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SAFETY ASSESSMENT OF TUNNEL LINING STRUCTURE WITH UNDERLYING CAVITIES BASED ON FUZZY COMPREHENSIVE EVALUATION IN MUDSTONE STRATUM

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ABSTRACT
This paper presents a study on the structural safety assessment of tunnel linings with underlying cavities based on a fuzzy comprehensive evaluation model in mudstone stratum. The weight and membership degree are determined using an improved method: field data analysis and numerical simulation. Field data analysis revealed that the proportion of cavities in the surrounding rocks of class IV and at the vault was the largest. Cavity length between 1m and 3m and cavity depth between 20cm and 40cm occupied the most significant proportion. Additionally, the impact of defect parameter changes on structural safety was investigated through numerical simulation. It is well known that the lining safety factors are greatly impacted by changes in surrounding rock classifications, cavity locations and depths. In contrast, changes in cavity lengths do not significantly affect the lining safety. The developed fuzzy comprehensive evaluation model consists of factor set, comment set, membership degree and weight set. They are determined according to the previous field data analysis and numerical analysis results. The developed evaluation model is validated by means of the numerical simulation based on the evaluation work of the specific engineering case.
Keywords : *Fuzzy Comprehensive Evaluation, Underlying Cavity, Field Data Analysis, Numerical Analysis*

1. Introduction

Tunnels have been increasingly used in railway engineering globally and especially in China due to the rapid rise of transportation infrastructure construction. There were 17,873 railway tunnels with a distance of 21,978km in operation in China by the end of 2022 (Gong et al., 2023). Tunnels play an important role in improving transportation networks, shortening operating distances, and increasing transportation capacity. With the rising number of tunnels, it is necessary to ensure tunnel maintenance is proportionate to its operational lifetime.

Tunnel distress has recently been examined in China, and lining defects, especially underlying cavities, are common in the tunnel lining (Liu et al., 2020; Zhao et al.,2019; Ye et al., 2021). The underlying cavity refers to the concrete lining and the surrounding rock are not in close contact, and there are gaps between the lining and the surrounding rocks. Lai et al. (2017) performed overall detection and examined underlying cavities in the Shitigou Tunnel. These cavity defects directly reduced the bearing capacity of the lining structure, resulting in cracks on the lining surface. Repairing voids and cracks requires significant maintenance costs and has an impact on economic productivity. Li and Wang (2017) reported that underlying cavities caused the concrete lining to peel off blocks in the Goujiagou Tunnel. These stripped concrete blocks hit the operating train and caused operational accidents, necessitating the closure of the tunnels for repairs. This adversely affects the tunnel safety and transportation efficiency. The accident caused by underlying cavity distress had a detrimental impact on the tunnel structure, which could jeopardize the safety of operational tunnels. Safety incidents in tunnel structures can cause interruption of train operations, leading to disruption of the transportation network. Furthermore, inadequate trade routes may result in goods needed by the public not being delivered in a timely manner, causing public safety incidents. Therefore, precautions should be taken to avoid operation accidents.

Regarding tunnels with cavities underneath the lining, it is essential to formulate systematic safety evaluation methods of tunnel lining structures and look into the crucial parts for maintenance of tunnel distress. By evaluating the existing condition of lining structures for safety and health concerns, the structural safety evaluation seeks to establish the structure's safety performance level. This evaluation acts as a guide for upcoming maintenance choices. However, structural safety evaluation is not conducted for lining distress in some tunnels, and maintenance is conducted based on subjective judgment (Zhang, Shi et al. 2017). Furthermore, structural safety evaluation is conducted, but the result is inaccurate; i.e., the tunnel distress was evaluated as minor, however, it was actually severe (Zhou 2018; An et al. 2020; Yan et al. 2021). The inaccurate evaluation resulted in severe consequences (Zhou 2018). Therefore, it is essential to carry out in-depth research on the structural safety evaluation and to propose an efficient evaluation method.

Research Gap

According to the current research (Xu et al. 2019; Zhang, Chen et al. 2020; Yan et al. 2021) regarding the structural safety evaluation of tunnel linings with underlying cavity distress, research gap exists in the following two aspects: (1) The safety evaluation methods are complex and laborious, and are difficult to be applied in engineering practice. (2) The safety evaluation methods are not suitable for the actual conditions of tunnel linings with underlying cavities, leading to inaccurate assessment results. Therefore, it is necessary to propose a more systematic and accurate evaluation method to guide maintenance decisions and mitigate safety risks.

Research Objectives

The main focus of this research is proposing a systematic and accurate safety evaluation method for tunnel linings with underlying cavities. The objectives of this work are: (1) To develop the fuzzy comprehensive evaluation model for tunnel linings with underlying cavities; (2) To determine the weight set and membership degree of the developed model based on the quantitative analysis of collected cavity data. This proposed evaluation method, based on the field collected defect data, will have good applicability to real-world engineering scenarios.

Research Hypothesis

This research is conducted based on the collected cavity data from tunnels excavated in mudstone stratum. The hypotheses developed in this work are: (1) The fuzzy comprehensive evaluation model is developed based on the mudstone stratum; (2) The evolutionary process of cavities over time is not taken into account when developing the evaluation model.

2. Literature Review

In recent years, there have been several methods to evaluate the safety of lining structures. Firstly, the numerical method has been used in the safety evaluation of lining with distress (Liu et al. 2020; Yan et al. 2021; Han et al. 2021). Zhang, Zhang et al. (2017) studied the mechanical performance of tunnel structures with defects through numerical simulation. Zhang, Ye et al. (2019) conducted numerical simulation to study the effect of cavities on the safety of the tunnel lining structure, and revealed that cavities underneath the lining in the vault have more adverse effects on the lining structure than those in the sidewalls. Han et al. (2021) developed a three-dimensional numerical model to evaluate the lining structure safety and revealed that underlying cavities affected the bearing capacity and stability of the tunnel structure.

Moreover, structural safety can be studied utilizing experimental tests. The experimental test was performed to investigate the structural safety of a double-arch tunnel. The structural design of the middle wall needed to be thoroughly examined and optimized based on the experimental results (Li et al., 2016). Min et al. (2018) investigated the effect of cavity size on tunnel structural safety by means of experimental tests. Although experimental tests provide a comprehensive view of the mechanical properties of the tunnel structure to the researcher (Zhang, Liu et al., 2019), they are time-consuming and laborious. Thus, researchers developed other evaluation techniques to assess the safety performance of tunnel structures.

The Analytic Hierarchy Process method has been used to conduct the structural safety evaluation of tunnel linings (Wang et al. 2015; Xu et al. 2019; Qiu et al. 2020). Xu et al. (2019) used this method to evaluate the health state of the Honggu Tunnel under construction. Qiu et al. (2020) developed a sustainable evaluation system to assess the safety performance of railway tunnels based on the Analytic Hierarchy Process Method. Furthermore, the structural safety of the tunnel lining was evaluated using the Artificial Neural Network model (Zhang, Nguyen et al. 2020). The Bayesian Network model was also used to evaluate the probability of structural failure of drill-and-blast tunnels (Zhang, Chen et al. 2020).

The fuzzy comprehensive evaluation method is also used to evaluate the safety of tunnel structures recently (Wang et al. 2015; Rao et al. 2015; Li et al. 2021). Based on the idea of subsection evaluation, the fuzzy comprehensive evaluation model was used to obtain the safety level of tunnel in operation (Hou et al.,2015). Factors such as concrete lining strength, cracking, water seepage, and mechanical and electrical installations were addressed in this evaluation model. Hu et al. (2018) developed a two-level fuzzy comprehensive evaluation method to assess the structural safety of the tunnel lining with cracks, cavities, insufficient strength and water leakage. Maintenance measures were proposed based on the evaluation results by using this model. Li et al. (2021) developed a five-level safety evaluation model based on the fuzzy mathematics theory to determine the health state of the gas pipeline tunnel. Existing studies lack the safety assessment specifically for tunnel linings with underlying cavities in mudstone formation. Therefore, this raises the necessity of conducting research on the fuzzy comprehensive evaluation of tunnel linings with underlying cavities in mudstone stratum.

