Safety Evaluation of Insufficient Lining Thickness Based on Fuzzy Comprehensive Evaluation in Tunnel

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Article Info

Abstract

This paper presents a study on the safety evaluation of the lining structure with insufficient thickness using fuzzy comprehensive evaluation method in railway tunnels. Determining weight and membership degree are two critical points of this evaluation method. These two points are determined based on field data analysis and numerical simulation. Most conventional determination methods are based on subjective judgment, while the method in this paper is based on engineering practice. Field data analysis revealed that the proportion of defects in the surrounding rocks of class IV and at the vault was the largest. Defect length between 3m and 4.5m and thickness ratio between 0.55 and 0.7 occupied the most significant proportion. Numerical simulation was also used to study the effect of the parameter changes on structural safety. It is known that the change of defect lengths has a not very obvious effect on the structural safety factor. In contrast, the changes in the other three parameters can significantly impact the lining. The factor set and comment set are determined according to the characteristic indicators from the collected field data. The membership degree and weight set are determined based on the on-site data and numerical investigation results. The fuzzy comprehensive evaluation model is established, and the structural safety evaluation work can be conducted. Then this model is validated through numerical simulation in the specific engineering case.

1. Introduction

Nowadays, many tunnels have been constructed and put into service in China due to the rapid rise of transportation infrastructure construction. The operating distance of China's railways has increased to 145000 km by 2020 [1]. The composite lining is the most commonly used structural form for tunnels constructed by the drilling and blasting method [2]. Tunnel distress has recently been examined in China, and lining defects, especially insufficient thickness, are common in the tunnel lining [3]. The insufficient lining thickness is defined as the actual thickness being thinner than the designed one. The insufficient thickness will directly weaken the structural bearing capacity, resulting in structural deformation [4]. Inadequate lining thickness poses a serious risk, potentially resulting in catastrophic outcomes such as fractures and collapses, which could jeopardize the safety of operational tunnels. Therefore, proactive measures must be implemented to prevent operational accidents.

The structural safety evaluation aims to assess the current state of the lining structure for safety and health considerations, determining its safety performance level. This assessment serves as a reference for future

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maintenance decisions. However, structural safety evaluation is not conducted for lining distress in some tunnels, and maintenance is conducted based on subjective judgment [5]. 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 [6-8]. The inaccurate evaluation resulted in severe consequences [6]. Therefore, carrying out thorough investigation on the tunnel safety assessment and proposing an effective assessment method is necessary.

In recent years, there have been several methods to evaluate the safety of lining structures [9-11]. Firstly, the numerical method has been used in the safety evaluation of lining [3,8,11]. Considering the underlying cavity and insufficient lining thickness, a numerical model in three dimensions was established to assess the structural safety condition [11]. The Analytic Hierarchy Process is another method used in structural safety evaluation [9,12,13]. A sustainable evaluation system was established for railway tunnels by this method [13]. Next, the fuzzy comprehensive evaluation method is also used to evaluate the safety of tunnel structures recently [9,14,15]. A safety risk evaluation method for the tunnel in the operation period was developed based on the fuzzy comprehensive evaluation theory, resulting in the safety level of tunnels [15]. Lastly, other methods that used in the structural safety evaluation are as follows. A two-level extension evaluation model was established to assess the health state of the tunnel structure [7]. The Artificial Neural Network method was adopted to evaluate the stability of the tunnel structure [16]. The Bayesian Network model was used to evaluate the probability of structural failure of drill-and-blast tunnels [17].

The primary approach for numerical simulation involves complex modeling and calculations [18]. In contrast, the Analytic Hierarchy Process method offers simplicity and convenience but requires careful weight determination [19]. The fuzzy comprehensive evaluation method is commonly employed and excels at accounting for uncertain factors in evaluations, with a crucial need for determining weights and membership degrees. In contrast, other methods are intricate and less convenient for engineering applications.

Determining weight and membership degree are two difficulties of the fuzzy comprehensive evaluation method [14]. First of all, the expert scoring method [10,20] was used to determine the weight. The weight determination in these methods is primarily subjective, and the evaluators greatly influence the evaluation results. Secondly, the membership degree was determined by using the existing membership function [12,21]. 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 [9]. 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.

This work aims to propose the improved fuzzy comprehensive evaluation method to assess the structural safety of lining with insufficient thickness in tunnels. The weight and membership degree are determined based on statistical analysis and numerical simulation. The statistical analysis is conducted based on the field collected data from the Suiyu Railway. Numerical simulation is used to analyze the influence of different parameters on the lining. Then, the structural safety evaluation model is developed. Lastly, the developed evaluation model is validated based on an engineering case.

2. Methodology

Structural safety in tunnels with defects is evaluated using the Fuzzy Comprehensive Evaluation Method. The basic 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 [22]. The workflow of fuzzy comprehensive evaluation can be divided into five steps, shown in Figure 1. Step 1 to Step 4 is to determine the factor set, comment set, weight set, and membership degree, preparing for the evaluation. Step 5 is to conduct the fuzzy evaluation and obtain the evaluation result.

