Research Article

Dynamic Risk Assessment of Karst Tunnel Collapse Based on Fuzzy-AHP: A Case Study of the LianHuaShan Tunnel, China

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Tunnel collapse in the karst tunnel occurs suddenly. Dynamic risk assessment for tunnel collapse is more accurate than static analysis, which is not enough at the stage. The study designs a new questionnaire to establish dynamic risk assessment for karst tunnel collapse, by a fuzzy analytic hierarchy process (F-AHP) method. The characteristics of the cave, dynamic monitoring, and prediction are fully considered in the assessment to strengthen the karst and dynamic characters: (1) the factors of dynamic risk assessment are selected based on advanced geological prediction, collapse investigation, and theoretical analysis as dynamic and static factors. Dynamic factors are classified as the rationality of advanced geological prediction method, reliability of data, the accuracy of data analysis, and timeliness and effectiveness of forecast information transmission. Karst cave characteristic factors are composed of cave scales, locations, and thickness of rock plate, based on collapse investigation and theoretical analysis to strengthen the character of karst. (2) A new questionnaire is designed in the consulting process to express the relative importance of factors by combining a Saaty scale method and a designed three-scale method. The judgment matrix by the new questionnaire can satisfy the consistency requirement, which is hard to satisfy in the traditional F-AHP method. (3) The dynamic risk assessment is carried out on different samples in the Lianhuashan tunnel. By comparing the dynamic assessment results with the occurrence of disasters, the rationality of the assessment is verified.

1. Introduction

With the rapid development of Western China, more tunnels will be built. The area of carbonate rock distribution accounts for more than 1/3 of Southwest China [1, 2], which is easy to form karst area. Collapse is one of the most serious geological disasters and frequently occurs in karst tunnel contraction, which not only causes huge economic losses and heavy casualties but also greatly endangers the safety of tunnel construction and the environment. Accurate risk assessment can be taken to ensure the safety of tunnel construction.

A dynamic risk assessment in construction contains a variety of feedbacks that enhance an accuracy of evaluation effectively. At this stage, a large amount of karst tunnel assessments focus on static factors, such as hydrogeological and geological engineering conditions [3] and characteristics of the tunnel [4, 5]. Dynamic risks assessment could be established based on dynamic feedback, such as geological forecast results [6], which are used to obtain geological conditions above the tunnel face. Dynamic assessment models are insufficient at this stage, as the models only consider the dynamic factors and ignore the static factors. The dynamic and static factors should be combined in the assessment.

The analysis of karst caves could express the feature of karst area effectively. At present, karst caves’ features are integrally considered in unfavorable geology. In unfavorable geology, characteristics of karst caves, such as the scale of caves and the thickness of water-resistant strata [7, 8], are
considered insufficiently. Elaboration of caves’ features in assessment would enhance karst characteristics. Thus, caves’ characteristics should be fully considered in the model. In addition, risk assessment of collapse should not only consider the disaster-related environmental factors as interval factors. The level of construction and management factors [9–13] should be taken into account as external factors, because the human activity is the main factor that induces tunnel collapse in construction.

Thus, in the dynamic risk assessment of karst tunnel collapse, the dynamic factors, static factors, interval factors, and external factors should be considered comprehensively. This is fuzzy and complex. Thus, it is necessary to use a variety of methods to define risk factors.

In risk assessment, the fuzzy analytic hierarchy process (F-AHP) is a popular multi-criteria decision analysis method. Pairwise comparison, which is proposed by Saaty [14], is used to determine the relative importance of the factor to criteria in the traditional F-AHP method. However, inconsistency and time consumption in the questionnaire are hard to eliminate. Li et al. [15] designed a sorting method to reduce inconsistency, but the number of factors is limited in his method. Lyu et al. [16] designed a new questionnaire using mode calculation. When multiple modes appear in a factor, the efficiency of the method would be impaired. Consequently, it is necessary to design a new method to obtain factors’ weight, which could eliminate inconsistency in comparison.

In the study, dynamic risk assessment for karst tunnel collapse is established to enhance the accuracy of evaluation and compensate for the fact that existing assessments are mainly static: (1) the dynamic factors, static factors, internal factors, and external factors are considered comprehensively, by advanced geological prediction, collapse investigations, and theoretical analysis. In the model, dynamic factors are classified as the rationality of selection of advanced geological prediction method, reliability of data, the accuracy of data analysis, and timeliness and effectiveness of forecast information transmission. Karst cave factors are composed of cave scales, locations, and thickness of rock plate to strengthen the character of karst area. (2) A new questionnaire is designed, by combining the Saaty scale method and the designed three-scale method, to compensate for consistency requirements, in which the traditional F-AHP is hard to satisfy. (3) The dynamic risk assessment is carried out on different samples in the Lianhuashan tunnel. By comparing the dynamic assessment results with the occurrence of disasters, the rationality of the assessment is verified.

2. Methods

2.1. F-AHP Method. F-AHP is a kind of evaluation method, which combines the advantages of the analytic hierarchy process (AHP) with a fuzzy set.

AHP, which is proposed by Saaty [17, 18], is a kind of analysis method that divides factors into several levels. The process of the method includes establishing hierarchical structure models according to the intrinsic relationship among factors, setting judgment matrixes through comparison of factors, and deciding the relationship of the importance of factors.

The main steps of the establishment of AHP are as follows:

(1) Identify factors, and divide factors into several hierarchical structures.
(2) Establish a judgment matrix.
(3) Apply certain methods to evaluate factors’ weight.
(4) Check the consistency.

To enhance the vagueness of humans though, Zadeh [19] proposed the fuzzy set theory. The goal of the theory is to establish the rationality of vagueness. F-AHP as a combination method is widely used in the evaluation of tunnel construction.

2.2. Factors Identification. The factors identification includes three methods: dynamic factors identification, accidents investigation, and theoretical analysis. The risk factors of karst tunnel collapse are determined by experts, based on the identification of the three methods.

(1) Dynamic Factors Identification. Dynamic factors are identified in the study based on the usage of advanced geological prediction in construction. The dynamic factors consider the selection of advanced geological prediction, the reliability of data from feedback, the rational analysis of data, and timelines and effectiveness of forecast information transmission.

(2) Accidents Investigation. Karst tunnel collapse accidents are collected from references. The accidents from different references could eliminate the inappropriateness of accident analysis. Features of karst caves are analyzed in the investigation. In the identification of karst caves features, the scale and location of caves are considered. The surrounding rock and unfavorable geology are also analyzed.

(3) Theoretical Analysis. Theoretical analysis is regarded as supplementary for the factors that are not taken into account from accidents investigation. The theoretical analysis is composed of internal factors and external factors.