The methodological advantages and limitations are discussed through the comparative analysis of different methods, as shown in Table 1. The comparative analysis includes factors such as accuracy of evaluation results, efficiency of evaluation process, ease of implementation, and applicability to real-world engineering scenarios. Although the numerical simulation approach can provide accurate results, it involves complex modeling and calculations. The experimental test method can also provide accurate results, but it is time-consuming and laborious (Min et al. 2018), leading to its poor applicability to real-world engineering scenarios. The Analytic Hierarchy Process approach, on the other hand, is straightforward and convenient but necessitates accurate weight calculation (Fattahi et al. 2014). Moreover, if the weights cannot be calculated accurately, inaccurate results will be acquired through this method. In contrast, the Artificial Neural Network method and Bayesian Network model are intricate and less convenient for engineering applications. The evaluation process of these two methods involves parameters that are difficult to define. Notably, the fuzzy comprehensive evaluation method is characterized by accuracy, efficiency, ease of implementation and applicability to engineering scenarios; nonetheless, it requires careful consideration when deciding on membership degree and weight.

Table 1 – Advantages And Limitations Of Existing Evaluation Methods

Item	Accuracy of evaluation results	Efficiency of evaluation process	Ease of implementation	Applicability to real-world engineering scenarios
Numerical simulation	Accurate results	Complex modeling and calculations	Not easy to implement	Good applicability
Experimental tests	Accurate results	Time-consuming and laborious	Not easy to implement	Poor applicability
Analytic Hierarchy Process method	Inaccurate results	Complex process of calculating weights accurately	Easy to implement	Good applicability
Artificial Neural Network method and Bayesian Network	Inaccurate results	The evaluation process involves parameters that are difficult to define.	Not easy to implement	Poor applicability

method

Determining membership degree and weight are two challenges of the fuzzy comprehensive evaluation approach (Rao et al. 2015). First off, the expert scoring method (Aliahmadi et al. 2011; Hu et al. 2018) was used to determine the weight. The weight determination in these methods is primarily subjective, and the evaluation findings are heavily influenced by the assessors. Secondly, the membership degree was determined by using the existing membership function (Chen and Zhang, 2015; Xu et al. 2019). The existing membership function is not necessarily in line with the engineering practice, which is a drawback of this method. The membership degree could also be determined through the questionnaire evaluation of experts (Wang et al. 2015). The accuracy of this method is greatly affected by the subjective judgments of experts. Hence, the determination of these two aspects needs in-depth research.

Research gap of the fuzzy comprehensive evaluation method exists in two aspects. Firstly, the existing determination methods of membership degree and weight are mostly subjective, and the assessors have a significant influence on the evaluation results. Secondly, the existing fuzzy comprehensive evaluation model does not conform to the tunnel engineering practice with underlying cavities, and does not have good engineering applicability. These knowledge gaps emphasize the significance of proposing an accurate and improved evaluation method in which membership degree and weight is determined based on actual engineering data.

This work aims to propose the improved fuzzy comprehensive evaluation method to evaluate the structural safety of lining with underlying cavities in tunnels. The investigation of cavities underneath the tunnel lining was conducted using non-destructive detection in the Suiyu Railway. Immediately following the defect data collection, quantitative analyses were conducted including: proportion analysis, relationship analysis, and numerical simulation. The weight and membership degree are determined by the quantitative analysis based on the field collected data. Then, the structural safety evaluation model is developed. Lastly, the developed evaluation model is validated based on an engineering case.

3. Research Methods

3.1 Workflow of Structural Safety Evaluation

Structural safety of tunnel linings with underlying cavities is evaluated using the Fuzzy Comprehensive Evaluation Method. The core idea of this method is first to determine the evaluation objectives, then analyze the influencing factors, quantitatively assign different factors and determine their weights, and finally conduct the evaluation process and obtain the evaluation results (Chen et al., 2018).

The workflow of fuzzy comprehensive evaluation can be divided into five steps, shown in Figure 1. Step 1 to Step 2 is to determine the factor set and comment set, preparing for the evaluation. The factor set refers to the factors that affect the safety evaluation result of the tunnel lining. The comment set refers to the grading of the evaluation results of the structural safety state. Then, Step 3 to Step 4 is to determine the weight set and membership degree. The weight set includes the weight of each factor in the evaluation process. The membership degree provides the likelihood that a factor causes a certain safety evaluation level. The impact of individual factors alone on the evaluation results is taken into account in Step 4. Next, Step 5 is to conduct the fuzzy evaluation and obtain the evaluation result. The impact of various factors on the evaluation results is synthesized in this step.

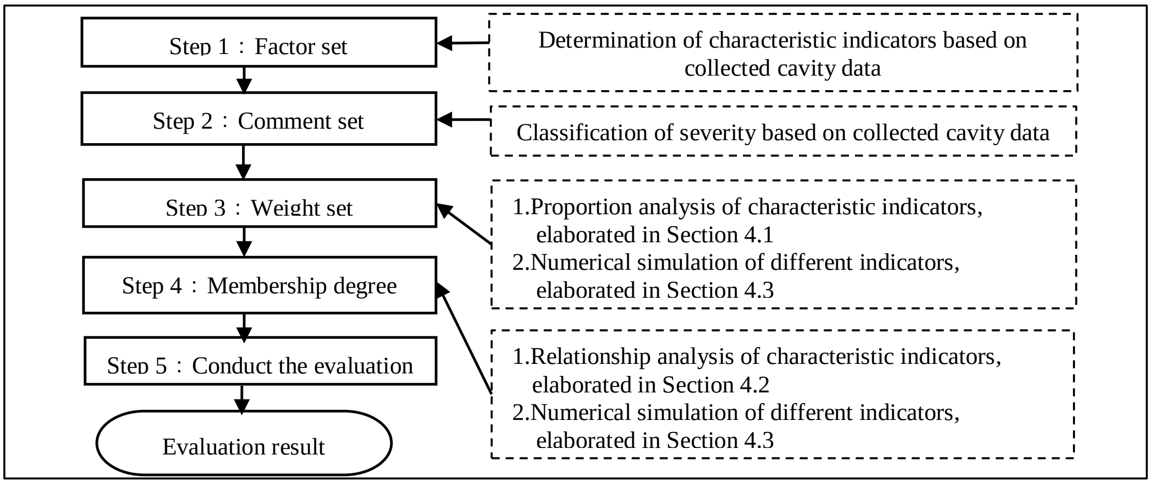

Fig. 1. Workflow Of Fuzzy Comprehensive Evaluation

Collecting the field cavity data lays the foundation for Step 1 and Step 2. The factor set is determined according to the characteristic indicators of defects, including surrounding rock classification, length, location and depth of underlying cavities. The comment set is determined by the classification of defect severity, namely: most serious, more serious, serious, slight. Step 3 and step 4 are the two critical steps of this evaluation process. The weight set is determined according to the proportion analysis and numerical simulation of different characteristic indicators based on the collected defect data. In contrast, the membership degree is determined according to the relationship analysis and numerical simulation of different characteristic indicators. Proportion analysis is done to obtain the percentage of cavities for each characterization indicator. The purpose of the relationship analysis is to capture the quantitative relationship between each indicator. The degree of influence of each indicator on the evaluation results can be obtained by numerical simulation. Based on the previous preparations (i.e., Setp1 to Step4), the structural safety evaluation is conducted, and the evaluation result is obtained.