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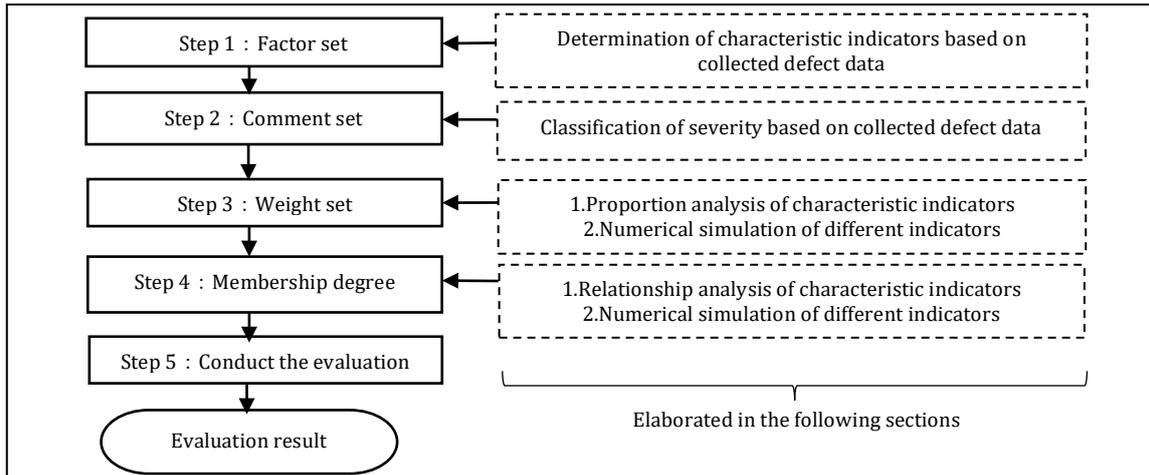
Fig. 1 *Workflow of fuzzy comprehensive evaluation*

Collecting defect data lays the foundation for Step 1 and Step 2. The factor set is determined according to the characteristic indicators of defects, and the comment set is determined by the classification of defect severity. 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. Based on the previous preparations (i.e., Step1 to Step4), the structural safety condition is assessed, and the evaluation result is obtained.

3. Data Collection of Insufficient Lining Thickness

3.1 Project Overview

This research focuses on the case study of the Suiyu Railway. The second line project of Suiyu Railway is located in southwest China, and the design speed of this railway is 200km/h. There are 41 tunnels on this railway. 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 adverse geology is karst, gas, underground river, and coal seam goaf. The inner contour of the tunnel lining was 810cm high and 773cm wide. The tunnel lining structure consisted of the initial support and secondary lining, as shown in Figure 2.
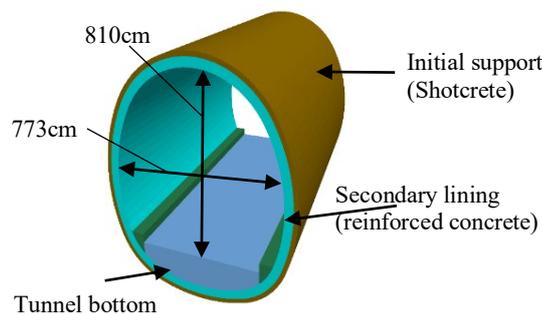

Fig. 2 *Tunnel lining structure*

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 [23]. The surrounding rock becomes weaker in turn from Class II to Class V. The lining thickness was designed according to the different classes of surrounding rocks. Parameters of composite lining structures for different surrounding rock classifications are in Table 1.

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Table 1 *Parameters of composite lining*

Surrounding rock classification	Class II	Class III	Class IV	Class V
Thickness of initial support (cm)	5	8	16	25
Thickness of secondary lining (cm)	30	35	40	45

3.2 Investigation of Defect Data

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.
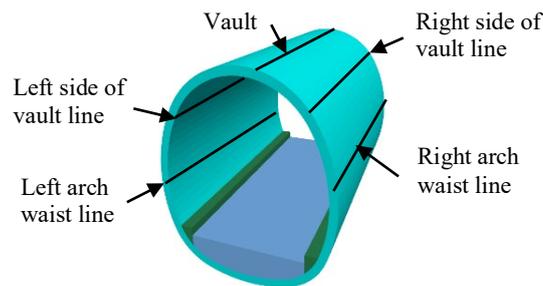
Fig. 3 *Arrangement of survey lines*

3.3 Data Collection and Characteristic Indicators of Defects

After the completion of defect detection in the Suiyu tunnels, a total of three hundred and fifty-six instances of inadequate thickness were identified. Prior to analyzing the defect data, it is essential to choose characteristic indicators and collect defect data in accordance with these selected indicators.

In the process of data analysis, the primary task is to determine the exact location of defects. Therefore, the location is chosen as the first characteristic indicator. Next, the dimensional characteristics of defects, such as length, also need to be studied. Then, the tunnel lining structure is built in the surrounding rocks, and the defect characteristics are related to the surrounding rocks. Therefore, the surrounding rock classification is also selected as a characteristic indicator.

The insufficient lining thickness may weaken the lining structure's bearing capacity and negatively impact the safety of tunnels [4]. To evaluate the safety level of lining structures with insufficient thickness, 'thickness ratio' is proposed as the last characteristic indicator. The thickness ratio is the ratio between the detection thickness and the designed thickness of the secondary lining. The designed thickness of the lining is shown in Table 1, from 30cm to 45cm.

Hence, the selected characteristic indicators of insufficient thickness are surrounding rock classification, length of defect, location of defect, and thickness ratio. Partial insufficient thickness data is collected and shown in Table 2. A total of 356 defect data is collected like this.