(4) Factors Determination by Experts. Experts are invited to determine risk assessment factors.

First of all, experts are selected by different occupations and units with various professional titles.

Second, the risk factors, which are composed of dynamic feedback, accidents investigation, and theory analysis, are sent to experts.

Third, the feedbacks from experts are collected. The risk factors would be retained, which are selected by more than half of the experts.
2.3. Weight Calculation

2.3.1. Limitation of Existing Methods. Pairwise comparison is used to determine the relative importance of the factor to criteria, based on a questionnaire [20]. When the consistency of judgment is satisfied, the pairwise comparison is valid. However, consistency is hard to be satisfied, because the consistency of the matrix mostly depends on the accuracy of judgment among experts [15]. In addition, the collection of judgment from experts is time consuming [16]. When judgment is inconsistent, future consulting is needed.

To eliminate inconsistency and reduce time consumption in the traditional method, Li et al. [15] designed a sorting method to establish the improved-AHP method (I-AHP). However, the number of factors is limited in I-AHP. This method is not effective when the number of elements is 3, 4, 8, and 9 [15]. Lyu et al. [16] designed a new questionnaire to determine factors’ weight. A mode calculation method is adopted in the questionnaire. When multiple modes appear in a factor, it is hard to determine the value of factors.

The advantages of I-AHP and Lyu method are eliminating inconsistency of questionnaire and reducing time consumption of experts, which occur in traditional pairwise comparison. However, the above methods still have deficiencies.

2.3.2. New Questionnaire and Weight Calculation. This study designs a new questionnaire to establish consistent judgment matrices. In the new questionnaire, the Saaty scale method and the three-scale method, which is designed in the study, are used comprehensively to determine the relative importance of factors to criteria. An expert’s professional title is listed in each questionnaire for data proceeding.

The new questionnaire is presented in Appendix A.

Step 1. Determine Relative Importance of Factor 1 to Factor i by the Saaty Scale Method: assignments of $a_{ij}$ ($i = 1$ to $n$) are obtained based on experts’ consulting results by Saaty scale method.

Step 2. Pairwise Comparison of Other Factors by Three-Scale Method: the relative importance of factor $i$ ($i 
eq 1$) to factor $j$ ($j 
eq 1$) is compared qualitatively by experts. The qualitative analysis includes “same important,” “more important,” and “less important.”

Step 3. Consistency Conformation: first of all, the values of “same important,” “more important,” and “less important” in three-scale method are assigned as $a_{ij-3S}$. The assignment of $a_{ij-3S}$ is a numerical interval. Second, the pairwise comparison of factors is assigned as $a_{ij-S}$, which is calculated based on the assessment of $a_{ij}$ and $a_{ij}$ in Step 1. Third, if the value of $a_{ij-S}$ is in the numerical interval of $a_{ij-3S}$, the consistency is satisfied. The $a_{ij}$ takes closest data in Saaty calibration. If the value of $a_{ij-S}$ is out of the numerical interval of $a_{ij-3S}$, then a further questionnaire is needed.

Step 4. $a_{ij}$ Value of Each Expert’s Feedback Is Weighted by Their Professional Titles: the new questionnaire could satisfy with the consistence if the value of $a_{ij-S}$ consists with the trend of $a_{ij-3S}$, because the $a_{ij-S}$ is obtained from the logical computation of $a_{ij}$ and $a_{ij}$ which are evaluated from experts quantitatively in Saaty scale method. The $a_{ij-3S}$ as a numerical interval qualitatively reflects relationship between factor $i$ and factor $j$. When the value of $a_{ij-S}$ is consistent with the trend of $a_{ij-3S}$, then the quantitative and qualitative feedbacks are compatible. In addition, the combination of quantitative and qualitative analysis can avoid failures of single evaluation.

So, the new questionnaire could estimate inconsistency in traditional method and ensure the accuracy of feedback from experts.

2.4. Membership Function. At this stage, the improved F-AHP method or F-AHP combined with other risk assessment methods is used to establish membership function in the model.

In a water inrush progress assessment, Peng et al. [10] and Wang et al. [9, 21] used a cloud model and the Saaty method to calculate objective and subjective weights. Vyas et al. [22] used an enterprise method to evaluate pavement condition. Singh [23] designed smoothed membership function to access water resources. Singh and Dubey [24] determined the membership function combined experts’ investigation with Yager’s unit interval method, to select a landfill disposal site.

The F-AHP method combined with cloud or entropy is based on a large number of statistical data. The cloud is composed of a plurality of cloud droplets [21]. The more cloud droplets, the more clearly the overall characteristics of concept can be reflected. The entropy method is determined by a frequency statistical method [21].

In this study, in a dynamic model, the dynamic feedback, hydrogeological and geological engineering conditions, characteristics of karst caves, the level of construction, and management factors are considered comprehensively. A large amount of the factors in the study use linguistic description, which is hard to obtain a large amount of data. Thus, the cloud or entropy method is not applicable to this study.

In the study, the membership function is described by linguistic and numerical values. So, the I-type function and triangular membership function are used to describe factors separately.

The main steps of the membership function determination are as follows:

1. Rank risk factors into several levels.
2. I-type function and triangular membership function are used to describe linguistic and numerical factors separately.
3. Form membership function.

The triangular membership function is established in each level, according to the upper and lower limits of each level. The I-type function is established based on the Karowski function.
3. Identification of Risk Factors

3.1. Dynamic Factors. To enhance the accuracy of geological and hydrogeological information, advanced geological prediction is often used in construction. The features of advanced geological prediction are considered as dynamic factors in the assessment.

3.1.1. Advanced Geological Prediction Method. Advance geological prediction generally adopts a variety of prediction methods. Advance geological prediction methods are mainly divided into geological analysis methods, main tunnel geological logging, prediction, and geophysical prospecting methods. Geophysical methods include the elastic wave method, electromagnetic wave method, infrared water exploration method, and transient electromagnetic detection method. Each advance geological prediction method has its characteristics and applicable conditions. To ensure the accuracy of geological prediction results, the rationality of the selection of advanced geological prediction methods will be evaluated in dynamic evaluation.

3.1.2. Reliability and Analysis of Data. Reliability of data from advanced geological prediction leads to the accuracy of geological and hydrogeological information. The analysis of data from prediction is crucial. Some advanced geological prediction methods require technicians to analyze the results. For example, tunnel seismic prediction (TSP), a kind of elastic wave method, should analyze the shape and velocity of the reflected wave to obtain information on the grade of surrounding rock, fault fracture zone, and rock saturation. The rationality of data and accuracy of data analysis are very important to the judgment of geological conditions.