3.2 Method of Cavity Data Collection

This research focuses on the case study of the Suiyu Railway, which is located in southwest China. There are 41 tunnels on this railway, and the design speed is 200km/h. The tunnels with composite lining were constructed by drilling and blasting methods. The geological structure of these tunnels primarily consists of gently inclined medium-thin mudstone interspersed with sandstone. The support structure of tunnels consisted of the initial support and secondary lining. The inner contour of the tunnel lining was 810cm high and 773cm wide, as shown in Figure 2. The surrounding rocks of tunnels on the Suiyu Railway was divided into Class II, Class III, Class IV, and Class V, which represent the classification based on the geologic characteristics of the surrounding rocks (China Railway Eryuan Engineering Group Co. Ltd., 2016). From Class II to Class V, the surrounding rock becomes weaker in turn, so the thickness of the lining structure was designed as 30cm, 35cm, 40cm, and 45cm, respectively.

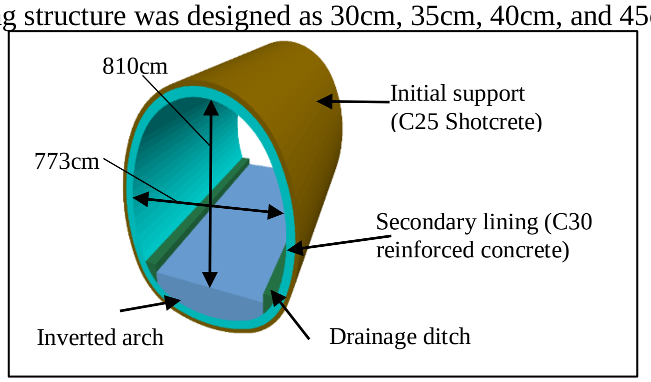

Fig. 2. Tunnel Lining Structure

The investigation of tunnel lining defects was conducted using non-destructive detection methods. The arrangement of survey lines is illustrated in Figure 3, encompassing five survey lines: the vault line, the left side of the vault line, the right side of the vault line, the left arch waist line, and the right arch waist line. After the completion of defect detection, a total of four hundred and forty-three instances of cavities underneath the lining were identified.

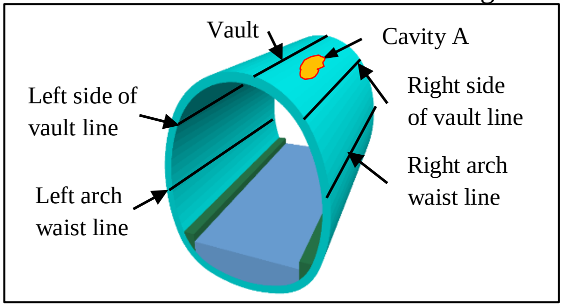

Fig. 3. Arrangement Of Survey Lines

The fuzzy comprehensive evaluation model is developed based on collected field defect data from non-destructive detection. The non-destructive detection method has two limitations: (1) it cannot detect cavities (namely Cavity A, as shown in Fig.3) that are not at the location of the survey line; and (2) the survey line needs to be encrypted in order to accurately capture all of the cavities, resulting in an increase in the cost and time of the detection work. These two limitations in data collection may have implications for the developing of the safety evaluation model. Encrypting survey lines and collecting large amounts of data for analysis are ways to attenuate this effect.

3.3 Validation Process of the Developed Evaluation Model

The validation of the developed model was implemented in two ways. Firstly, the evaluation model was applied to the assessment of cavity defects in the Songlinbao Tunnel. Maintenance measures were determined based on the evaluation results. The accuracy and applicability of the developed evaluation model is judged based on the non-destructive detection results after maintenance. Secondly, numerical simulation is carried out to solve the lining safety factor based on the actual engineering situation of the Songlinbao Tunnel. The accuracy of the evaluation results of the developed model is verified based on the correspondence between the safety factor and the safety level in the existing research results (Wang et al., 2015). The validation process of the developed evaluation model would strengthen the robustness of the study's findings.

4. Quantitative Analysis of Collected Cavity Data

Quantitative analysis, which includes relationship analysis, proportion analysis, and numerical simulation, is carried out following the defect data collection. The quantitative analysis results prepare for developing the structural safety evaluation model.

Since the cavity is an irregular three-dimensional geometry, the following assumptions for the cavity dimensions are made in the quantitative analysis. (1) The cavity length in the analysis process refers to the length along the direction of the survey line. (2) The cavity depth in the analysis refers to the maximum depth of the cavity.

4.1 Proportion Analysis

Considering the different characteristic indicators, the percentage of underlying cavities is shown in Figure 4, which presents the results of the proportion analysis. The chart provides information about various defect lengths related to underlying cavities. The largest percentage of defects, accounting for 43.79%, falls within the range of 1m to 3m. The next most common type of cavities, at 32.51%, occurs within the range of 3m to 5m. Furthermore, 19.41% of cavities are found in the shortest length category, ranging from 0 to 1m. Another 4.29% of cavities are categorized as length greater than 5 meters. Based on the proportion analysis of cavity length, it can be concluded that most defect lengths fall within the medium range.

The figure also provides information on the proportion of surrounding rock classifications associated with cavities underneath the lining. The highest percentage, 52.82%, is observed in tunnel linings with surrounding rock classified as Class IV. The next most common type of surrounding rock, Class V, accounts for 29.57%. Furthermore, cavities are present underneath

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tunnel linings with Class III surrounding rock, representing 12.87% of the total defects in this category. A further 4.74 percent belong to the surrounding rock of Class II.

Next, the chart provides a breakdown of underlying cavities occurring at various locations. The most prominent percentage, accounting for 65.24% of the total, is found at the vault. Following closely behind, the left and right sides of the vault exhibit similar frequencies of insufficient thickness, comprising 16.25% on the left, and 15.58% on the right, respectively. The arch waist represents a less common location for cavities, with 1.58% of defects occurring on the left and 1.35% on the right.

Finally, the figure illustrates the distribution of cavity depths. The predominant range of cavity depth falls between 20cm and 40cm, constituting 48.76% of the total. Following closely, cavity depth ranging from 40cm to 60cm make up the next significant proportion at 37.70%. The cavity depth of less than 20cm represents 11.51%, indicating a relatively smaller depth of cavities beneath the tunnel lining. A minor proportion, amounting to 2.03%, is associated with the cavity depth greater than 60cm. Thus, the most substantial proportion of cavity depths falls within the range of 20cm to 40cm.