Table 2 *Partial insufficient thickness data*

No.	Tunnel	Surrounding rock classification	Length of defect(m)	Location of defect	Thickness ratio
1	Tang Jia Wan	IV	3.5	right of vault	0.75
2	Tang Jia Wan	IV	3.5	left of vault	0.81
3	Tang Jia Wan	IV	2	right of vault	0.84
4	Tang Jia Wan	IV	3.5	right of vault	0.85
5	Su Jia Wan	IV	3	vault	0.75
6	Su Jia Wan	IV	4	right of vault	0.83

| 7 | Su Jia Wan | IV | 2 | vault | 0.79 |

4. Proportion Analysis of Characteristic Indicators

Statistical data analysis is conducted based on 356 defects of insufficient thickness in these tunnels, which benefits the safety evaluation of the lining. Firstly, the proportion of defects based on different indicators is analyzed. Then, the relationship between the thickness ratio and the other three indicators is analyzed.

Considering the different characteristic indicators, the percentage of lining defects with insufficient thickness is shown in Figure 4, which presents the results of the proportion analysis.

The chart provides information about various defect lengths related to insufficient thickness. The maximum length for this type of defect is 21 meters. The largest percentage of defects, accounting for 35.39%, falls within the range of 3 meters to 4.5 meters. The next most common type of defect, at 30.34%, occurs within the range of 1.5 meters to 3 meters. Furthermore, 20.22% of defects are found in the shortest length category, ranging from 0 meters to 1.5 meters. Another 14.04% of defects are categorized as the longest, spanning from 4.5 meters to 21 meters. Based on the proportion analysis of defect 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 insufficient thickness defects. The highest percentage, 61.80%, is observed in tunnel linings with surrounding rock classified as Class IV. The next most common type of surrounding rock, Class III, accounts for 23.88% of these defects. Furthermore, defects related to insufficient thickness are present in tunnel linings with Class V surrounding rock, representing 12.92% of the total defects in this category. A further 1.4 percent belong to the surrounding rock of Class II.

Next, the chart in Figure 4 provides a breakdown of insufficient thickness defects occurring at various locations. The most prominent percentage, accounting for 40.73% of the total, is found at the vault. Following closely behind, both the left and right sides of the vault exhibit similar frequencies of insufficient thickness, each comprising approximately 20% of the total defects. The arch waist represents a less common location for insufficient thickness, with 10.11% of defects occurring on the left and 8.43% on the right.

Finally, Figure 4 illustrates the distribution of various thickness ratios, offering insights into the extent of insufficient thickness. Based on the collected defect data, the highest ratio observed between detected thickness and designed thickness is 0.99. The predominant range of thickness ratios falls between 0.55 and 0.7, constituting 48.31% of the total. Following closely, thickness ratios ranging from 0.7 to 0.85 make up the next significant proportion at 25.56%. The interval between 0.85 and 0.99 represents 19.1%, indicating a relatively smaller lack of thickness. A minor proportion, amounting to 7.02%, is associated with thickness ratios below 0.55. Thus, the most substantial proportion of thickness ratios falls within the range of 0.55 to 0.7.
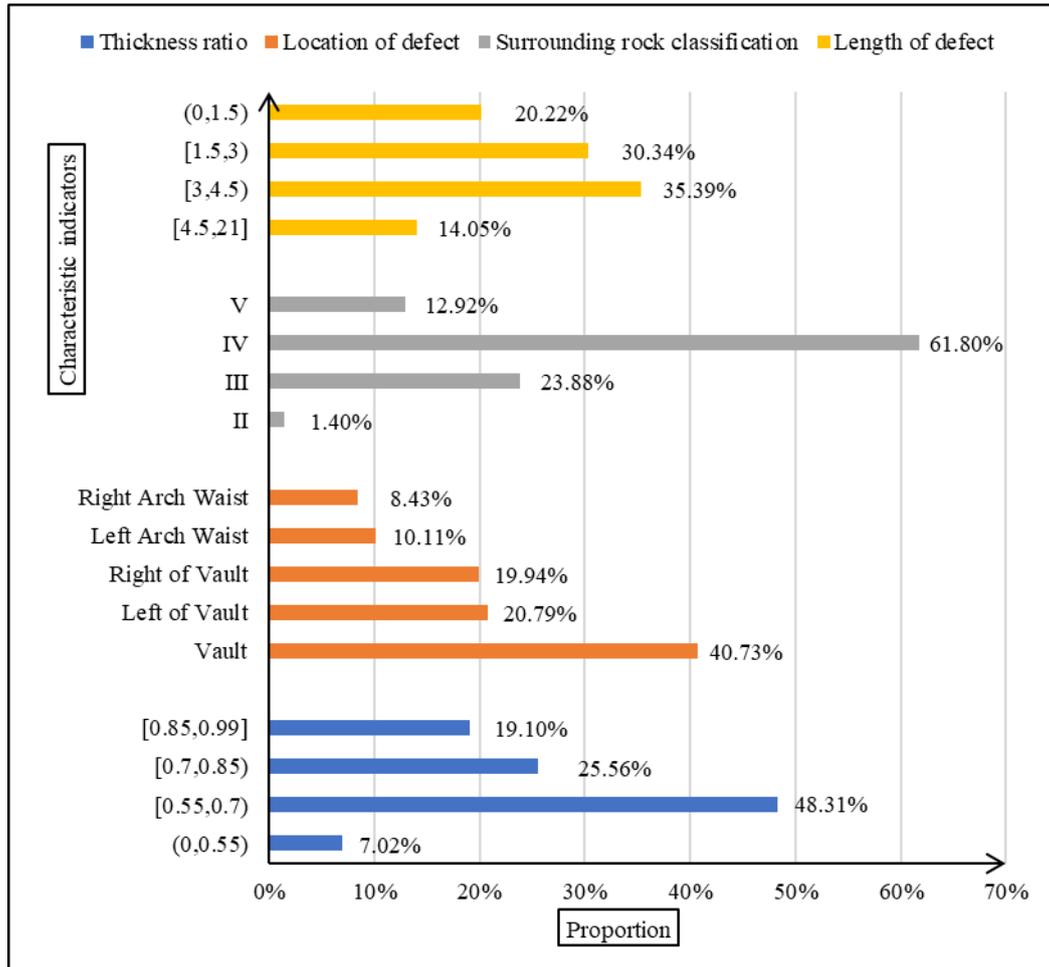
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Fig. 4 *Proportion of defects based on different characteristic indicators*

