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# RETRACTED ARTICLE Fuzzy Evaluation Model for In-service Karst Highway Tunnel Structural Safety

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## Abstract

To analyze in-service tunnel structure safety, the coupling effect of a multi-factor should be considered. The karst highway tunnel structure safety is classified into five grades based on a railway tunnel health evaluation model. The factors affecting tunnel structure safety are addressed using an analytic hierarchy process. Qualitative indices are classified into five levels according to tunnel safety. A membership function that follows the Gaussian distribution is applied to determine quantitative evaluation indices. Those factors are assigned weights by expert scoring method of system theory, and the treated karst caves are set up as an uncompacted backfill model. A three-grade fuzzy comprehensive evaluation model is finally built for in-service highway tunnel structure safety in the karst area. The safety of Hui-long-shan tunnel is evaluated, and the safety value is judged by the maximum membership law according to the proposed model.

Keywords: *in-service highway tunnel, tunnel structure safety, treated karst cave, fuzzy evaluation model*

## 1. Introduction

“Safety First, Precaution Crucial” is the main policy in engineering construction and service. This is particularly important in underground constructions, especially tunnels. Most of the traditional decision making methods for tunnel structural safety are based on the investigation and detection of tunnel damage, and a diagnosis model that analyzes tunnel safety is established. However, the traditional methods are still not perfect. First, they cannot be used as calculation models for all tunnel damages. Second, the correlations between damages are not fully considered. These methods cannot accurately assess tunnel safety by using a single analysis. Therefore, the multi-factor coupling effect should be considered in assessing tunnel structural safety.

Fuzzy theory is a new method that is used for comprehensive evaluation. Based on fuzzy theory and the fuzzy relation composite principle, factors with fuzzy boundaries can be simply quantified. A fuzzy comprehensive evaluation can be used to guarantee the qualitative evaluation indices to quantify and the quantitative indices to approximate accurate values (Kaufmann, 1988; Li, 1991; Chen, 1998; Joo *et al.,* 2001; Xin *et al.,* 2001; Panou *et al.,* 2002; Lu *et al.,* 2003). Some scholars have established a multi-level fuzzy comprehensive judgment model for the safety of railway tunnels and deep foundation pit support structures. Hong and Liu (2011) attempted to establish a mathematical model for the quantitative determination of railway tunnel health, but this model could only provide qualitative determination. A multi-level fuzzy comprehensive evaluation model for deep excavation engineering and its support system has been presented by Lv (1999). Wang (2012) sorted tunnel damages and evaluated the health status for an in-service tunnel with a three-grade fuzzy evaluation model, but the influence of karst caves was not considered. Li (2004) provided an evaluation method for a complex soft ground with a fuzzy comprehensive evaluation and a discrete sample model.

Based on the above-mentioned studies and other available information (Al-Labadi *et al.,* 2005, 2009; Cheng *et al.,* 2007; Ebrahim *et al.,* 2012; Li *et al.,* 2013; Kazaras *et al.,* 2013), some studies have analyzed structural safety assessment using fuzzy theory. However, no study on the structural safety of in-service karst tunnel involving the afore-mentioned methods is available. Many qualitative and quantitative indices show uncertainty, ambiguity, or complexity in the karst highway tunnel safety evaluation. In the present paper, a fuzzy comprehensive evaluation model for evaluating in-service karst highway tunnel safety is proposed based on the fuzzy theory. An engineering example is analyzed to verify the feasibility of the proposed method.

## 2. The Safety Classification

The safety classification on karst highway tunnel (Yang, 2012), which is based on the related health evaluation model of railway tunnel, is shown in Table 1. According to seven major parameters, the highway tunnel safety is divided into five grades,

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as follows: safe (I), generally safe (II), minimally unsafe (III), unsafe (IV), and extremely unsafe (V). Grade I means no potential safety hazard and no influence on traffic. The in-service tunnel structure system needs normal repair and maintenance. Grade II also means safety hazards exist in an in-service tunnel structure system, but they do not influence traffic safety. The highway tunnel safety can return to Grade I by adopting necessary maintenance. Grade III shows that the in-service tunnel structure system has some potential safety hazards and is unsafe. The hazards have not influenced traffic safety yet. Maintenance enhancement is needed to reinstate safety to Grade II. Grade IV is unsafe for in-service tunnels and may compromise traffic safety. If timely and reliable conservation measures are not taken, tunnel safety level may drop to Grade V. Grade V is extremely unsafe, and the factors contributing to the lack of security are endangering traffic. Maintenance measures should be taken immediately. ***Notes***: **Maintenance** means taking necessary actions to keep tunnels serving normally. **Repair** means to take necessary measures to make tunnels hold their original function when damages occur.