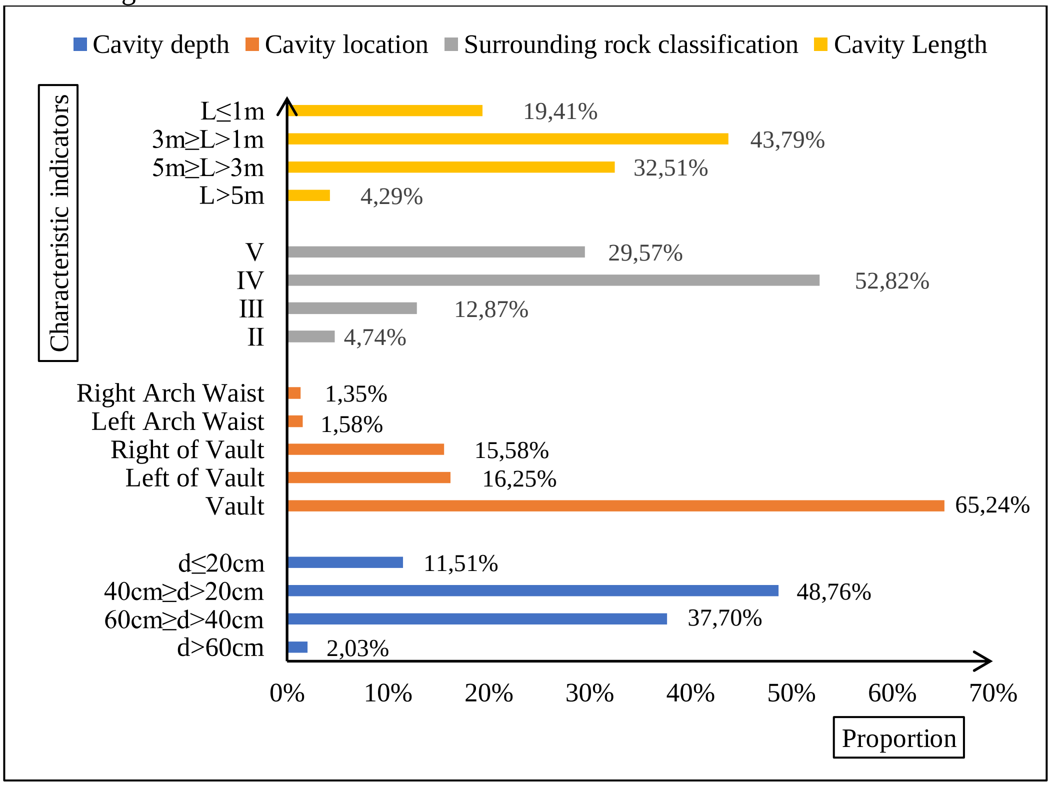

Fig. 4. Proportion of Cavities Based on Different Characteristic Indicators

4.2 Relationship Analysis

a. Relationship between Surrounding Rock Classification and Cavity Depth

The relationship between surrounding rock classification and cavity depth is shown in Figure 5. The inner circle shows the proportion of different rock classifications. The number of underlying cavities in class IV (indicated in grey colour) is the largest, as this part occupies the largest area in the inner circle. The outer circle presents the proportion of cavities with different depths at a specific surrounding rock classification. In all the surrounding rock classifications, a depth between 20cm and 40cm ("C" in Figure 5) is the most considerable proportion interval, with the proportion of 42.9 percent in class II, 47.4% in class III, 52.6% in class IV, and 43.5% in class V.

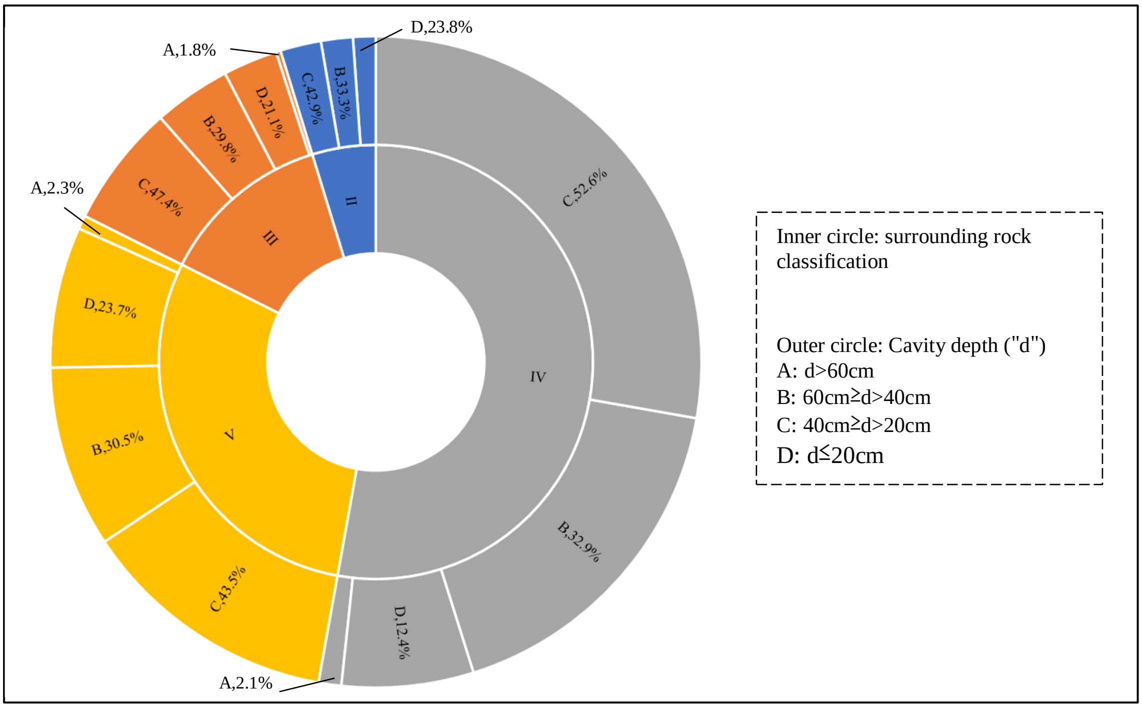

Fig. 5. Relationship Between Surrounding Rock Classification And Cavity Depth

b. Relationship between Cavity Length and Cavity Depth

The relationship between the length and depth of cavities is shown in Figure 6. The inner circle shows different length intervals. Cavities with lengths of 1~3m (indicated in grey colour) occupies a relatively large proportion. The outer circle presents the proportion of cavities with different depths at a specific length interval. The depth between 20cm and 40cm ("C" in Figure 6) is the most significant proportion interval in all the length intervals. Using the defect length group 1~3m as an illustration, a depth of between 20 and 40 cm makes up the majority, namely 56.2%. The next largest type is the depth of 40~60cm, with a proportion of 23.2 percent. Then, 17 percent of cavities exist in the depth less than 20cm. A further 3.6 percent belongs to the depth greater than 60cm.

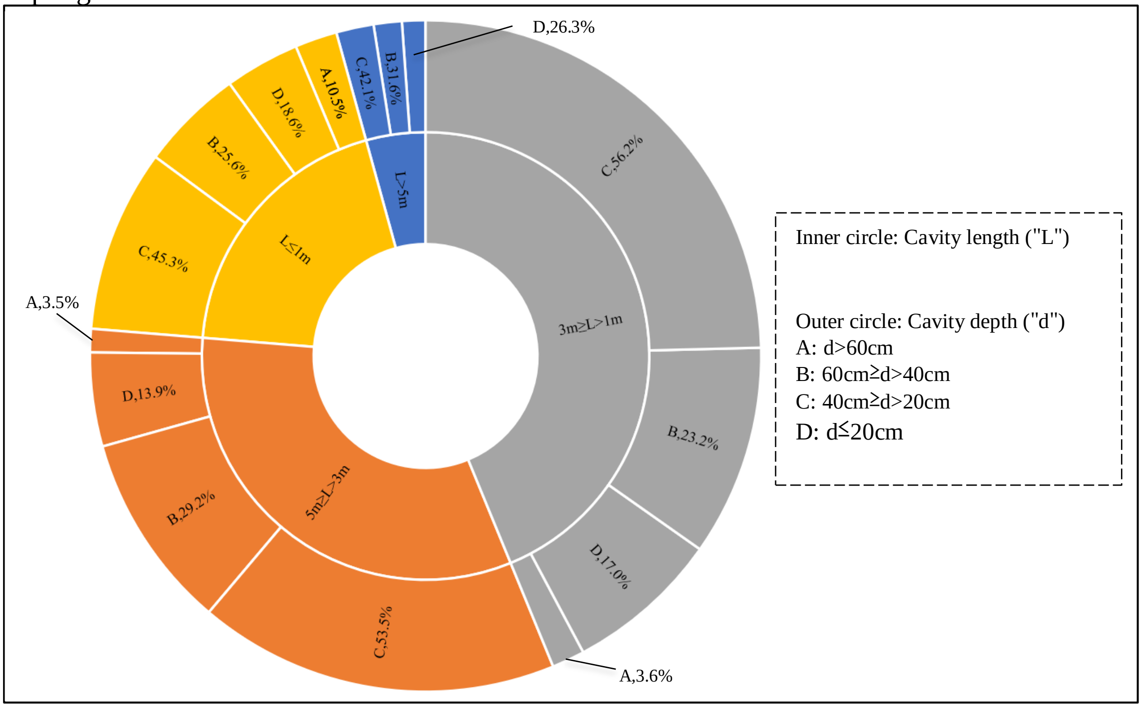

Fig. 6. Relationship Between Cavity Length And Depth

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c. Relationship between Cavity Location and Cavity Depth

The relationship between the location and depth of cavities is shown in Figure 7. The inner circle shows the locations of cavities, and the vault (indicated in blue colour) is the most popular location of cavities. The outer circle presents the proportion of cavities with different depths at a specific defect location. In all the locations, the depth between 20cm and 40cm ("C" in Figure 7) is the largest proportion interval, with a proportion of 48.8 percent for cavities in the vault, 50.4% at the left or right of the vault, and 53.8% at the arch waist.