3.1.3. Information Feedback. Timeliness and effectiveness of forecast information transmission also have a significant impact on the results of risk assessment. Timely and effective transmissions of data can feedback unfavorable geology in front of the face timely. Effective measures could be taken to ensure the safety of construction.

Consequently, the rationale of selection of advanced geological prediction method, reliability of data and accuracy of data analysis, timeliness, and effectiveness of forecast information transmission should be considered as dynamic factors in the assessment.

Sometimes information on geological and hydrogeological is different from the geological survey, which is complete before construction. In a dynamic evaluation model, the geological conditions obtained from the survey would be modified from geological prediction.

3.2. Factors from Collapse Accidents. Based on karst tunnel collapse in different tunnels, karst cave characteristics and surrounding rock are sorted out, as shown in Figure 1. The tunnel investigation of the study includes Liu Guantun tunnel, Shang Pilin tunnel, Shao (Guan) Gan (Zhou) expressway, Gui Zhou tunnel, Huang Zhushan tunnel, No.1 tunnel in Qichong village, Hua Gushan tunnel, Left line of Hyde tunnel [25], and Shang Jiawan tunnel.

Other factors, such as construction, management, characteristics of tunnels, are identified in theoretical analysis.

Figure 1 shows that most of the surrounding rocks of collapse tunnels are limestone and mudstone. Moreover, many surrounding rocks are strongly weathered, and fissures are developed. Most of the cave’s location is on the top of the tunnel. Some caves are on the right and the left of the tunnel. With the enhancement of the cave scale, the possibility of tunnel collapse grows. The analysis of collapse shows that the volume of caves near tunnels is more than 50 m³. From the accident data collected, it can be seen that the surrounding rock, unfavorable geology, locations of caves, and scales of karst caves are the main factors affecting the collapse of the karst tunnel.

3.3. Theoretical Analysis of Factors. Risk factors from accidents analysis shown in Figure 1 focus on surrounding rock and feature of caves. Theoretical analysis is regarded to supply the factors that are not taken into account in karst tunnel accidents, as shown in Figure 1.

3.3.1. Objective Factors

(1) Rock Strength. With the decrease of rock strength, the probability of collapse and the scale of collapse increase.

(2) Rock Mass Structure. There are five types of rock mass structure, that is, integral, massive, layered, cataclastic, and scattered. The influence of rock mass structure types on tunnel collapse is different. Among them, when the tunnel passes through the cataclastic and scattered rock mass, it is most likely to collapse.

(3) Structural Fracture Zone. In the process of tunnel construction, it is inevitable to encounter various adverse geological structures, such as fault fracture zone, weak interlayer, strong fold belt, and rock vein penetrating contact alteration zone. The rock mass integrity in these structural fracture zones is poor, which is more prone to collapse. Among the fractured zones, the shattered fault zone is an important influencing factor of collapse.

(4) Ground Pressure. Ground pressure mainly includes bias pressure, ancient landslide, plastic ground pressure, and high ground stress area. In the bias pressure section, due to the shallow buried depth, it is easy to collapse. Due to improper treatment of engineering measures in an ancient landslide, the tunnel collapse will be caused. Plastic ground pressure often causes extrusion failure of the tunnel. Generally, a collapse will not occur in a high geo-stress area, but a rockburst is easy to occur.

(5) Groundwater. In the area where groundwater is rich, the strength of rock mass is often reduced due to the softening, erosion, and immersion of water. Rainfall could change the groundwater level and impact the stability of surrounding rock.
(6) Buried Depth. The failure mode of the surrounding rock varies with the depth of the tunnel. When the tunnel is buried deeply, the collapsed arch always appears in the collapse accidents. In a shallow burying tunnel, puking often occurs in collapse accidents.

In the shallow buried tunnel, there will be more chances to encounter strong weathered broken rock mass. Consequently, the possibility of a collapse of a shallow tunnel is higher than that of a deep tunnel. However, when the tunnel depth is less than 10 m, the chance of collapsing is relatively small, which is due to the strengthening of support in the shallow buried section of the tunnel.

3.3.2. Subjective Factors

(1) Tunnel Route. In a selection of tunnel routes, sufficient geological information should be obtained. In process of tunnel excavation, avoiding unfavorable geological would ensure the stability of the tunnel.

(2) Tunnel Shape and Scale. The shape of the tunnel determines the stress distribution characteristics of the surrounding rock. The failure of the surrounding rock would be caused by the redistributed stress when stress exceeds the strength of the surrounding rock.

The influence of tunnel scale on the stability of surrounding rock is significant. In the same kind of surrounding rock, the larger the tunnel section, the worse the stability of the surrounding rock, and the higher the probability of collapse.

(3) Construction and Management. Improper construction is a direct cause of the collapse. Improper construction mainly reflects on excessive vibration, improper excavation method, untimely support, and improper arrangement of construction procedures.

The management in the process of construction is also important, which could ensure the quality of construction.

From the theoretical analysis of factors, the main factors for the tunnel collapse include rock strength, structural fracture zone, water, tunnel design, the rationality of construction, and management.

3.4. Factors Determination. Based on the factors from dynamic prediction, accidents investigation, and theoretical analysis, experts are selected to determine factors in the study. The experts participating in the survey are selected from design institutes, research institutes, universities, and construction units to ensure the scientific, authority, and reliability of factors determination. Experts are composed of geotechnical or tunnel researchers, tunnel designers, and constructors. The composition of experts is shown in Figure 2. The background of each expert is shown in Appendix B.

Considering the characteristics and types of each factor, the risk factors, which are determined by experts, are classified. The hierarchical structure of risk assessment is established, as shown in Figure 3.

4. Weight Calculation

4.1. New Questionnaire Design. The traditional questionnaire in the AHP method asks experts to compare two factors directly. However, the inconsistency is inevitable, because the judgment matrix originates from pairwise comparisons may not be consistent, in which the relationship between two factors from the questionnaire and the quantified relationship is obtained indirectly.

This study designs a new questionnaire, which satisfies the consistency of judgment matrix from experts’ responses. In the new questionnaire, the Saaty scale method and the three-scale method, which is designed in the study, are used comprehensively to determine the relative importance of factors to criteria.

The new consulting questionnaire is presented in Appendix A:

(1) Determine the Relative Importance of Factor 1 to Factor i by the Saaty Scale Method. Assignments of $a_{ij}$ ($i = 1$ to $n$) is obtained based on experts’ consulting results by Saaty scale method. In this step, experts are encouraged to assign different scores (1/9-9) to different factors in the same layer to enhance the usability of judgment matrix.