Tunnel safety level is normally related to tunnel defects, lining cracks, original engineering geology, hydrogeology, structural design, and construction process. Moreover, the following factors should be considered: surrounding rock deterioration during tunnel service, load changes caused by lining dehiscence, lining deterioration, rapid lining deformation, and tunnel clearance deficiency. An accurate assessment of the influence of these factors on tunnel safety is difficult to achieve. In the evaluation model, the data of tunnel construction, service state, tunnel structure damages, and tunnel inspection of lining state are first collected and analyzed. The main parameters that affect tunnel structural safety are then graded (Table 1).

## 3. Hierarchical Division of Influencing Factors

In fuzzy theory, many factors are fuzzy and need to be considered for the evaluation of complex systems. Moreover, most of these factors are in different layers, which means some of these factors are determined by a number of other layers. For example, in the safety evaluation of highway tunnel, the state of the contact between surrounding rock and lining, surrounding rock deterioration, lining deterioration, leakage, frost damage, and lining material deterioration must be mentioned. These factors are in the first level. Some of these first level factors also include multiple levels, such as the evaluation of the contact state between surrounding rock and lining, which in turn is determined by the cavity behind lining, the uncompacted backfill behind lining, and the uncompacted basis, all of which are in the second level. Some second level factors are determined by third level factors, such as the evaluation of cavities behind lining, which is decided by **kLc** of vault and haunch. ***Notes***: **kLc** is the continuous length of hoop or longitudinal horizontal survey line with cavities behind the lining; **sLc** is the continuous length of hoop or longitudinal horizontal survey line with uncompacted backfill behind the lining; **dLc** is the continuous length of hoop or longitudinal horizontal survey line with uncompacted basis. Therefore, a multi-level fuzzy comprehensive evaluation should be adopted for the multi-factor and multi-level systems.

Hierarchical division of the various factors is performed according to a multi-level fuzzy comprehensive evaluation method (Fig. 1). A total of 21 single factors are included in the one-grade evaluation. These single factors are used to evaluate 10 two-grade factors, as follows: cavity, uncompacted backfill, vault crushing, cracks, construction joint leakage, crack leakage, lining concrete leakage, drainage system, hanging ice, and rock frost heave. The two-grade evaluation contains the two-grade factors and 17 new single factors, which are applied to evaluate six three-grade factors. These factors are contact states between surrounding rock and lining, lining dehiscence, leakage, frost damage, lining deterioration, lining deformation, and tunnel clearance deficiency. In the three-grade evaluation, three-grade factors and two new single factors are selected to evaluate the in-service tunnel safety.

## 4. Three-grade Fuzzy Comprehensive Evaluation Model

### 4.1 Main Parameters

According to the hierarchical division of factors for tunnel safety, the three-grade fuzzy comprehensive evaluation model can be set up as follows (Eq. (1)):