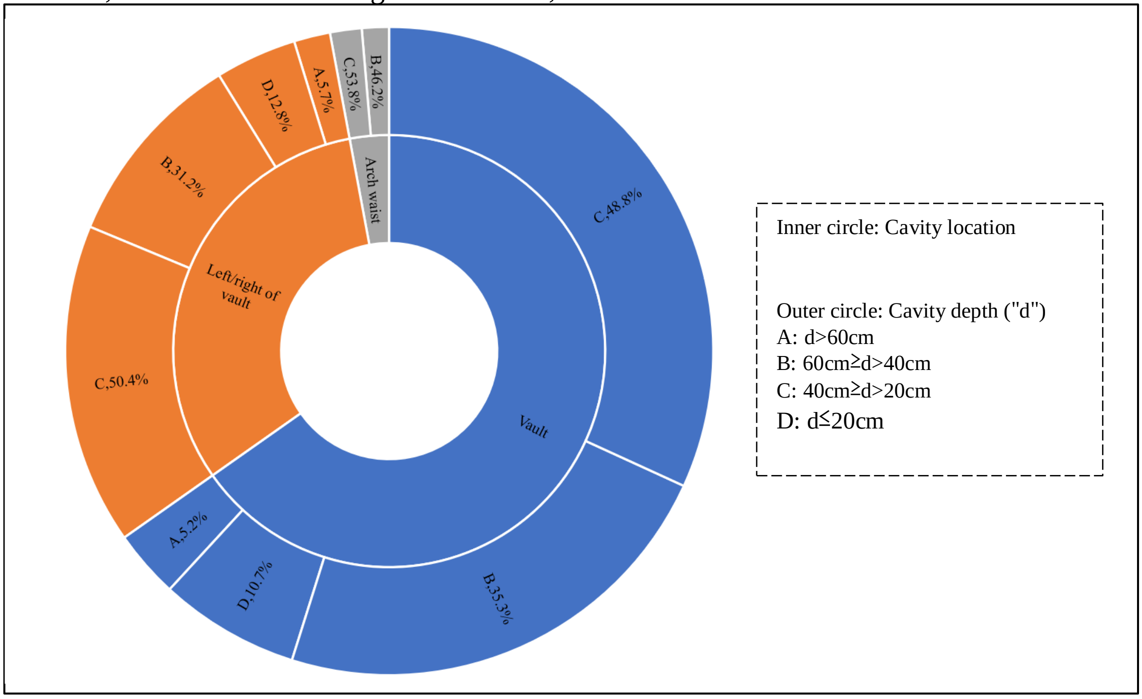


Fig. 7. Relationship Between Cavity Location And Depth

Although the quantitative analyses provide a detailed understanding of the distributional characteristics of underlying cavities, the analyses have the following limitations: (1) the cavity width was not taken into account, due to the fact that the results of the non-destructive detection did not provide the width value; and (2) the characterization of the lining thickness at the cavity is not analyzed.

4.3 Numerical Simulation Analysis

a. Numerical Models and Material Properties

Numerical simulations were implemented to explore the effects of changes in the values of the characteristic indicators on the tunnel structural safety. This can further help determine the weight and membership degree in the safety evaluation process.

The assumptions made in the numerical simulation analysis are as follows: (1) The tunnel is excavated in the homogeneous and continuous surrounding rocks, and the stress-strain relationship of surrounding rocks follows the Mohr-Column model; (2) The stress-strain relationship of the tunnel lining follows the linear elastic model; (3) The effect of underground water is not taken into account.

FLAC3D numerical modelling software was utilized, and twelve working conditions were proposed in this study, which are shown in Table 2. These working conditions were divided into four groups to study the effect of parameter changes on the tunnel structural safety, which are illustrated in Table 3.

Table 2 - Working Conditions

Serial number	Surrounding rock classification	Cavity location	Cavity depth /m	Cavity length /m
Condition 1	II	Vault	0.4	\
Condition 2	III	Vault	0.4	\
Condition 3	IV	Vault	0.4	\
Condition 4	V	Vault	0.4	\

Condition 5	IV	Right of vault	0.4	\
Condition 6	IV	Right arch waist	0.4	\
Condition 7	IV	Vault	0.2	\
Condition 8	IV	Vault	0.6	\
Condition 9	IV	Vault	0.8	\
Condition 10	IV	Vault	0.4	2
Condition 11	IV	Vault	0.4	4
Condition 12	IV	Vault	0.4	6

Notes: For Condition 1 to Condition 9, two-dimensional numerical simulations were carried out are, i.e., the analysis of plane strain problems. Therefore, the cavity length was not formulated (refer to "\" in this table).

Table 3 - Grouping of Working Conditions

Group	Working conditions	Research objective
First group	Condition 1, 2, 3, 4	To study the influence of different surrounding rock classifications on the tunnel structural safety
Second group	Condition 3, 5, 6	To study impact of different cavity locations on structural safety
Third group	Condition 3, 7, 8, 9	to study the influence of different cavity depths on structural safety
Fourth group	Condition 10, 11, 12	To study the influence of different cavity lengths on structural safety

The calculation model is established according to the review of the engineering case. The buried depth of the selected section is 35m. The calculation model is 100m horizontally and 85m vertically. The size and boundary condition of the cross-section in the model is shown in Figure 8. The vertical displacement of the bottom boundary (i.e., boundary I) in the model is constrained. The horizontal displacement of the model's left (i.e., boundary II) and right boundaries (i.e., boundary III) is also constrained. The top boundary (i.e., boundary IV) of this model is the surface of the earth.

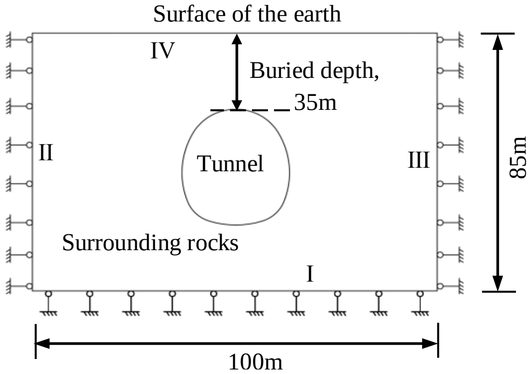


Fig. 8. Cross-Section Of Developed Numerical Model

For the first, second and third group of working conditions, the 2D numerical model was stablished, which is shown in Figure 9. For the fourth working condition group, the 3D numerical model was stablished, which is shown in Figure 10. The length of the 3D model along the tunnel's axial direction is 14m.