(2) Pairwise Comparison of Other Factors by Three-Scale Method. The three-scale method is designed to compare relative importance of factors qualitatively. The judgment of pairwise comparison is composed by “same important,” “more important,” and “less important.” The three-scale method is used to
compare relative importance of factor \(i\) \((i \neq 1)\) to factor \(j\) \((j \neq 1)\).

(3) **Consistency of Questionnaire.** First, the values of “same important,” “more important,” and “less important” in the three-scale method are assigned as \(a_{ij}^{3s}\). The assignment of \(a_{ij}^{3s}\) is a numerical interval. Second, the pairwise comparison of factors is assigned as \(a_{ij}^{Ss}\), which is calculated based on the assessment of \(a_{1i}\) and \(a_{1j}\) in Step 1. Third, if the value of \(a_{ij}^{Ss}\) is in the numerical interval of \(a_{ij}^{3s}\), the consistency is satisfied. The \(a_{ij}\) takes the closest data in Saaty calibration. If the value of \(a_{ij}^{Ss}\) is out of the numerical interval of \(a_{ij}^{3s}\), then a further questionnaire is needed.

(4) **The \(a_{ij}\) Value of Each Expert’s Feedback Is Weighted by Their Professional Titles.** The judgment of pairwise comparison of factor \(i\) \((i \neq 1)\) to factor \(j\) \((j \neq 1)\) is classified into three types, which could eliminate...
inconsistency in a traditional F-AHP method. In the traditional method, experts need to quantify the relative importance between two factors directly. The quantification of $a_{ij}$ from experts’ judgment may not consistent with the value from the logical calculation based on $a_{ij}$ and $a_{ji}$.

The new questionnaire could satisfy the consistency if the value of $a_{ij}$ is consistent with the trend of $a_{ij}$, because $a_{ij}$ is obtained from the logical computation of $a_{ij}$ and $a_{ji}$ which are evaluated by the experts quantitatively in the Saaty scale method. The $a_{ij}$ as a numerical interval qualitatively reflects the relationship between factor $i$ and factor $j$. When the $a_{ij}$ is consistent with the trend of $a_{ij}$, the quantitative and qualitative feedbacks are compatible. In addition, the combination of quantitative and qualitative analyses can avoid failures of single evaluation.

So, the new questionnaire could eliminate inconsistency in the traditional method and ensure the accuracy of feedback from experts.

### 4.2. Saaty Scale Calibration

Saaty relative scale method is used in the study to determine the relative importance of factor 1 to factor $i$. In the process of calculation, the importance degree of the main influencing factors is compared. Saaty divides the factors’ relationship into 1–9 levels, which represent the comparison of the importance of each factor to the target and describes it with $a_{ij}$ as listed in Table 1.

### 4.3. Three-Scale Calibration

The three-scale method is designed to compare factor $i$ ($i \neq 1$) to factor $j$ ($j \neq 1$) pairwise. The judgments from experts are qualitative. The relationship of factors is defined as “same important,” “more important,” and “less important.” The evaluation in the three-scale method is qualitative.

### 4.4. Consistency Certification

The relationship between factor $i$ ($i \neq 1$) to factor $j$ ($j \neq 1$) from the three-scale method should be consistent with calculation results from Saaty scale calibration. The steps of consistency certification are listed in Table 2

1. The values of “same important,” “more important,” and “less important” in the three-scale method are assigned as $a_{ij}$. The assignment of $a_{ij}$ is a numerical interval, as listed in Table 2.
2. Based on the calibration in the Saaty scale method, the pairwise comparison of factor $a_{ij}$ is assigned by the values of $a_{ij}$ and $a_{ji}$. The assignment conforms to the relative importance calculation logic.
3. The consistency would be certified, by comparing $a_{ij}$ based on calculation in the Saaty scale method with $a_{ij}$ from calibration in the three-scale method.

If the value of $a_{ij}$ is in the numerical interval of $a_{ij}$, then the consistency is satisfied. The $a_{ij}$ takes closest data in Saaty calibration. If the value of $a_{ij}$ is out of the numerical interval of $a_{ij}$, then a further questionnaire is needed.

For example, in the Saaty scale method from a questionnaire, the expert calibrated $a_{14} = 7$ and $a_{15} = 3$. In the Saaty scale method, the pairwise comparison of factor $a_{ij}$ is calculated as $a_{ij} = 3/7$. The experts fill the questionnaire to compare the relative importance between factor 4 and factor 5 qualitatively. If the feedback is “same important,” the calibration of $a_{ij}$ is 1/3 to 3, based on Table 2. The value of $a_{ij} = 3/7$ is in the numerical interval of $a_{ij} = 1/3 - 3$. The consistency is satisfied. The $a_{ij}$ takes closest data in Saaty calibration. So, the value is calculated as $a_{ij} = 1/2$.

If the feedback of relative importance between factor 4 and factor 5 is “more important,” then the calibration of $a_{ij}$ is 4 to 9, based on Table 2. If the value of $a_{ij} = 3/7$ is out of the numerical interval of $a_{ij} = 4 - 9$, then the consistency is not satisfied, and a further questionnaire is needed.

### 4.5. Weight Calculation

Based on the consistency certification, the weight of each factor could be calculated.

Ensuring the scientific authority, and reliability of the judgment matrix results, the experts are selected from different units to determine the value of $a_{ij}$ in the judgment matrix. The composition of experts is shown in Figure 2.

Experts’ surveys are introduced to determine the value of $a_{ij}$ in the judgment matrix in the study, based on the new questionnaire in 4.4. According to the difference in professional titles, the $a_{ij}$ value of each expert’s feedback is weighted by experts’ professional titles, after consistency certification. The weighted processed data should satisfy the rule of Saaty calibration. The weight is 1.0 for a senior title, 0.9 for an intermediate title, and 0.7 for a junior title.

The $a_{ij}$ value is obtained from experts. After weighted by professional titles, the judgment matrix is established as shown in the following equation:

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix}.$$  (1)

The characteristic of each element in the judgment matrix is as follows:

$$a_{ij} > 0$$

$$a_{ii} = 1$$

$$a_{ij} = \frac{1}{a_{ji}}.$$  (2)

The elements of each line in the judgment matrix $A$ are multiplied as follows:

$$M_i = \prod_{j=1}^{n} a_{ij}, i = 1, 2, \ldots, n.$$  (3)

The result of the multiplication of elements in each line is to the nth power as follows:
5. Determination of Membership Function

5.1. Membership Function Form. In this study, the I-type function is used when risk factors are described by language. When the factors can be described by a numerical value, the triangular membership function is used. The triangular fuzzy number, which is simply denoted as \((l, u, m)\), is one of the most commonly employed fuzzy numbers \([16]\). Managers and engineers are comfortable providing estimation in terms of a most likely value and a possible range. In this respect, the triangular membership function is suitable for assessing construction risks \([20]\). The triangular membership function has been widely used in a fuzzy-AHP mode when real-life problems are evaluated, such as the selection of a landfill disposal site \([24]\) and risk assessment of geohazards in railway \([26]\).