5. Relationship Analysis of Characteristic Indicators

5.1 Relationship Between Surrounding Rock Classification and Thickness Ratio

The relationship between surrounding rock classification and thickness ratio is shown in Figure 5. The inner circle shows the proportion of different rock classifications. The number of lining defects 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 defects with different thickness ratios at a specific surrounding rock classification. In all the surrounding rock classifications, a thickness ratio between 0.55 and 0.7("B" in Figure 5) is the most considerable proportion interval, with the proportion of 37.6 percent in class III (indicated in orange), 50.9% in class IV, and 54.3% in class V (indicated in yellow mustard). Furthermore, all the defects with insufficient thickness belong to a thickness ratio between 0.55 and 0.7 in the surrounding rocks of Class II (indicated in blue).

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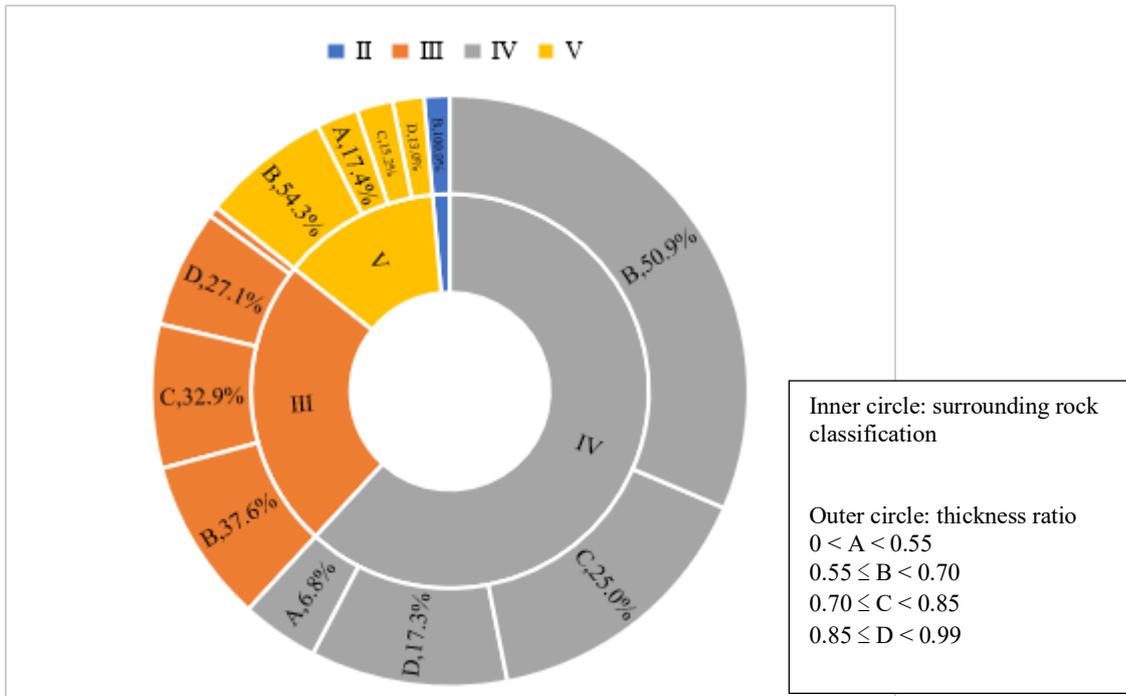
Fig. 5 *Relationship between surrounding rock classification and thickness ratio*

5.2 Relationship Between Defect Length and Thickness Ratio

The relationship between defect length and thickness ratio is shown in Figure 6. The inner circle shows different intervals of defect length. Insufficient thickness with lengths of 1.5~3m and 3~4.5m occupies a relatively large proportion. The outer circle presents the proportion of defects with different thickness ratios at a specific length interval. The thickness ratio between 0.55 and 0.7("B" in Figure 6) is the most significant proportion interval in all the defect length intervals. Taking the defect length group of 1.5~3m as an example, a thickness ratio of 0.55~0.7 occupies the most significant proportion, namely 53.2%. The next largest type is the ratio of 0.7~0.85, with a proportion of 23.8 percent. Then, 19 percent of defects exist in the thickness ratio of 0.85~0.99. A further 4 percent belongs to the thickness ratio internal of 0~0.55.