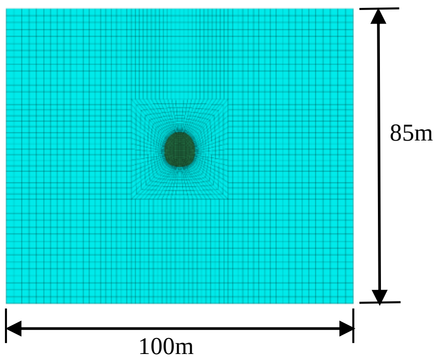


Fig. 9. 2D numerical model

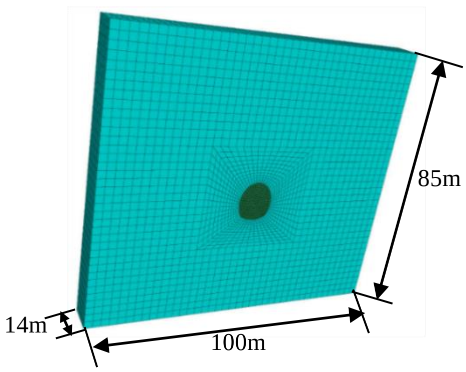


Fig. 10. 3D numerical model

The Mohr-Column model was used to simulate surrounding rocks, and the linear elastic model was used to simulate the tunnel lining. The mechanical parameters of the surrounding rock and tunnel lining were taken with reference to Code for Design of Railway Tunnel (China Railway Eryuan Engineering Group Co. Ltd. 2016). The elastic modulus and Poisson’s ratio of the tunnel lining in all the working conditions are 31GPa and 0.2, separately. As Condition One to Condition Four were developed to explore the impact of different surrounding rock classifications on structural safety, mechanical parameters of surrounding rocks vary from Condition One to Condition Four. In contrast, there is no change in the parameters of surrounding rocks from Condition Five to Condition Twelve. The properties of the surrounding rock under different working conditions are shown in Table 4.

Table 4 - Variable Properties of Surrounding Rocks

Condition	Elastic modulus (GPa)	Poisson’s ratio	internal friction angle (°)	Cohesion (MPa)
Condition1	25	1.7	55	0.22
Condition2	10	1	45	0.27
Condition3	5	0.5	33	0.32
Condition4	1	0.1	24	0.4
Condition5 to 12	5	0.5	33	0.32

b. Influence of Different Characteristic Indicators on Lining Safety

Inner force values at the lining defect are extracted in the four condition groups (refer to Table 2). The safety factor of the lining is calculated according to the Code for Design of Railway Tunnel (China Railway Eryuan Engineering Group Co. Ltd. 2016). The results of inner forces and safety factors under different working conditions are shown in Table 5.

Table 5 - Inner Forces (Absolute Value) And Safety Factors Under Different Working Conditions

Group	Condition	Axial force (kN)	Bending moment (kN·m)	Safety factor
First group	Condition1	65	13.4	11.66
	Condition2	175	34.8	7.98
	Condition3	787	42.5	4.97
	Condition4	1345	67.9	3.12
Second group	Condition3	787	42.5	4.97
	Condition5	439	27.8	6.32
	Condition6	194	13.5	8.43
Third group	Condition7	591	21.6	7.23
	Condition3	787	42.5	4.97
	Condition8	1004	68.8	3.08
	Condition9	1402	92.9	2.12
Fourth group	Condition10	796	44.3	4.84
	Condition11	812	46.5	4.73
	Condition12	832	49.1	4.43

The first group is used to study the influence of different surrounding rock classifications on the tunnel structural safety. The surrounding rocks become weaker when surrounding rock classification varies from Class II to Class V. Then axial force and the bending moment value of the lining become more significant. The safety factor of the lining gradually decreases following the trend of the inner force. The structural safety of the lining decreases when there is a cavity defect underneath the lining, especially as the surrounding rock becomes weaker.

The second condition group is used to study the influence of different cavity locations on the tunnel structural safety. When a cavity defect appears on either the left or right side of the vault, it leads to a reduction in the axial force and bending moment values within the lining, as opposed to cavities occurring directly at the vault itself. This reduction results in an increase in the safety factor. On the other hand, if there is a cavity defect on either side of the arch waist, it similarly causes a decrease in the axial force and bending moment values within the lining, but this comparison is made in relation to cavities located on the left or right side of the vault. Cavities at the vault have the most significant adverse impact on the lining structure, while cavities at the arch waist have the most negligible adverse impact.

The third group of conditions is dedicated to examining the impact of varying cavity depths on the safety of the tunnel structure. As the cavity depth increases, more significant axial force values and bending moments are examined within the lining. The safety factor of the lining progressively decreases in tandem with the inner force trend. Notably, the lining structure with smaller depth cavities offer greater safety factor.

The fourth group of conditions aims to investigate the impact of varying cavity lengths on the safety of the tunnel structure. As the cavity length increases, there is minimal change (about 4.3%) in the axial force distribution and slight variation (about 9.7%) in the bending moment within the tunnel cross-section, resulting in a relatively consistent structural safety factor. However, it should be noted that there is a slight decrease in this safety factor, though it is not significant.

Although the numerical simulation analysis can provide safety factors of the lining structure, the cumbersome modeling process and the laborious analysis process of numerical simulation are limitations to the application of this method. Therefore, more concise and efficient safety evaluation method need to be explored.

4. Results and Discussions

5.1 Safety Evaluation Model of Lining with Underlying Cavities

Based on the results of the previous quantitative analysis (i.e., proportion analysis, relationship analysis, and numerical analysis), the safety evaluation model of tunnel lining structure with underlying cavities is established.

Two assumptions are made in the fuzzy comprehensive evaluation model. Firstly, the width of the cavity is not involved during the evaluation process. Secondly, the safety evaluation is conducted based on the dimensional data of cavities at the time of defect detection, and the evolutionary process of cavities over time is not taken into account.

a. Factor set

The first step of the fuzzy comprehensive evaluation is determining the factors affecting the evaluation results, namely factor set. If the number of influencing factors is "n", then the factor set is shown in Equation (1). The factor set is determined according to the characteristic indicators of cavities. The factor set of structural safety evaluation of lining is shown in Equation (2).

$$U = \{u_1, u_2, \cdots, u_n\} \tag{1}$$

$$V = \{Surrounding\ rock\ classification, Cavity\ Length, Cavity\ Location, Cavity\ depth\} \tag{2}$$

b. Comment set

Comment set is the different degree of the evaluation result. If the number of comments is "m", then the comment set is shown in Equation (3). The severity degree of lining determines the comment set, which is shown in Equation (4).

$$V = \{v_1, v_2, \cdots, v_m\} \tag{3}$$

$$V = \{Most\ serious, More\ serious, Serious, Slightly\} \tag{4}$$

c. Membership degree and fuzzy evaluation matrix

If the membership degree of the factor "u_i" corresponding to the comment "v_j" is "r_{ij}", then the evaluation matrix is shown in Equation (5).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{5}$$

The membership degree of structural safety evaluation of tunnel lining is determined according to the previous relationship analysis and numerical simulation, which is shown in Table 6. Then the membership degree results are shown in Table 7.

Table 6 - Determination Process of Membership Degree

Membership degree	According to relationship analysis	According to numerical simulation
Surrounding rock classification	In the surrounding rocks of class IV, the proportion of cavities is the largest.	The weaker the surrounding rock, the lower the safety factor of lining structures with underlying cavities.
Cavity length	The distribution characteristics of cavity depth are almost the same in different cavity length intervals. The depth between 20cm and 40cm is	The structural safety factor somewhat declines as the defect length increases.

	the most significant proportion interval.	
Cavity location	In all the locations, the cavity depth between 20cm and 40cm is the largest proportion.	The lining is most negatively impacted by underlying cavities at the vault, and least negatively impacted by cavities at the arch waist.
Cavity depth	The largest percentage of depth falls within the range of 20cm to 40cm related to the different surrounding rock classifications, different cavity length and different location.	Variations in the depth of cavities have a significant impact on the structural safety of the lining. The safety factor decreases with the increasing depth of cavities.