Table 1. The Karst Highway Tunnel Safety Classification

| Safety grade / Major parameters | I | II | | III | | | IV | | | V | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Safe | Generally safe | | Minimally unsafe | | | Unsafe | | | Extremely unsafe | | |
| Contact state between surrounding rock and lining | None | 1 | 1 or 2 | 2 | 1 or 2 or 3 | 1 or 2 or 3 | 3 | 1 or 2 or 3 or 4 | 1 or 2 or 3 or 4 | 4 | 4 | 3 |
| Surrounding rock deterioration | None | 1 | 1 or 2 | 2 | 1 or 2 or 3 | 1 or 2 or 3 | 3 | 1 or 2 or 3 | 1 or 2 or 3 | 4 | 1 or 2 or 3 | A parameter rate as level 4. |
| Lining dehiscence | None | 1 | 1 | 2 | 2 | 1 or 2 | 3 | 3 | 1 or 2 or 3 | 4 | 1 or 2 or 3 | |
| Leakage and frost damage | None | 1 | 1 or 2 | 2 | 1 or 2 or 3 | 1 or 2 or 3 | 3 | 1 or 2 or 3 or 4 | 1 or 2 or 3 or 4 | 4 | 1 or 2 or 3 | |
| Lining deterioration | None | 1 | 1 | 2 | 1 or 2 | 2 | 3 | 1 or 2 or 3 | 3 | 4 | 1 or 2 or 3 | |
| Lining deformation and clearance deficiency | None | 1 | 1 or 2 | 2 | 1 or 2 or 3 | 1 or 2 or 3 | 3 | 1 or 2 or 3 | 1 or 2 or 3 | 4 | 1 or 2 or 3 | |
| Impact on traffic safety | None | 1 | | 2 | | | 3 | | | 4 | | |

Notes: In this table, 1, 2, 3, and 4 represent the main parameter levels; "or" indicates which level meets the requirements if one case occurs.