Fig. 6 *Relationship between defect length and thickness ratio*

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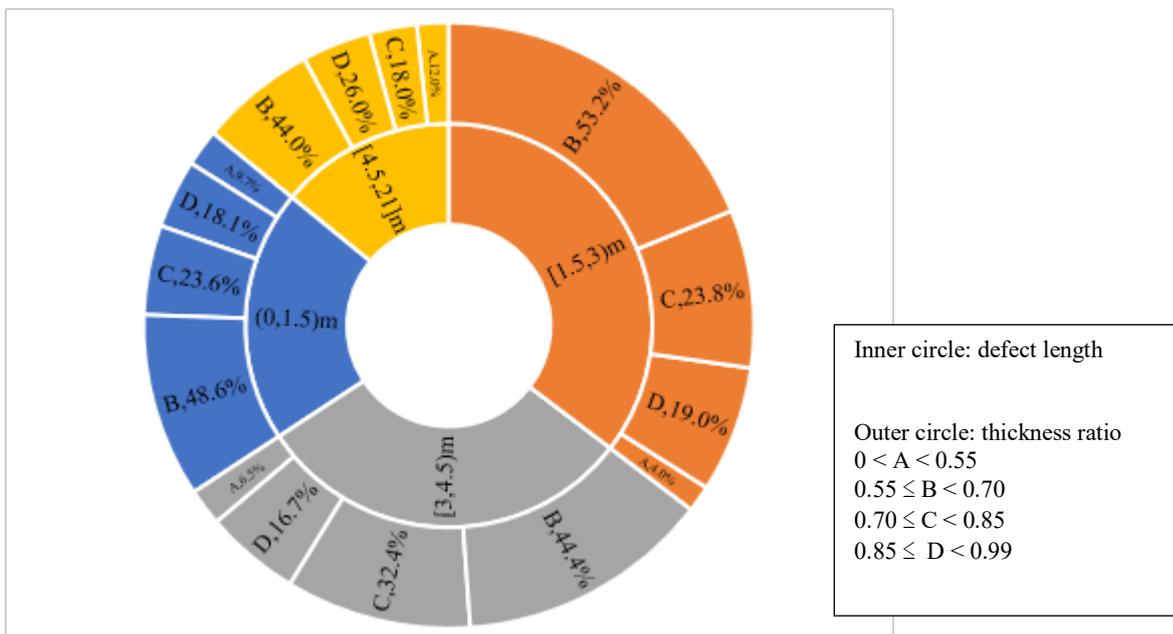
5.3 Relationship between Defect Location and Thickness Ratio

The relationship between defect location and thickness ratio is shown in Figure 7. The inner circle shows the locations of defects. The vault, left or right of the vault, is the most popular location of insufficient thickness. The outer circle presents the proportion of defects with different thickness ratios at a specific defect location. In all the defect locations, the thickness ratio between 0.55 and 0.7("B" in Figure 7) is the largest proportion interval, with a proportion of 55.2 percent for the defects in the vault, 44.1% at the left or right of the vault, and 42.4% at the arch waist.

Inner circle: defect Location

Outer circle: thickness ratio
$0 < A < 0.55$
$0.55 \leq B < 0.70$
$0.70 \leq C < 0.85$
$0.85 \leq D < 0.99$
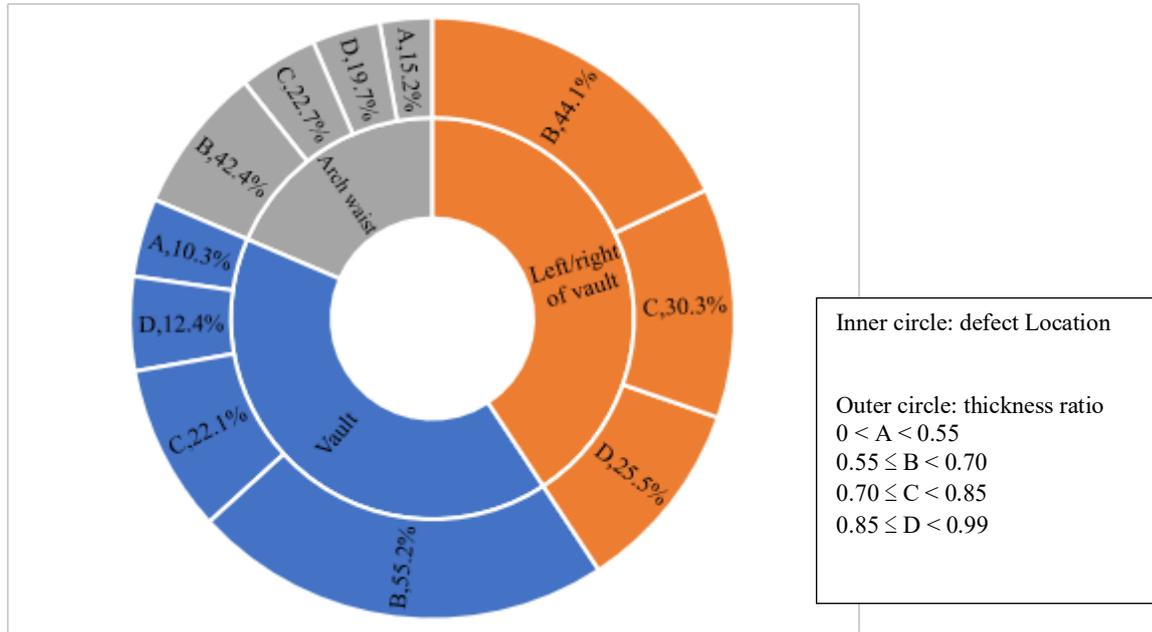
Fig. 7 *Relationship between defect location and thickness ratio*

6. Numerical Simulation of Characteristic Indicators

6.1 Numerical Models and Material Properties

Numerical investigation was 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. FLAC3D software was used, and twelve working conditions were developed, which are shown in Table 3. These working conditions were divided into four groups to study the effect of parameter changes on structural safety, which are illustrated in Table 4.

Table 3 *Working conditions*

| Serial number	Surrounding rock classification	Location of defect	Thickness ratio of Lining	Length of defect /m
Condition 1	II	Vault	0.6	\
Condition 2	III	Vault	0.6	\
Condition 3	IV	Vault	0.6	\
Condition 4	V	Vault	0.6	\
Condition 5	IV	Left of Vault	0.6	\
Condition 6	IV	Left Arch Waist	0.6	\
Condition 7	IV	Vault	0.4	\
Condition 8	IV	Vault	0.8	\
Condition 9	IV	Vault	0.9	\
Condition 10	IV	Vault	0.6	2
Condition 11	IV	Vault	0.6	4

| Condition 12 | IV | Vault | 0.6 | 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 defect length was not formulated (refer to "\" in this table).

