | It is distributed over a large area at the vault, and the value is 0.5.                   |
| Length of surrounding rock cavity | Length of surrounding rock cavity: 3 m                                                    |
| Depth of surrounding rock cavity  | Depth of surrounding rock cavity: 400 mm                                                  |
| Defects in lining thickness       | The thickness of vault lining is insufficient, and the value is 0.4.                       |
| Insufficiency degree of lining thickness | The missing thickness is 20 cm, and the insufficiency degree of thickness is 0.5.         |
| Crack length of lining structure  | Crack length: 6 m                                                                         |
| Crack width of lining structure   | Crack width: 5 mm                                                                         |
| Degradation of initial support strength | Degree of degradation of initial support strength: 50%                                   |
| Axial force on main structure     | 1668.45 kN                                                                                 |
| Bending moment on main structure  | 406.31 kN·m                                                                               |

### 3.2. Comprehensive Risk Evaluation

The risk inducing environment, faults and fracture zones, and cavities provide crack channels for groundwater infiltration, resulting in the increase of the water leakage risk in the tunnel structure. Moreover, the surrounding rock cavity behind the lining makes the faults and fracture zones have greater adverse effects on the mechanical properties of the tunnel structure. In case of any leakage in...
the tunnel structure, if the flow rate of leakage water is larger, the corresponding area of leakage water will become greater. The influence of the depth of surrounding rock cavity on the tunnel structure is greater than that of the length on the tunnel structure, while the influence of the cavity position on the tunnel structure is relatively weak. The relative weights about faults and fracture zones, tunnel leakage water and surrounding rock cavities behind the lining determined based on this are shown in Table 5.

Table 5. Relative Weights of Indexes in the Risk Inducing Environment.

| \( B_1 \) | \( b_{11} \) | \( b_{12} \) | \( b_{13} \) | \( b_{14} \) | \( b_{15} \) | \( b_{16} \) |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| \( b_{11} \) | 1         | 3         | 2         | 1/2       | 1/3       | 1/4       |
| \( b_{12} \) | 1/3       | 1         | 3         | 1/4       | 1/5       | 1/6       |
| \( b_{13} \) | 1/2       | 1/3       | 1         | 1/5       | 1/6       | 1/7       |
| \( b_{14} \) | 2         | 4         | 5         | 1         | 1/2       | 1/3       |
| \( b_{15} \) | 3         | 5         | 6         | 2         | 1         | 1/2       |
| \( b_{16} \) | 4         | 6         | 7         | 3         | 2         | 1         |

According to the calculation, the weight set composed of indexes in the risk inducing environment is as follows:

\[
a_i = (0.097 \ 0.055 \ 0.037 \ 0.167 \ 0.258 \ 0.386) \quad (8)
\]

\[
\lambda_{\text{max}} = 6.242, \quad CI = 0.048 \quad \text{and} \quad CR = 0.039 \leq 0.1 \quad (\text{meeting the consistency requirements})
\]

For structure defects, the degradation of initial support strength and the insufficiency of lining thickness will lead to the increase of tunnel structure stress, resulting in the increase of cracks on the lining structure. As the secondary lining is the main load-bearing member in the tunnel structure, the importance to structure of the initial support is less than that of the secondary lining. The influence of the insufficiency degree of lining thickness on the tunnel structure is greater than that of the position with missing thickness on the tunnel structure. Therefore, the determined relative weights about the insufficiency of lining thickness, cracks in lining structure and degradation of initial support strength are shown in Table 6.

Table 6. Relative Weights of Indexes in the Case of Structure Defects.

| \( B_2 \) | \( b_{21} \) | \( b_{22} \) | \( b_{23} \) | \( b_{24} \) | \( b_{25} \) |
|-----------|-----------|-----------|-----------|-----------|-----------|
| \( b_{21} \) | 1         | 1/5       | 3         | 3         | 2         |
| \( b_{22} \) | 5         | 1         | 5         | 5         | 3         |
| \( b_{23} \) | 1/3       | 1/5       | 1         | 1         | 1/3       |
| \( b_{24} \) | 1/3       | 1/5       | 1         | 1         | 1/3       |
| \( b_{25} \) | 1/2       | 1/3       | 3         | 3         | 1         |

According to the calculation, the weight set composed of indexes in the case of structure defects is as follows:

\[
a_i = (0.196 \ 0.497 \ 0.071 \ 0.071 \ 0.165) \quad (9)
\]

\[
\lambda_{\text{max}} = 5.229, \quad CI = 0.057 \quad \text{and} \quad CR = 0.0511 \leq 0.1 \quad (\text{meeting the consistency requirements})
\]

For the load effect, the numerical calculation shows that the main structure of the support works is mainly subject to axial force, and the bending moment is far less than the axial force. Therefore, the determined relative weights of the axial force and bending moment on the main structure are shown in Table 7.