Table 7 - Results of Membership Degree

Factor	Comment	Most serious	More serious	Serious	Slightly
Surrounding rock classification	II	0.05	0.10	0.20	0.55
	III	0.05	0.20	0.55	0.10
	IV	0.20	0.55	0.10	0.05
	V	0.55	0.20	0.10	0.05
Cavity length ("L")	L≤1m	0.10	0.10	0.45	0.25
	3m≥L>1m	0.10	0.25	0.45	0.10
	5m≥L>3m	0.25	0.45	0.10	0.10
	L>5m	0.45	0.25	0.10	0.10
Cavity location	Vault	0.60	0.20	0.15	0.05
	Left / right of vault	0.20	0.60	0.15	0.05
	Left / right arch waist	0.15	0.20	0.60	0.05
Cavity depth ("d")	d≤20cm	0.05	0.10	0.20	0.65
	40cm≥d>20cm	0.05	0.20	0.65	0.10
	60cm≥d>40cm	0.20	0.65	0.10	0.05
	d>60cm	0.65	0.20	0.10	0.05

d. Weight set

The weight set is the set of different weight values for every factor. The weight indicates the influence degree of each factor on the evaluation result. The number of weight values is equal to the number of factors, so the weight set is shown in Equation (6).

$$A = \{a_1, a_2, \cdots, a_n\} \tag{6}$$

The previous proportion analysis indicates that the proportion of cavities defects varying in depth and location varies considerably. The previous numerical simulation results speak for themselves: when the cavity depth and location change, the safety factor of the tunnel lining changes obviously; the lining safety factor remains largely unchanged as the defect length varies. Thus, the weight matrix is determined as shown in Table 8.

Table 8 - Determination of Weight

Factor	Weight	Order of importance
Surrounding rock classification	0.25	Not very important
Cavity length	0.15	Slightly important
Cavity location	0.65	Very important
Cavity depth	0.45	Obviously important

The relationship between the weight of each factor is Cavity depth > Cavity location > Surrounding rock classification > Cavity length. Following the 1-9 scale method (Hu et al., 2018), the weight set of structural safety evaluation of lining is shown in Equation (7).

$$A = \{0.25, 0.15, 0.65, 0.45\} \tag{7}$$

e. Conduct the fuzzy comprehensive evaluation

The single-factor weight set only reflects the influence of one factor on the evaluation object. The final step of this fuzzy comprehensive evaluation is to synthesize the influence of all factors to obtain a reasonable evaluation result, shown in Equation (8).

$$B = A \cdot R = \{b_1, b_2, \cdots, b_m\} \tag{8}$$

According to the principle of maximum membership degree (Rao et al., 2015), if the comment "v_j" (refer to Equation (3)) corresponds to the maximum membership degree "b_j" (refer to Equation (8)), then the comment "v_j" is the final evaluation result.

Train loads can affect the cavities underneath the lining, causing the size of cavities to change over time. The fuzzy comprehensive evaluation process does not address the development of cavities over time, which is the limitation of this method.

5.2 Application of the Evaluation Model

The structural safety evaluation of an engineering case is conducted using the developed evaluation model. With a total length of 1308m, the Songlinbao Tunnel was located in the Southwest China, and was excavated in a mudstone stratum. A cavity (shown in Figure 11) was detected beneath the lining structure. This cavity is examined at the vault underneath the lining, and the surrounding rock classification of this defect is IV. The length and depth of this cavity is 4m and 50cm, respectively.

Fig. 11. Cavity image in the Songlinbao Tunnel

Detailed information on the fuzzy comprehensive evaluation process based on the engineering case is shown in Table 9. The maximum value of the evaluation result is 0.628 in accordance with "more serious" in the comment set, which is shown in Table 9. Therefore, the structural safety level of the lining is "more serious" according to the principle of maximum membership.

Table 9 - Detailed Information of The Evaluation Process

Item	Value
Factor set	$\left\{\begin{matrix} Surrounding\ rock\ classification, \\ Cavity\ Length, Cavity\ Location, \\ Cavity\ depth \end{matrix}\right\}$
Comment set	$\{Most\ serious, More\ serious, Serious, Slightly\}$
Fuzzy evaluation matrix	$\begin{bmatrix} 0.20 & 0.55 & 0.10 & 0.05 \\ 0.25 & 0.45 & 0.10 & 0.10 \\ 0.60 & 0.20 & 0.15 & 0.05 \\ 0.20 & 0.65 & 0.10 & 0.05 \end{bmatrix}$
Weight set	$\{0.25, 0.15, 0.65, 0.45\}$
Evaluation result	$\{0.567, 0.628, 0.183, 0.083\}$

For most serious and more serious safety level, shotcrete combined with anchor rods and shotcrete were used to repair the cavities, respectively. Serious and slight cavities were repaired by grouting, with the amount of grouting varying according to the size of cavities. Since the evaluation level of the underlying cavity in Songlinbao Tunnel was more serious, the shotcrete scheme was applied to the maintenance work. Moreover, reinforcing mesh and shotcrete were applied jointly, in order to strengthen the linkage of shotcrete with the existing lining structure. Images of maintenance work in the Songlinbao Tunnel are shown in Fig.12. The non-destructive detection was conducted in this tunnel after maintenance. The detection results showed that there was no cavity underneath the lining. It implies that the evaluation result was accurate and the maintenance achieved good results.

(a) Reinforcing mesh (b) Construction of shotcrete (c) Completion of cavity maintenance

Fig. 12. Maintenance image of cavity in the Songlinbao Tunnel

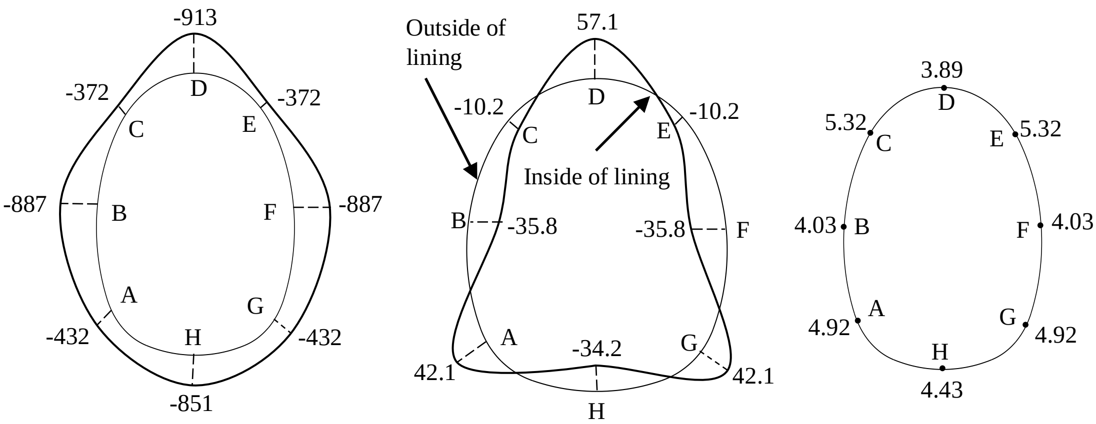
5.3 Validation of the Evaluation Model by Numerical Simulation

The numerical simulation method is adopted to validate the developed evaluation model. For the cavity case shown in Section 5.2 in the Songlinbao Tunnel, the inner force and safety factor of the tunnel lining are calculated through numerical simulation. The numerical model is similar to Figure 9. The surrounding rock is simulated by Mohr-Column model, its elastic modulus is 5GPa, Poisson's ratio is 0.5, internal friction angle is 33°, and cohesion is 0.32MPa. The tunnel lining is simulated by the linear elastic model. The elastic modulus and Poisson's ratio of the tunnel lining are 31GPa and 0.2, separately. The axial forces and bending moments of the lining structure can be calculated through the numerical model.Based on the axial forces and bending moments, the safety factors are calculated according to the calculation principle of the section strength check for eccentrically compressed reinforced concrete members, as illustrated in the Code for Design of Railway Tunnel (China Railway Eryuan Engineering Group Co.Ltd. 2016). Inner forces and safety factors of lining structure in the Songlinbao Tunnel are shown in Fig. 13.