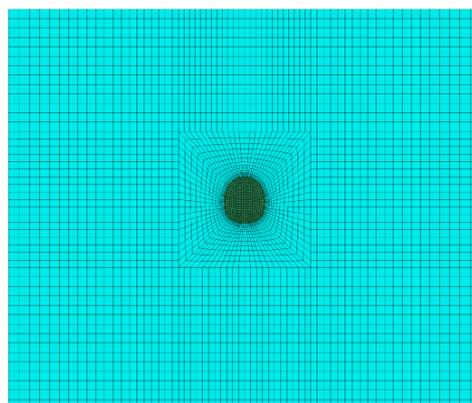**Table 4** *Grouping of working conditions*

Group	Working conditions	Research objective
The first group	Condition 1, 2, 3, 4	To study the influence of different surrounding rock classifications on the tunnel structural safety
The second group	Condition 3, 5, 6	To study the influence of different defect locations on the tunnel structural safety
The third group	Condition 3, 7, 8, 9	to study the influence of different thickness ratios on the tunnel structural safety
The fourth group	Condition 10, 11, 12	To study the influence of different defect lengths on the tunnel 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.
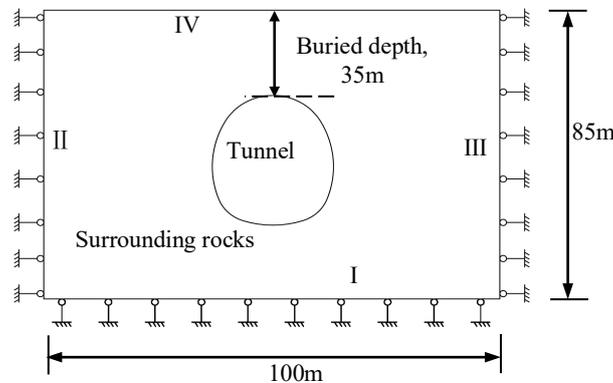

Fig. 8 *Cross-section of developed numerical model*

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*

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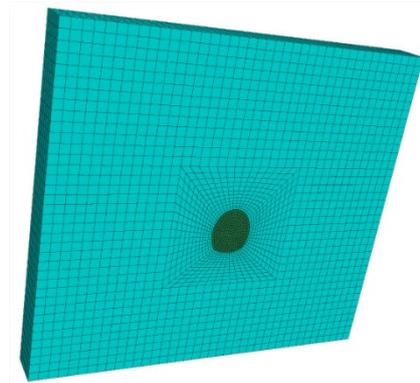
Fig. 10 *3D numerical model*

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 [23]. The elastic modulus and Poisson's ratio of the tunnel lining in all the working conditions are 31GPa and 0.2, separately. The invariant properties of the surrounding rock and tunnel lining under different working conditions are shown in Table 5.

Table 5 *Variable properties of rocks and concrete lining*

| Condition | Surrounding rock | | | | Concrete lining |
	Elastic modulus (GPa)	Poisson's ratio (MPa)	Internal friction angle (°)	Cohesion (MPa)	Thickness (m)
Condition1	25	1.7	55	0.22	0.24
Condition2	10	1	45	0.27	0.24
Condition3	5	0.5	33	0.32	0.24
Condition4	1	0.1	24	0.4	0.24
Condition5	5	0.5	33	0.32	0.24
Condition6	5	0.5	33	0.32	0.24
Condition7	5	0.5	33	0.32	0.16
Condition8	5	0.5	33	0.32	0.32
Condition9	5	0.5	33	0.32	0.36
Condition10\11\12	5	0.5	33	0.32	0.24

6.2 Stress Characteristics of Lining with Insufficient Thickness

From the numerical calculation results of Condition 3, the inner force of lining structure is shown in Figure 11. As seen in Figure 11(a), the axial force of the lining cross-section is symmetrically distributed concerning the central axis. Tension is represented by positive axial forces and pressure by negative axial forces. The axial force at the arch waist (refer to B, F) is relatively large, while the axial force at the inverted arch (i.e., H) and vault (i.e., D) is relatively tiny. The maximum axial force is -1004 kN at the arch waist of the lining (refer to B, F).