Table 7. Relative Weights of Indexes under Loads.

| \( B_3 \) | \( b_{31} \) | \( b_{32} \) |
|-----------|-----------|-----------|
| \( b_{31} \) | 1         | 5         |
| \( b_{32} \) | 1/5       | 1         |

According to the calculation, the weight set composed of indexes under loads is as follows:

\[
a_i = (0.833 \ 0.167) \quad (10)
\]
\[ \lambda_{\text{max}} = 2.000 \quad CI = 0 \quad CR = 0.1 \text{ (meeting the consistency requirements)} \]

As the root cause of structure defects, the load effect has the greatest influence on the soundness of the main structure of the tunnel. Moreover, the structure defects make the status of the tunnel structure in the risk inducing environment more unfavorable. Therefore, the relative weights of the risk inducing environment, structure defects and load effect are shown in Table 8.

Table 8. Relative Weights of Factors at Criterion Level.

| B     | B_{11} | B_{21} | B_{31} |
|-------|--------|--------|--------|
| B_{11} | 1      | 1/3    | 1/5    |
| B_{21} | 3      | 1      | 1/3    |
| B_{31} | 5      | 3      | 1      |

The obtained weight set composed of factors at the criterion level is as follows:

\[ A = (0.105 \ 0.258 \ 0.637) \]  

\[ \lambda_{\text{max}} = 3.039 \quad CI = 0.019 \quad CR = 0.033 \quad 0.1 \text{ (meeting the consistency requirements)} \]

To sum up, the weight values of influencing factors for the soundness status of the main structure of the Jinjishan Tunnel are shown in Table 9.

Table 9. Weight Values of Influencing Factors for Soundness Status of Main Structure of the Jinjishan Tunnel.

| Criterion level | Weight at criterion level | Index level                  | Weight at index level |
|-----------------|---------------------------|------------------------------|-----------------------|
| Risk inducing environment | 0.105                     | Fault and fracture zone 0.097 |                       |
|                  |                           | Flow rate of leakage water 0.055 |                       |
|                  |                           | Area of leakage water 0.037 |                       |
|                  |                           | Range of surrounding rock cavity 0.165 |                       |
|                  |                           | Length of surrounding rock cavity 0.258 |                       |
|                  |                           | Depth of surrounding rock cavity 0.386 |                       |
|                  |                           | Defects in lining thickness 0.196 |                       |
|                  |                           | Effective thickness ratio of lining 0.497 |                       |
|                  |                           | Crack length of lining structure 0.071 |                       |
| Structure defects | 0.258                     | Crack width of lining structure 0.071 |                       |
|                  |                           | Degree of degradation of initial support strength 0.165 |                       |
| Load effect      | 0.637                     | Axial force on main structure 0.833 |                       |
|                  |                           | Bending moment on main structure 0.167 |                       |
As for the determination of membership functions, the evaluation on influencing factors involves quantitative and qualitative indexes, and the properties of factors are different. Therefore, the membership functions established shall also be different. In this paper, the membership functions include the trapezoidal function, lower semi-trapezoid function and normal distribution function.