The Karowski fuzzy membership function, as a kind of I-type function, which is widely used in assessment, is used to calculate the assignment value in the study, when risk factors are described by language, as listed in Table 7.

For factors described by the data, the triangular membership function is used to calculate the assignment value when risk factors are described by values. The function is shown as follows:

\[
\mu_{A(x)} = \begin{cases} 
0 & x < a \\
\frac{x - a}{b - a} & a \leq x < b \\
\frac{c - x}{c - b} & b \leq x < c \\
0 & c \leq x.
\end{cases}
\]

5.2. Classification of Influencing Factors. According to the general situation of tunnel engineering, influencing factors are classified into five levels.

For factors described by the data, the triangular membership function can be determined according to the upper and lower limits of each level. For factors described by language, experts can determine the value of the membership function based on the Karowski fuzzy membership function and the level of the risk factors.

The steps to classify the factors are as follows: first, the value interval of factors is determined according to the project. Second, according to the value interval of factors, the values are divided into 5 grades on an average. For example, the bias angle of the tunnel is generally lower than 40°, so the value range of the bias factor is generally taken as 0–40°. The classification of bias is based on 5 levels as follows: bias angle \(\leq 10°, 10°–20°, 20°–30°, 30°–40°, \text{ and } > 40°\). The factors, which are described by language, are divided into 5 levels based on the contribution to a tunnel collapse.
## Table 3: Average random consistency indicator RI.

<table>
<thead>
<tr>
<th>Order of A</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.52</td>
<td>0.9</td>
<td>1.12</td>
<td>1.26</td>
<td>1.36</td>
<td>1.41</td>
<td>1.46</td>
<td>1.49</td>
<td>1.52</td>
<td>1.54</td>
<td>1.56</td>
<td>1.58</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Note. Table 3 is reproduced from Li et al. [15]

## Table 4: Judgment matrix of layer A to tunnel collapse risk assessment index.

<table>
<thead>
<tr>
<th></th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
<th>A₄</th>
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<td>A₂ 1/6</td>
<td>1</td>
<td>1</td>
<td>1/2</td>
<td>1/2</td>
</tr>
<tr>
<td>A₃ 1/4</td>
<td>1/2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A₄</td>
<td>1/2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Feature vector \( W = [0.52, 0.11, 0.10, 0.26]^T \), \( \lambda_{max} = 4.15 \), CI = 0.05, CR = 0.06 < 0.1, satisfying consistency.

## Table 5: Judgment matrix of layer B to layer A.

<table>
<thead>
<tr>
<th></th>
<th>B₁₁</th>
<th>B₁₂</th>
<th>B₁₃</th>
<th>B₁₄</th>
<th>B₂₁</th>
<th>B₂₂</th>
<th>B₂₃</th>
<th>B₂₄</th>
<th>B₃₁</th>
<th>B₃₂</th>
<th>B₃₃</th>
<th>B₃₄</th>
<th>B₄₁</th>
<th>B₄₂</th>
<th>B₄₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁₁</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>B₂₁</td>
<td>1</td>
<td>7</td>
<td>B₃₁</td>
<td>1</td>
<td>5</td>
<td>B₄₁</td>
<td>1</td>
<td>1/3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>B₁₂</td>
<td>1/2</td>
<td>1</td>
<td>1/2</td>
<td>3</td>
<td>B₂₂</td>
<td>1/7</td>
<td>1</td>
<td>B₃₂</td>
<td>1/5</td>
<td>1</td>
<td>B₄₂</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>B₁₃</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B₁₄</td>
<td>1/7</td>
<td>1/3</td>
<td>1/5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Feature vector: \( W = [0.39, 0.19, 0.36, 0.06]^T \), \( \lambda_{max} = 4.96 \), CI = 0.004, CR = 0.004 < 0.1, satisfying consistency.

## Table 6: Judgment matrix of layer C to layer B.

<table>
<thead>
<tr>
<th></th>
<th>C₁₁₁</th>
<th>C₁₁₂</th>
<th>C₁₁₃</th>
<th>C₁₁₄</th>
<th>C₁₄₁</th>
<th>C₁₄₂</th>
<th>C₁₃₁</th>
<th>C₁₃₂</th>
<th>C₁₃₃</th>
<th>C₁₃₄</th>
<th>C₁₄₁</th>
<th>C₁₄₂</th>
<th>C₁₃₁</th>
<th>C₁₃₂</th>
<th>C₁₃₃</th>
<th>C₁₃₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁₁₁</td>
<td>1</td>
<td>7</td>
<td>C₁₁₃</td>
<td>1</td>
<td>1/5</td>
<td>1/7</td>
<td>C₁₄₁</td>
<td>1</td>
<td>1/4</td>
<td>C₁₃₁</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>C₃₂₁</td>
<td>1</td>
</tr>
<tr>
<td>C₁₁₂</td>
<td>1/7</td>
<td>1</td>
<td>C₁₁₃</td>
<td>5</td>
<td>1</td>
<td>1/3</td>
<td>C₁₄₂</td>
<td>4</td>
<td>1</td>
<td>C₁₃₂</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>C₃₂₂</td>
<td>5</td>
</tr>
<tr>
<td>C₁₁₃</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Feature vector: \( W = [0.88, 0.13]^T \), \( \lambda_{max} = 4.25 \), CI = 0.03, CR = 0.06 < 0.1, satisfying consistency.