As can be seen in Figure 13(a), the axial force is symmetrically distributed concerning the central axis. All sections of the lining are subjected to negative axial forces, indicating pressure. The maximum axial force is -913kN at the vault (refer to D), which is due to the cavity underneath the vault lining. The axial forces at the spandrel (i.e., C, E) and archfoot (i.e., A, G) are relatively tiny.

As can be seen in Figure 13(b), the bending moment is similarly symmetrically distributed with respect to the central axis. Positive bending moments indicate tension on the outside of the lining, while negative bending moments indicate tension inside. The largest bending moment is exhibited at the vault (i.e., 57.1 kN·m at Section D), as the underlying cavity exists at the vault. The bending moment at the base of the side wall (i.e., A, G) comes after the maximum moment at the vault. The moment value is comparatively small for other sections.

The safety factors of the lining structure are shown in Figure 13(c). The vault exhibits the minimum safety factor (i.e., 3.89), which is due to the underlying cavity weakening the load bearing capacity of the vault lining structure. Other sections present considerable safety factors. The maximum safety factor (namely 5.32) occurs at the spandrel (i.e., C, E).



(a) Axial forces (kN) (b) Bending moments (kN·m) (c) Safety factors

Fig. 13. Inner forces and safety factors of lining structure in the Songlinbao Tunnel

The results of the axial force, bending moment and safety factor (namely Section D shown in Fig.13) at the lining defect are 913kN, 57.1 kN·m, and 3.89, respectively. Tunnel lining structures can be categorized into different safety levels based on different safety factors (Wang et al., 2015; China Railway Eryuan Engineering Group Co. Ltd., 2016). As the safety factor ("α") falls within the following ranges, namely "$0< \alpha <2.4$", "$2.4\leq \alpha <5.5$", "$5.5\leq \alpha <8$", "$8\leq \alpha <+\infty$", the safety levels are "Most serious", "More serious", "Serious", and "Slightly", respectively.

As the safety factor of the tunnel lining is 3.89, so the safety level of lining is "more serious". The fuzzy comprehensive evaluation result is consistent with the numerical simulation evaluation result, so the developed evaluation model in this paper is validated.

Therefore, the fuzzy comprehensive evaluation model is utilized to assess the safety of lining structures with underlying cavities, which can avoid the complexity of numerical modelling and ensure the accuracy of the assessment results. The proposed fuzzy comprehensive evaluation model is based on tunnels excavated in mudstone and has undergone validation in the Songlinbao Tunnel. However, tunnel construction encounters varying geological conditions, which can lead to different distribution characteristics of cavities underneath the lining. Developing evaluation models suitable for a wide range of geological conditions will be the next research focus.

5.4 Comparison of Fuzzy Comprehensive Evaluation Model with Existing Evaluation Approaches

The comparison of the developed fuzzy comprehensive evaluation model and existing evaluation approaches is conducted, as shown in Table 10. The comparison items include: comprehensiveness of factors involved, simplicity of evaluation process, efficiency of evaluation approach, and accuracy of evaluation results. The "√" mark indicates that the assessment method is characterized in this comparison item, and the "×" mark indicates that the evaluation method is not well characterized for this item.

Table 10 – Comparison Of Existing Evaluation Approaches

Item	Experimental tests	Numerical simulation	Analytic Hierarchy Process method	Artificial Neural Network method and Bayesian Network method	Fuzzy Comprehensive Evaluation method
Comprehensiveness of factors involved	√	√	×	×	√
Simplicity of evaluation process	×	×	√	×	√
Efficiency of evaluation approach	×	×	√	√	√
Accuracy of evaluation results	√	√	×	×	√

As can be seen in Table 10, the experimental test and numerical simulation method are not characterized by simplicity and efficiency of evaluation process. Analytic Hierarchy Process method, Artificial Neural Network method and Bayesian Network method do not allow for an integrated consideration of the various factors affecting the evaluation results. Moreover, these three methods cannot provide the accurate evaluation results. In contrast, the proposed fuzzy comprehensive evaluation method is characterized by simplicity and efficiency, and can provide a comprehensive consideration of the various influencing factors, leading to accurate assessment results.

The fuzzy comprehensive evaluation method proposed in this paper was applied to the safety assessment of underlying cavities in forty-one tunnels on the Suiyu Railway in China. The safety assessment of all the cavities was completed in only half a month, the safety level of cavities was determined, and different maintenance measures were proposed. Shotcrete combined with anchor rods were used to repair the most serious cavities. Shotcrete was applied to more serious cavities. Serious and slight cavities were repaired by grouting, with the amount of grouting varying according to the size of cavities. After the maintenance work was completed, the non-destructive detection was conducted again, and showed that there were no cavities underneath the lining.

The proposed fuzzy comprehensive evaluation method is accurate, simple and efficient. The structural safety evaluation work for by using this method reduces time and resource requirements while ensuring the accuracy of assessment results. Underlying cavity defects are common in operational tunnels through numerous reports, and the proposed fuzzy assessment method holds substantial promise for practical implementation in engineering scenarios.

Possible avenues for future researches on the fuzzy comprehensive evaluation method for underlying cavities are suggested as follows: (i) extending the application of the developed model to other geologic conditions besides mudstone stratum; (ii) incorporating more influencing factors into the evaluation model, such as the width of cavities, groundwater conditions, etc.; and (iii) integrating advanced data analytics to enhance the accuracy of the assessment results.

5. Conclusion

This paper delves into the safety assessment of lining structures with underlying cavities, employing the fuzzy comprehensive evaluation method. The safety evaluation model is formulated subsequent to collecting defect data, conducting data analysis, and performing numerical simulations. The ensuing conclusions can be drawn;

(1) Proportion of cavities based on different indicators is analyzed. The most significant percentage of cavity length is between 1m and 3m, and the most depth of underlying cavities is between 20cm and 40cm. Cavities occur most frequently in the class IV surrounding rocks and at the vault. After that, an analysis is done on the correlation between cavity depth and the other three indicators. The depth between 20cm and 40cm is the most significant proportion interval related to the surrounding rock classification, cavity location, and cavity length.

(2) Numerical simulation is performed to explore the effect of these parameters on the structural safety of linings. The safety factor of the lining is not significantly affected by changes in cavity lengths. In contrast, the changes in the other three parameters can have a significant impact on the structural safety factor.

(3) According to the previous field data analysis (refer to proportion analysis and relationship analysis) and the numerical analysis, the safety evaluation model of tunnel lining with underlying cavities is developed. The factor set and comment set comprise four factors, respectively. The membership degree is determined based on prior relationship analysis and numerical simulations. Simultaneously, the weight matrix is established through proportion analysis and numerical simulations conducted previously.

(4) The evaluation model presented in this paper undergoes validation through numerical simulations. The method for determining membership degrees and weights, as proposed in this paper, relies on field data analysis and numerical simulations. When compared to methods reliant on subjective judgment, the approach outlined in this paper represents an enhancement in the evaluation process.

(5) Cavities underneath the lining are common in tunnels. Assessing the severity of cavities and applying appropriate maintenance measures is important to ensure the structural safety of tunnels. The fuzzy comprehensive evaluation method reduces time and resources while ensuring the accuracy of the evaluation results. "Shotcrete + anchor rods", shotcrete, and grouting are applied to cavities according to the severity levels of evaluation results. The evaluation method proposed in this paper can be widely used in the structural safety assessment of tunnels.

(6) Possible avenues for future researches on the evaluation method are suggested: (i) extending the application of the developed model to various geologic conditions; (ii) incorporating more influencing factors into the evaluation model; and (iii) integrating advanced data analytics to enhance the accuracy. Additionally, optimizing the design scheme according to the geological conditions, ensuring the quality of grouting, and guaranteeing the quality of concrete construction are the fundamental ways to reduce the underlying cavities.

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