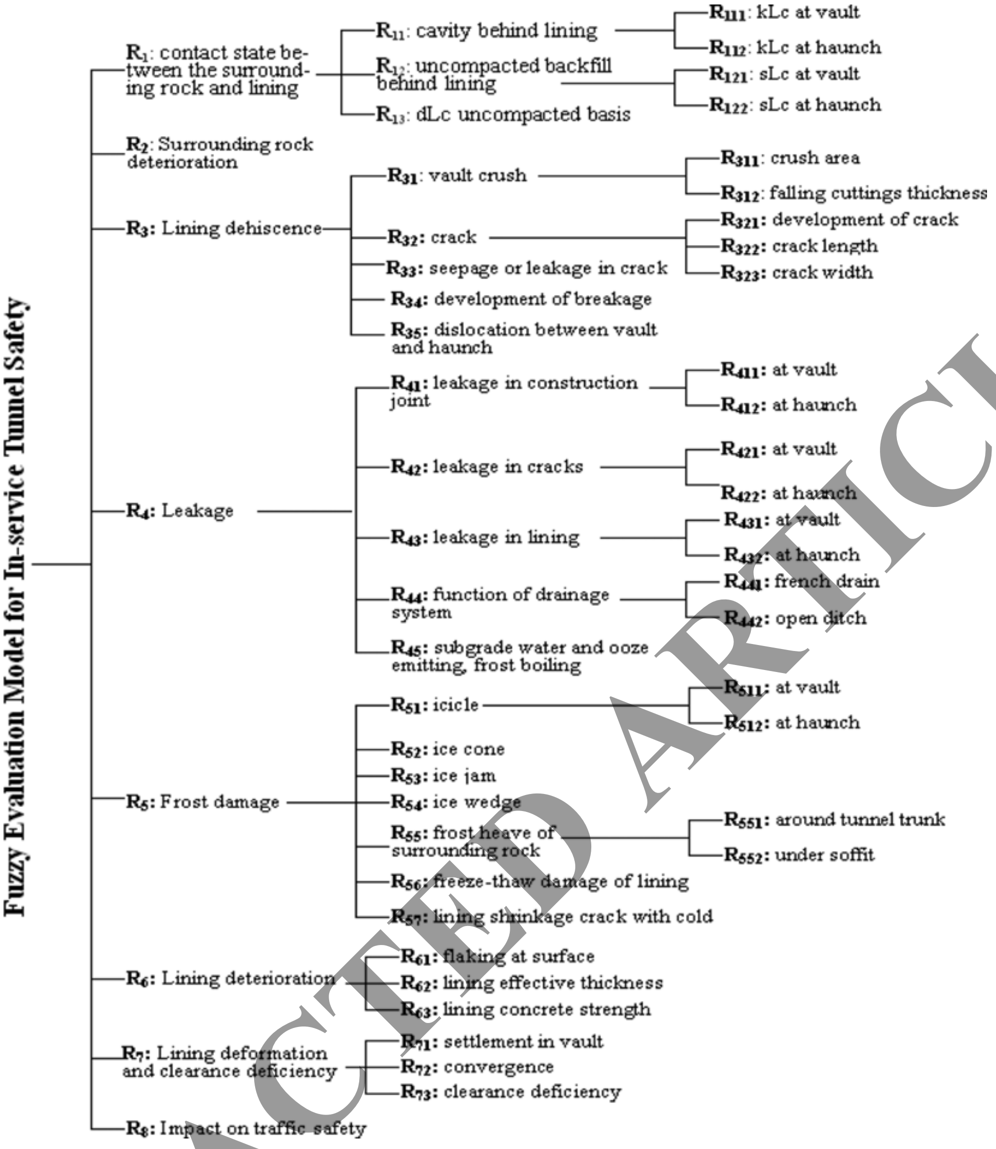

Fig. 1. Hierarchical Divisions of Tunnel Safety Factors

$$B = A\cdot P = A\cdot\begin{bmatrix} A_1\cdot P_1 \\ A_2\cdot P_2 \\ \cdots \\ A_n\cdot P_n \end{bmatrix} = A\cdot\begin{bmatrix} A_1\cdot\begin{bmatrix} A_{11}\cdot P_{11} \\ A_{12}\cdot P_{12} \\ \cdots \\ A_{21}\cdot P_{1n} \end{bmatrix} \\ A_2\cdot\begin{bmatrix} A_{21}\cdot P_{21} \\ A_{22}\cdot P_{22} \\ \cdots \\ A_{2n}\cdot P_{2n} \end{bmatrix} \\ A_n\cdot\begin{bmatrix} A_{n1}\cdot P_{n1} \\ A_{n2}\cdot P_{n2} \\ \cdots \\ A_{nn}\cdot P_{nn} \end{bmatrix} \end{bmatrix} \tag{1}$$

In Eq. (1), $A$ is the weight vector in a three-grade evaluation, $A_i$ ($i = 1...,\ 2,\ ...,\ n$) is the weight vector of a two-grade evaluation, and $A_{ij}$ ($i = 1, 2, ..., nj = 1, 2, ..., m$) is the weight vector in a one-grade evaluation. $P$ shows the fuzzy evaluation matrix for a three-grade evaluation, $P_i$ ($i = 1, 2, \ldots, n$) shows the fuzzy evaluation matrix from a two-grade evaluation, and $P_{ij}$ ($i = 1, 2, \ldots n; j = 1, 2, \ldots, m$) shows the fuzzy evaluation matrix of a one-grade evaluation. $B$ is the object of fuzzy comprehensive evaluation. "·" indicates the composition operator in that fuzzy matrix. Moreover, three weight vectors ($A$, $A_i$, and $A_{ij}$), three fuzzy matrixes ($P$, $P_i$, and $P_{ij}$) and a composition operator ("·") are present, all of which need to be determined in Eq. (1).

## 4.2 The Fuzzy Evaluation Matrix

In the fuzzy evaluation matrix, the membership function is applied to determine the quantitative evaluation indices. The Gaussian distribution is adopted for these quantitative indices, and the membership function of safety level ***N*** for the evaluation indices $\boldsymbol{R}_{ij}$ and $\boldsymbol{R}_{ijk}$ (Eq. (2)) is as follows:

$$A_N(x) = e^{-[(x-a)/b]^2} \tag{2}$$

In Eq. (2), *x* means the index value of $\boldsymbol{R}_{ij}$ or $\boldsymbol{R}_{ijk}$; ***a*** comes from the average value of the upper and lower limits in the interval of $[x_1, x_2]$ for $\boldsymbol{R}_{ij}$ or $\boldsymbol{R}_{ijk}$, i.e., $\boldsymbol{a} = (x_1+x_2)/2$. When the boundary values of the indices belong to two levels, they have the same membership values as the two levels and are thereby are set as 0.5 (Eq. (3)), as follows:

$$e^{-[(x_1-x_2)/(2b)]^2} = 0.5 \tag{3}$$

***b*** can be calculated from Eq. (3) (Eq. (4)), as follows:

$$b = (x_1 - x_2)/1.665 \tag{4}$$

In Eqs. (3) and 4, $\boldsymbol{x}_1$ is the lower limit value, and $\boldsymbol{x}_2$ is the upper limit value. The membership is normalized when Eq. (5) is satisfied, as follows:

$$\sum_{k=1}^{5} A_k(x) \neq 1 \tag{5}$$

The quantitative index values are from Table 2. Every qualitative index (Fig. 1) is a discrete single factor, and its membership values can be obtained from Table 3. By the influence of tunnel safety, the qualitative indices are classified into five levels, as follows: no influence, slight influence, minor serious influence, serious influence, and extremely serious influence. In case of no influence, the membership function value is determined by the axial compressive strength standard value, with 95% guaranteed rate in the design of concrete structures. The criteria of the classification indicators can be obtained from Yang (2012).