## Table 7: Karwowski fuzzy membership function.

<table>
<thead>
<tr>
<th>Fuzzy language variable</th>
<th>Membership function</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>0</td>
</tr>
<tr>
<td>Medium</td>
<td>0.2</td>
</tr>
<tr>
<td>Low</td>
<td>0.7</td>
</tr>
<tr>
<td>Unknown</td>
<td>0.7</td>
</tr>
<tr>
<td>Undefined</td>
<td>0.1</td>
</tr>
<tr>
<td>More or less high</td>
<td>0.3</td>
</tr>
<tr>
<td>Very high</td>
<td>0.5</td>
</tr>
<tr>
<td>Likely</td>
<td>0.9</td>
</tr>
<tr>
<td>Unlikely</td>
<td>0.0</td>
</tr>
<tr>
<td>Not likely</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Note. Table 7 is reproduced from Zahabi and Kaber [27].
<table>
<thead>
<tr>
<th>Classification of factors</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade of surrounding rock</td>
<td>$C_{111}$</td>
<td>I, II</td>
<td>III</td>
<td>IV</td>
<td>V</td>
</tr>
<tr>
<td>Bias</td>
<td>$C_{112}$</td>
<td>$\leq 10^\circ$</td>
<td>$10^\circ$–$20^\circ$</td>
<td>$20^\circ$–$30^\circ$</td>
<td>$30^\circ$–$40^\circ$</td>
</tr>
<tr>
<td>Unfavorable geology</td>
<td>$B_{12}$</td>
<td>No fault layer</td>
<td>Small faults</td>
<td>Medium faults</td>
<td>Structural plane is developed</td>
</tr>
<tr>
<td>Scale of karst caves</td>
<td>$C_{131}$</td>
<td>No cave</td>
<td>Small</td>
<td>Medium</td>
<td>Medium-large</td>
</tr>
<tr>
<td>Location of karst caves</td>
<td>$C_{132}$</td>
<td>Bottom of tunnel</td>
<td>Bottom-side wall of tunnel</td>
<td>Side wall of tunnel</td>
<td>Side wall-arch of tunnel</td>
</tr>
<tr>
<td>Thickness of rock plate</td>
<td>$C_{133}$</td>
<td>Thick</td>
<td>Medium</td>
<td>Thin</td>
<td>Intrude into the tunnel contour partly</td>
</tr>
<tr>
<td>Groundwater</td>
<td>$C_{141}$</td>
<td>Undeveloped</td>
<td>Weak developed</td>
<td>Development</td>
<td>Abundant</td>
</tr>
<tr>
<td>Water seepage on the face</td>
<td>$C_{142}$</td>
<td>No water seepage</td>
<td>The face is wet</td>
<td>Dropwise seepage</td>
<td>Femoral seepage</td>
</tr>
<tr>
<td>Tunnel depth</td>
<td>$B_{21}$</td>
<td>$&gt; 40$ m</td>
<td>20 m–40 m</td>
<td>10 m–20 m</td>
<td>5 m–10 m</td>
</tr>
<tr>
<td>Tunnel width</td>
<td>$B_{22}$</td>
<td>$&lt; 7$ m</td>
<td>7 m–10.5 m</td>
<td>10.5 m–14 m</td>
<td>14 m–17.5 m</td>
</tr>
<tr>
<td>Excavation method</td>
<td>$C_{311}$</td>
<td>Very reasonable</td>
<td>Reasonable</td>
<td>Basically reasonable</td>
<td>Less reasonable</td>
</tr>
<tr>
<td>Advance support</td>
<td>$C_{312}$</td>
<td>Very reasonable</td>
<td>Reasonable</td>
<td>Basically reasonable</td>
<td>Less reasonable</td>
</tr>
<tr>
<td>Grouting</td>
<td>$C_{313}$</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
<td>Weak</td>
</tr>
<tr>
<td>Blasting disturbance</td>
<td>$C_{314}$</td>
<td>Negligible</td>
<td>Weak</td>
<td>Moderate</td>
<td>Large</td>
</tr>
<tr>
<td>Construction machines and equipments</td>
<td>$C_{321}$</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
<td>Insufficient</td>
</tr>
<tr>
<td>Quality of constructors</td>
<td>$C_{322}$</td>
<td>Excellent skills</td>
<td>High skills</td>
<td>Average skills</td>
<td>Lack skills</td>
</tr>
<tr>
<td>Management level</td>
<td>$C_{323}$</td>
<td>Rich experience</td>
<td>Strong experience</td>
<td>General experience</td>
<td>Lack experience</td>
</tr>
<tr>
<td>Advanced geological prediction method</td>
<td>$B_{41}$</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
<td>Weak</td>
</tr>
<tr>
<td>Reliability and analysis of data</td>
<td>$B_{42}$</td>
<td>Excellent</td>
<td>Good</td>
<td>Basically reliable</td>
<td>In doubt</td>
</tr>
<tr>
<td>Information feedback</td>
<td>$B_{43}$</td>
<td>Excellent</td>
<td>Good</td>
<td>Average</td>
<td>Weak</td>
</tr>
</tbody>
</table>
The classification of various factors is listed in Table 8. The triangular fuzzy number is defined based on the classification of factors, which could be described by a numerical method. The triangular fuzzy number is listed in Table 9.

The linguistic fuzzy number is defined based on the classification of factors. Based on the classification of each factor, the level of factor is determined. The experts, invited to assessment, could obtain fuzzy numbers based on the factor’s level and the Karwowski fuzzy membership function, as listed in Table 7.

6. Estimation and Result of Risk Probability

6.1. Estimation of Risk Probability. The fuzzy estimation is obtained by multiplying the feature vector by the membership function, as follows:

\[ B = W_i \cdot R_i = [W_{i1}, W_{i2}, ..., W_{in}] \cdot \begin{bmatrix} R_{i1} & R_{i2} & \cdots & R_{in} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{bmatrix} \]

(10)

The feature vector of the factor layer obtains from Table 4. The feature vector of the index layer obtains from Table 5. The feature vector of the subindex layer obtains from Table 6.

Factors’ value, which could be described by numerical value, is assigned by Formula (9). Other factors, which could not be described by numerical value, are classified in Table 8. The factors’ value that is assigned based on fuzzy language is listed in Table 7.

6.2. Relationship between Results and Probability. The common evaluation results are processed by the maximum value method, and the evaluation index corresponding to the maximum membership degree is taken as the risk evaluation result. The risk probability level standard divides the risk probability into five levels according to the possibility of the accident, as listed in Table 10.

7. Application

Taking the Lianhuashan tunnel in Liuzhou City as the verification engineering, the rationality of the evaluation system in the study is verified by comparing the dynamic assessment results of collapse disasters with the actual occurrence of disasters.

7.1. Engineering Overview. The left line of the Lianhuashan tunnel in Liuzhou city is 1870 meters long, and the right line is 1871 meters long. The karst cave rate of geological exploration boreholes in the Lianhuashan tunnel is 84%, and the linear karst rate is 16.7%.

The underground water in the Lianhuashan tunnel is not easy to be gathered. In the tunnel, water conditions in the site vary greatly, and the water quantity is uneven. Controlled by the development degree of cracks and connectivity, water seepage occurs differently during the tunnel excavation process.

7.2. Risk Assessment in YK3+012–YK2+982 Sections. YK3+012–YK2+982 sections with relatively dense karst caves are selected as examples to carry out a risk assessment of tunnel collapse.

7.2.1. Basic Information of Influencing Factors

(1) Engineering Geology and Hydrogeology. After updating the geological prediction results, the surrounding rock grade of YK3+012–YK2+982 sections is changed to V grade.