As seen in Figure 11(b), the moment of the lining cross-section is also symmetrically distributed concerning the central axis. Tension on the outside of the lining is represented by positive bending moments, while tension on the inside is represented by negative bending moments, as shown in Figure 11(b). The moment at the foot of the side wall (i.e., A, G) is relatively large; next is the moment in the inverted arch (i.e., H). The moment value in other positions of lining is relatively tiny. The maximum bending moment is 33.1 kN·m at the foot of the side wall of the lining (refer to A, G).
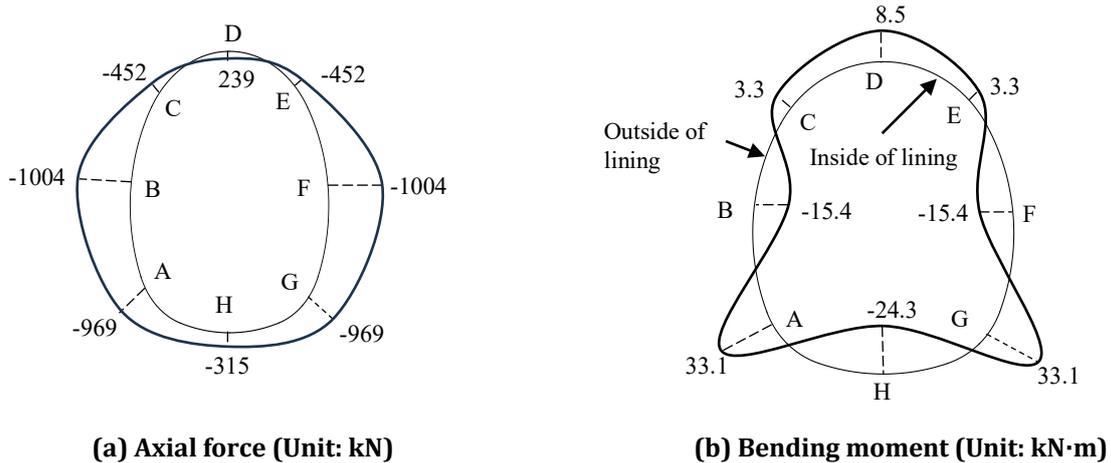
(a) Axial force (Unit: kN)   (b) Bending moment (Unit: kN·m)

Fig. 11 *Inner force of lining structure*

6.3 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 4). The structural safety factor is calculated according to the Code for Design of Railway Tunnel [23]. The results of inner forces and safety factors are shown in Table 6.

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 an insufficient thickness defect, especially as the surrounding rock becomes weaker.

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

The third group of conditions is dedicated to examining the impact of varying thickness ratios on the safety of the tunnel structure. As the thickness ratio increases, the actual thickness of the lining also grows, resulting in more significant axial force values and bending moments within the lining. The safety factor of the lining progressively rises in tandem with the inner force trend. Notably, in cases of insufficient thickness defects, a thicker lining enhances the structural safety of the lining, with higher thickness correlating to increased safety.

The fourth group of conditions aims to investigate the impact of varying defect lengths on the safety of the tunnel structure. As the defect length increases, there is minimal change (about 10.9%) in the internal force distribution within the 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.

Table 6 *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	29	1.9	12.35
	Condition2	134	5.4	8.98
	Condition3	239	8.5	5.89
	Condition4	1194	28.6	3.08
Second group	Condition3	239	8.5	5.89
	Condition5	209	7.8	6.47
	Condition6	189	6.7	7.52

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Third group	Condition7	191	4.6	1.32
	Condition3	239	8.5	5.89
	Condition8	274	12.8	8.21
	Condition9	288	14.9	9.30
Fourth group	Condition10	259	8.8	5.29
	Condition11	272	9.1	5.15
	Condition12	291	9.9	5.07

7. Results and Discussion of Fuzzy Comprehensive Evaluation Model

7.1 Fuzzy Comprehensive Evaluation Model of Lining Structure

The fuzzy comprehensive evaluation method is adopted to evaluate the structural safety of the lining with insufficient thickness. Based on the previous statistical and numerical analysis, the safety evaluation model of tunnel lining structure is established.

7.1.1 Factor Set

The first step of the fuzzy comprehensive evaluation is determining the factors affecting the 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 defects. The factor set of structural safety evaluation of lining is shown in Equation (2).

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

$$U = \left\{ \begin{array}{c} Surrounding\ rock\ classification, \\ Length\ of\ defect, Location\ of\ defect, \\ Thickness\ ratio \end{array} \right\} \tag{2}$$

7.1.2 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 comment set of structural safety evaluation of lining is determined according to the severity degree of the lining. This comment set is shown in Equation (4).

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

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

7.1.3 Membership Degree and Fuzzy Evaluation Matrix

If the membership degree of the factor ui corresponding to the comment vj is rij, 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 7. Then the results of the membership degree are shown in Table 8.

Table 7 *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 defects is the largest.	The weaker the surrounding rock is, the smaller the safety factor of lining is.
Length of defect	For the intervals of different defect lengths, the distribution characteristics of thickness ratio are almost the same.	With the increase of the defect length, the structural safety factor slightly decreases.
Location of defect	For the defects located in the vault, the thickness ratio between 0 and 0.7 has the largest proportion.	Defects of insufficient thickness at the vault have the greatest adverse impact on the lining, while defects at the arch waist have the least adverse impact.
Thickness ratio	For the different surrounding rock classifications, lengths and positions, the thickness ratio between 0 and 0.7 has the relatively large proportion.	When defect of insufficient thickness exists, the thicker the lining is, the higher the structural safety of lining is.

Table 8 *Results of membership degree*

Factor	Comment	Most serious	More serious	Serious	Slightly
Surrounding rock classification	II	0.1	0.1	0.2	0.5
	III	0.1	0.2	0.5	0.1
	IV	0.2	0.5	0.1	0.1
	V	0.5	0.2	0.1	0.1
Length of defect	(0,1.5) m	0.1	0.1	0.5	0.2
	[1.5,3) m	0.1	0.2	0.5	0.1
	[3,4.5) m	0.2	0.5	0.1	0.1
	[4.5, 21] m	0.5	0.2	0.1	0.1
Location of defect	Vault	0.6	0.2	0.15	0.05
	Left / right of vault	0.2	0.6	0.15	0.05
	Arch waist	0.15	0.2	0.6	0.05
Thickness ratio	(0,0.55)	0.6	0.2	0.1	0.1
	[0.55, 0.7)	0.2	0.6	0.1	0.1
	[0.7, 0.85)	0.1	0.2	0.6	0.1
	[0.85, 0.99]	0.1	0.1	0.2	0.6

7.1.4 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 weight matrix of structural safety evaluation of tunnel lining is determined according to the previous proportion analysis and numerical simulation. The analysis process for determining weight is shown in Table 9.