The values for the on-site inspection of the Jinjishan Tunnel in Table 4 are introduced into the membership function to find solutions, and the comprehensive evaluation matrix obtained is as follows:

\[
R_i = \begin{bmatrix}
0.00 & 0.00 & 0.50 & 0.50 \\
0.00 & 0.42 & 0.58 & 0.00 \\
0.00 & 0.50 & 0.50 & 0.00 \\
0.00 & 0.50 & 0.50 & 0.00 \\
0.00 & 0.10 & 0.90 & 0.00 \\
\end{bmatrix}
\]

(12)

\[
R_2 = \begin{bmatrix}
0.00 & 0.00 & 0.50 & 0.50 \\
0.00 & 0.50 & 0.50 & 0.00 \\
0.00 & 0.50 & 0.50 & 0.00 \\
0.00 & 0.00 & 0.50 & 0.50 \\
0.00 & 0.00 & 0.50 & 0.50 \\
\end{bmatrix}
\]

(13)

\[
R_3 = \begin{bmatrix}
0.00 & 0.677 & 0.323 & 0.000 \\
0.00 & 0.203 & 0.797 & 0.000 \\
\end{bmatrix}
\]

(14)

The result of the first-level fuzzy comprehensive evaluation is:

\[
C_1 = a_i \ast R_i = a_i = (0.097 \ 0.055 \ 0.037 \ 0.167 \ 0.258 \ 0.386) \ast
\]

\[
= (0.0000 \ 0.2356 \ 0.7159 \ 0.0485)
\]

(15)

\[
C_2 = a_2 \ast R_2 = (0.196 \ 0.497 \ 0.071 \ 0.071 \ 0.165) \ast
\]

\[
= (0.0000 \ 0.0618 \ 0.7222 \ 0.2160)
\]

(16)

\[
C_3 = a_3 \ast R_3 = (0.833 \ 0.167) \ast
\]

\[
= (0.0000 \ 0.5978 \ 0.4022 \ 0.0000)
\]

(17)

The final result is:

\[
R = \begin{bmatrix}
0.0000 & 0.2356 & 0.7159 & 0.0485 \\
0.0000 & 0.0618 & 0.7222 & 0.2160 \\
0.0000 & 0.5978 & 0.4022 & 0.0000 \\
\end{bmatrix}
\]

(18)

The result of the second-level fuzzy comprehensive evaluation is:
The matrix $C$ is processed with the maximum membership principle, and the final evaluation result of tunnel structure safety is Grade III. The structure is potentially unsafe and subject to general damage and some observable tunnel damage, and the safety performance decreases. Monitoring shall be strengthened and corresponding maintenance measures shall be taken during use. The results of comprehensive risk evaluation are consistent with the actual engineering conditions, which verifies the effectiveness of the evaluation model.

4. Risk Prevention and Control Measures for Tunnels
According to the above risk assessment results, the structure of the Jinjishan Tunnel is potentially unsafe. Moreover, the Jinjishan Tunnel has a large traffic volume, and it is also the trunk line of the city. In order to effectively reduce the tunnel risks, the following five measures are proposed to control risks.

• For the sections with cavities and voids on the arch back, the arch back grouting shall be adopted for reinforcement;
• For areas with dense cracks in lining, the shotcrete and steel meshes or gumming carbon fibers shall be adopted for reinforcement;
• For cracks 0.15~2mm wide, the method of non-destructive grouting for patching may be adopted for treatment; for cracks 2~5 mm wide, the method of gouging for grouting shall be adopted for treatment.
• Measures such as gouging for drainage and blocking, and coating of waterproof materials shall be taken to deal with leakage water;
• A long-term and dynamic tunnel deformation and force measurement system shall be established in the tunnel to conduct the long-term measurement for the tunnel, analyze its stress status, and guide the maintenance by the maintenance team.

5. Conclusions
• The risk influencing factors and their weights during the tunnel operation period were researched based on FCE and AHP. The results show that the main control factor of tunnel risk during the operation period is the load effect, followed by structure defects and the risk inducing environment.
• Based on the engineering experience and AHP-FCE, the fuzzy set of weights for risk influencing factors of complex mountain tunnels was established, the membership functions of factors at the index level were determined, the comprehensive evaluation matrix of tunnel risks was obtained, and the fuzzy comprehensive evaluation method for risks of complex mountain tunnels was proposed.
• The above-mentioned fuzzy comprehensive evaluation method for risks of complex mountain tunnels was used to evaluate the risks of the Jinjishan Tunnel during the operation period. The results show that the risk of the tunnel structure is at Grade III and the structure is potentially unsafe, which is in line with the actual engineering conditions and verifies the effectiveness of the evaluation method. In addition, corresponding risk prevention and control measures were put forward, providing reference for similar projects.

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