The lithology of the section is mainly gray-black thin-to-middle siliceous limestone, with argillaceous limestone in some parts. Affected by the rock joint cutting, the rock mass is relatively broken, the joint fissures are relatively developed, the rock mass is fragmentary structure, and the stability of surrounding rock is poor.

The karst in the survey section is relatively developed, and sometimes the filling cavity or karst fissures are developed, among which, around YK2+996–YK2+991 and YK2+986, the rock mass is broken and weak. The groundwater in the survey section is weakly developed, and the main form of water outflow is seepage, with a local point exposed. The sketch of the position of karst caves tunnels is shown in Figure 4.

(2) Construction and Management

(i) Construction Factors

(a) The double side wall heading method is adopted for construction, in which the side wall is excavated by the upper and lower steps method, and the central part is excavated by three steps. The longitudinal spacing of the side wall is...
controlled between 8 m and 12 m, and the excavation and support cycle footage of each step is controlled between 0.6 m and 0.8 m. The initial support must fall to the bottom in time and be closed to form a ring. The distance between the closed ring and the face of the tunnel should not be more than 15 m. The inverted arch must be poured as a whole instead of in sections. The secondary lining shall be poured in time. The distance from a tunnel face to a secondary lining shall not be more than 40 m. The secondary lining shall be poured as a whole, and the pouring shall not be interrupted.

(b) The advance support adopts the self-advancing bolt with a diameter of φ5, the length of each bolt is 9 m, and the lap length is not less than 3 m. During the construction, it is necessary to close the initial support into a ring timely, use C15 rubble concrete or C20 concrete to replace the inverted soft base, and combine it with the grouting reinforcement of φ 70 steel pipes.

(c) The advance small pipe and self-advancing anchor must be used to reinforce the surrounding rock by grouting according to the design requirements.

(d) It is strictly forbidden to carry out a blasting operation in each heading at the same time, so as to prevent the superposition of breaking wave peak value. The blasting dynamic peak acceleration shall not be greater than 15 cm/s.

After experts’ discussion, the rationality of excavation method is determined to level II. A grouting factor is determined to level I. Blasting disturbance is determined to level I. In order to ensure the safety, it is suggested to use the more conservative level II in the risk assessment.

(ii) Management Factors

(a) Mainly new and good equipment, some construction machinery and equipment are newly purchased, and the quantity is sufficient and the surplus is sufficient.

(b) According to the technical characteristics of the project, the positions and human resources are allocated to ensure that the workers are skilled in one subject and multifunctional, and the special operators work with certificates.

After experts’ discussion, the construction equipment are determined to level I, but in order to ensure safety, it is recommended to calculate by the conservative level II in the risk assessment; the quality of constructors is determined to level II, and the management level is determined to level II.

(3) Dynamic Monitoring and Forecasting Technology. During the construction, the whole process of advanced geological prediction and continuous surrounding rock measurement are carried out. During the construction, all tunnels adopt the full-section geological sketch; after the excavation, the whole tunnel carries on the uninterrupted surrounding rock measurement work and grasps the surrounding rock change information after the excavation in time. The advanced geological prediction method mainly includes the following steps: ① the geological sketch is carried out in time with the tunnel excavation, then the sketch is carried out once for each excavation cycle in complex and key sections, and the sketch interval in general sections is not more than 10 m. ② TSP is carried out (can be replaced by other seismic
reflected, reflection methods). Geological radar is mainly suitable for karst detection. The range of one prediction is not more than 30 m. The effective detection length in a karst development area is judged according to the radar waveform, and the overlapping length of two times is not less than 5 m. Advanced geological drilling is carried out.

The sketch of the monitoring and geological prediction is shown in Figure 5.

After experts’ discussion, the advanced geological prediction level is determined to level II, and the reliability of monitoring and measuring data is determined to level I, but in order to ensure the safety risk assessment, it is suggested to use the more conservative level II for calculation. The information feedback is determined to level I, but it is suggested to select the more conservative level II for calculation in the risk assessment.

Factor grading in YK3 + 012–YK2 + 982 sections is listed in Table 11.

The Karwowski fuzzy membership function is used to calculate the assignment value in Table 7, when risk assessment factors are described by language. The triangular membership function is used to assign the factors, which can be described by a numerical value.

### Table 11: Factor grading in YK3 + 012–YK2 + 982 sections.

<table>
<thead>
<tr>
<th>Layer A</th>
<th>Layer B</th>
<th>Layer C</th>
<th>Factor grading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering geology and hydrogeology</td>
<td>Geology, topography, and geomorphology</td>
<td>Grade of surrounding rock C_{111}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bias effect C_{112}</td>
<td></td>
</tr>
<tr>
<td>A_1</td>
<td></td>
<td>Scale of karst caves C_{131}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Location of karst caves C_{132}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness of rock plate C_{133}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Karst caves B_{13}</td>
<td>The development of groundwater C_{141}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The impact of water B_{14}</td>
<td>Water seepage on the face C_{142}</td>
<td></td>
</tr>
<tr>
<td>Tunnel design</td>
<td>Tunnel span B_{21}</td>
<td>Excavation method C_{311}</td>
<td></td>
</tr>
<tr>
<td>A_2</td>
<td>Tunnel depth B_{22}</td>
<td>Advance support C_{312}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction B_{31}</td>
<td>Grouting effect C_{313}</td>
<td></td>
</tr>
<tr>
<td>Construction and management</td>
<td></td>
<td>Blasting disturbance C_{314}</td>
<td></td>
</tr>
<tr>
<td>A_3</td>
<td></td>
<td>Construction equipments C_{321}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Management B_{32}</td>
<td>Quality of constructors C_{322}</td>
<td></td>
</tr>
<tr>
<td>Dynamic monitoring and forecasting technology</td>
<td>Advanced geological prediction B_{41}</td>
<td>Management level C_{323}</td>
<td></td>
</tr>
<tr>
<td>A_4</td>
<td>Reliability of monitoring and measuring data</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Information feedback B_{43}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Longitudinal range (Advanced geological drilling)

Longitudinal range (TSP)

Longitudinal range=30 m (Ground penetrating radar)

Longitudinal range=100 m (TSP)

Figure 5: Sketch of the monitoring and geological prediction.
7.2.2. Risk Assessment. The risk assessment results of tunnel collapse probability are obtained by calculation, and the normalized results are listed in Table 12. According to the calculation, the possibility of tunnel collapse in this mileage section is impossible, but the result is biased to the probability of casual. Therefore, attention should be paid during the construction. Advanced detection was strengthened in the construction process. Compared with the construction suggestions and the model calculation results, it can be seen that the construction suggestions are consistent with the calculation results.