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Table 9 *Determination of weight*

Factor	Weight	Order of importance	According to proportion analysis	According to numerical simulation
Surrounding rock classification	0.3	Slightly important	The proportion difference of different length is relatively small, while the proportion difference of other three factors is relatively large.	When the defect location and thickness ratio change, the safety factor of lining changes obviously. When the defect length changes, the lining safety factor does not change significantly.
Length of defect	0.1	Not very important		
Location of defect	0.6	Very important		
Thickness ratio	0.5	Obviously important		

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

$$A = \{0.3, 0.1, 0.6, 0.5\} \tag{7}$$

7.1.5 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 [14], if the comment vj (refer to Equation (3)) corresponds to the maximum membership degree bj (refer to Equation (8)), then the comment vj is the final evaluation result.

7.2 Application of the Evaluation Model

A fuzzy comprehensive evaluation model is applied to the structural safety evaluation of an engineering case. An inadequacy in thickness is present in the lining of a tunnel along the Suiyu Railway. An investigation into this lining defect has been conducted, and comprehensive details regarding the defect can be found in Table 10.

Table 10 *Detailed information of the defect*

Characteristic indicator	Value
Surrounding rock classification	IV
Length of defect	4m
Location of defect	vault
Thickness of Lining	26cm
Thickness ratio	0.65

Detailed information on the fuzzy comprehensive evaluation process is shown in Table 11. The maximum value of the evaluation result is 0.62 in accordance with 'more serious' in the comment set (refer to Equation (4)). The structural safety level of the lining is 'more serious' according to the principle of maximum membership.

Table 11 *Detailed information of the evaluation process*

Item	Value
Factor set	{Surrounding rock classification, Length of defect, Location of defect, Thickness ratio}
Comment set	{Most serious, More serious, Serious, Slightly}

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Fuzzy evaluation matrix	$\begin{bmatrix} 0.2 & 0.5 & 0.1 & 0.1 \\ 0.2 & 0.5 & 0.1 & 0.1 \\ 0.6 & 0.2 & 0.15 & 0.05 \\ 0.2 & 0.6 & 0.1 & 0.1 \end{bmatrix}$
Weight set	$\{0.3, 0.1, 0.6, 0.5\}$
Evaluation result	$\{0.54, 0.62, 0.18, 0.12\}$

7.3 Validation of the Evaluation Model

The numerical investigation is adopted to analyse the inner force and safety factor of the tunnel lining structure with the insufficient thickness defect (refer to Table 10). The numerical model is similar to Figure 10. The results of the axial force, bending moment and safety factor at the lining defect are 265kN, 8.8 kN·m, and 5.20, respectively.

Tunnel lining structures can be categorized into different safety levels based on different safety factors [9,23]. The safety factor and safety level of lining structure are shown in Table 12.

As the safety factor of the tunnel lining is 5.20, 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 fuzzy comprehensive evaluation model in this paper is validated.

Table 12 *Safety factor and safety level of lining*

Safety factor, α	Safety level
$0 < \alpha < 2.4$	Most serious
$2.4 \leq \alpha < 5.5$	More serious
$5.5 \leq \alpha < 8$	Serious
$8 \leq \alpha < +\infty$	Slightly

Therefore, the fuzzy comprehensive evaluation model is used to assess the safety of lining structures with insufficient thickness, which can avoid the trouble of numerical modelling and also ensure the correctness of the assessment results.

Consequently, the fuzzy comprehensive evaluation model is utilized to assess the safety of tunnel structures with insufficient lining thickness. This approach avoids the complexity of numerical modeling and ensures the accuracy of assessment results. The proposed fuzzy comprehensive evaluation model is based on tunnels excavated in mudstone and has undergone validation on the Suiyu Railway. However, tunnels are constructed within varying geological conditions, which can lead to different distribution characteristics of lining defects. Developing evaluation models within various geological conditions will be the next research focus.

8. Conclusion

This paper delves into the safety assessment of tunnel structures with insufficient lining thickness, 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) Defect data is collected according to the characteristic indicators. The selected characteristic indicators of insufficient thickness are surrounding rock classification, length of defect, location of defect, and thickness ratio.
2) Proportion of defects based on different indicators is analyzed. The most significant percentage of defect length is between 3m and 4.5m, and the most significant thickness ratio is between 0.55 and 0.7. The proportion of defects in rocks of class IV and at the vault is the largest. Then, the relationship between the thickness ratio and the other three indicators is analyzed. Regarding surrounding rock classification, defect location, and defect length, a thickness ratio between 0.55 and 0.7 is the most significant proportion interval.
3) Numerical simulation is conducted to explore the effect of these parameters on the structural safety of lining with defects. The change of defect lengths has a not very obvious effect on the safety factor of the lining. In contrast, the changes in the other three parameters can have an obvious impact on the structural safety factor.

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4) According to the previous statistical analysis (refer to proportion analysis and relationship analysis) and numerical analysis, the fuzzy evaluation model is established. The factor set comprises four factors, while the comment set also consists of four comments. 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.

5) 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.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** *Yiming Wang, Hazrina Mansor;* **data collection:** *Yiming Wang;* **analysis and interpretation of results:** *Yiming Wang, Hazrina Mansor, Thevaneyan Krishta David;* **draft manuscript preparation:** *Yiming Wang, Hazrina Mansor, Thevaneyan Krishta David. All authors reviewed the results and approved the final version of the manuscript.*

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