### Table 12: Probability of tunnel collapse (YK3 + 012–YK2 + 982).

<table>
<thead>
<tr>
<th>Fuzzy estimation results of YK3 + 012–YK2 + 982</th>
<th>Very unlikely</th>
<th>Impossible</th>
<th>Casual</th>
<th>Could happen</th>
<th>Likely to happen</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.181</td>
<td>0.217</td>
<td>0.214</td>
<td>0.204</td>
<td>0.183</td>
<td>0.181</td>
</tr>
</tbody>
</table>

### Table 13: Probability of tunnel collapse (several sections).

<table>
<thead>
<tr>
<th>Sections</th>
<th>Fuzzy estimation results</th>
<th>Probability</th>
<th>Tunnel collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZK1 + 358</td>
<td>0.135 0.201 0.204 0.223</td>
<td>Likely to happen</td>
<td>There is a large collapse in the vault, forming a collapse cavity</td>
</tr>
<tr>
<td>ZK3 + 070</td>
<td>0.141 0.205 0.213 0.235</td>
<td>Could happen</td>
<td>The soil at the arch of the tunnel face collapsed</td>
</tr>
<tr>
<td>YK3 + 074</td>
<td>0.159 0.210 0.203 0.223</td>
<td>Could happen</td>
<td>The soil mass on the upper right side of the arch of the tunnel face collapsed</td>
</tr>
</tbody>
</table>

**Figure 6:** The large collapse in the vault (ZK1 + 358).

**Figure 7:** The collapse on the tunnel face (ZK3 + 070).

**Figure 8:** The collapse on the tunnel face (YK3 + 074).
and a dynamic risk assessment is established to enhance the accuracy of evaluation and compensate for the fact that existing assessments are mainly static. In the assessment, a new questionnaire is designed to eliminate inconsistency existing in the traditional F-AHP method. The major conclusions are summarized as follows:

(1) The dynamic factors, static factors, internal factors, and external factors are considered comprehensively, by advanced geological prediction, collapse investigations, and theoretical analysis. Dynamic factors are classified as the rationality of selection of advanced geological prediction method, reliability of data, the accuracy of data analysis, and timeliness and effectiveness of forecast information transmission. Karst cave characteristic factors are composed of cave scales, locations, and thickness of rock plate to strengthen the character of karst area.

(2) A new questionnaire is designed to express the relative importance of assessment factors by combining the Saaty scale method and designed three-scale method. The judgment matrix by the new questionnaire can

---

### Table 14: New questionnaire for dynamic risk assessment of karst tunnel collapse (layer 1).

<table>
<thead>
<tr>
<th>Expert’s professional title</th>
<th>Senior titles</th>
<th>Intermediate titles</th>
<th>Junior titles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration rule</td>
<td>Please use Saaty relative scale method for scoring</td>
<td>Quantitative results of relative importance between factor 1 to factor 1</td>
<td></td>
</tr>
<tr>
<td>Calibration meaning</td>
<td>Same importance</td>
<td>a_{ij} = 1</td>
<td>Same importance</td>
</tr>
<tr>
<td>a_{ij} = 3</td>
<td>Slightly more importance</td>
<td>a_{ij} = 1/3</td>
<td>Slightly less importance</td>
</tr>
<tr>
<td>a_{ij} = 5</td>
<td>Significantly more importance</td>
<td>a_{ij} = 1/5</td>
<td>Significantly less importance</td>
</tr>
<tr>
<td>a_{ij} = 7</td>
<td>Intensively more importance</td>
<td>a_{ij} = 1/7</td>
<td>Intensively less importance</td>
</tr>
<tr>
<td>a_{ij} = 9</td>
<td>Extremely more importance</td>
<td>a_{ij} = 1/9</td>
<td>Extremely less importance</td>
</tr>
<tr>
<td>a_{ij} = 2, 4, 6, 8</td>
<td>Represents the median value of the adjacent judgment</td>
<td>a_{ij} = 1/2, 1/4, 1/6, and 1/8</td>
<td>Represents the median value of the adjacent judgment</td>
</tr>
</tbody>
</table>

### Table 15: Summary of experts’ backgrounds in the questionnaire.

<table>
<thead>
<tr>
<th>Experts’ number</th>
<th>Professional title</th>
<th>Occupation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Senior Researcher</td>
<td>Researcher</td>
<td>Research institute</td>
</tr>
<tr>
<td>2</td>
<td>Senior Researcher</td>
<td>Researcher</td>
<td>University</td>
</tr>
<tr>
<td>3</td>
<td>Senior Tunnel designer</td>
<td>Tunnel designer</td>
<td>Design institute</td>
</tr>
<tr>
<td>4</td>
<td>Senior Tunnel designer</td>
<td>Tunnel designer</td>
<td>Research institute</td>
</tr>
<tr>
<td>5</td>
<td>Intermediate Researcher</td>
<td>Tunnel designer</td>
<td>University</td>
</tr>
<tr>
<td>6</td>
<td>Intermediate Tunnel designer</td>
<td>Tunnel designer</td>
<td>Research institute</td>
</tr>
<tr>
<td>7</td>
<td>Intermediate Tunnel designer</td>
<td>Tunnel designer</td>
<td>Design institute</td>
</tr>
<tr>
<td>8</td>
<td>Intermediate Constructor</td>
<td>Constructor</td>
<td>Construction unit</td>
</tr>
<tr>
<td>9</td>
<td>Primary Constructor</td>
<td>Constructor</td>
<td>Construction unit</td>
</tr>
<tr>
<td>10</td>
<td>Primary Constructor</td>
<td>Constructor</td>
<td>Construction unit</td>
</tr>
</tbody>
</table>
satisfy the consistency requirement. The traditional F-AHP method cannot satisfy the requirement.

(3) The dynamic risk assessment is carried out on different samples in the Lianhuashan tunnel. By comparing the dynamic assessment results with the occurrence of disasters, the rationality of the assessment is verified.

The study introduces a dynamic risk assessment of karst tunnel collapse. Dynamic factors in the study focus on dynamic feedback, such as geological forecast results. With advances in engineering, more type of dynamic feedback will increase and will be considered.

Appendix

A. New Consulting Questionnaire

Table 14 lists the new questionnaire. The table in the new questionnaire includes many factors in the same layer. The expert’s professional title should be selected in the questionnaire. The feedback of each expert will be weighted based on a professional title.

B. Background of the Invited Experts

Table 15 lists the summary of experts’ backgrounds, invited to the study. The background includes experts’ professional title, occupation, and unit.

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 they have no conflicts of interest.

References