Table 2. Quantitative Assessment Index Values and Divisions

| Single factors | Safe | General safe | Minor unsafe | Unsafe | Extremely unsafe |
|---|---|---|---|---|---|
| $\boldsymbol{R}_{13}$ / m | 0–3 | 3–9 | 9–15 | 15–18 | >18 |
| $\boldsymbol{R}_{35}$ / cm | 0–1 | 1–3 | 3–5 | 5–10 | >10 |
| $\boldsymbol{R}_{111}$ / m | 0–3 | 3–5 | 5–7 | 7–$L_2$* | $L_2$ |
| $\boldsymbol{R}_{112}$ / m | 0–3 | 3–5 | 5–7 | 7–$L_2$ | $L_2$ |
| $\boldsymbol{R}_{121}$ / m | 0–3 | 3–5 | 5–7 | 7–$L_2$ | $L_2$ |
| $\boldsymbol{R}_{122}$ / m | 0–3 | 3–5 | 5–7 | 7–$L_2$ | $L_2$ |
| $\boldsymbol{R}_{311}$ / $m^2$ | 0–0.2 | 0.2–1 | 1–3 | 3–5 | >5 |
| $\boldsymbol{R}_{312}$ / m | 0–1 | 1–3 | 3–5 | 5–10 | >10 |
| $\boldsymbol{R}_{322}$ / m | 0–3 | 3–5 | 5–10 | 10–15 | >15 |
| $\boldsymbol{R}_{323}$ / mm | 0–3 | 3–5 | 5–10 | 10–20 | >20 |

*$L_2$ means the length of construction section.

### 4.3 Weight Vector

In all levels of the fuzzy comprehensive evaluation, the weight vector determines the impact of various factors, and the weight assignation directly affects the evaluation results. Moreover, this weight assignment comes from the fuzzy statistical theory and the use of expert scoring method. Therefore, according to engineering and experts, the average values are taken as the weight set of the fuzzy evaluation (Table 4) according to the degree of importance of various factors that affect in-service highway tunnel structural safety.

### 4.4 Matrix Operation

To retain all the useful information in this fuzzy model, the operator of ***M*(•, +)** is used for the fuzzy matrix composition operation by fuzzy mathematics theory. Neither the weight coefficients nor evaluation matrix coefficients have an upper limit.

Table 3. Qualitative Index Membership Function Values

| Single factors | Index values | Safe | Generally safe | Minimally unsafe | Unsafe | Extremely unsafe |
|---|---|---|---|---|---|---|
| $\boldsymbol{R}_1$–$\boldsymbol{R}_8$, $\boldsymbol{R}_{11}$–$\boldsymbol{R}_{12}$, $\boldsymbol{R}_{31}$–$\boldsymbol{R}_{34}$, $\boldsymbol{R}_{41}$–$\boldsymbol{R}_{45}$, $\boldsymbol{R}_{51}$–$\boldsymbol{R}_{57}$, $\boldsymbol{R}_{61}$–$\boldsymbol{R}_{63}$, $\boldsymbol{R}_{71}$–$\boldsymbol{R}_{73}$, $\boldsymbol{R}_{321}$, $\boldsymbol{R}_{411}$–$\boldsymbol{R}_{412}$, $\boldsymbol{R}_{421}$–$\boldsymbol{R}_{422}$, $\boldsymbol{R}_{431}$–$\boldsymbol{R}_{432}$, $\boldsymbol{R}_{441}$–$\boldsymbol{R}_{442}$, $\boldsymbol{R}_{511}$–$\boldsymbol{R}_{512}$, $\boldsymbol{R}_{551}$–$\boldsymbol{R}_{552}$ | No influence | 0.95 | 0.03 | 0.02 | 0.00 | 0.00 |
| | Slight influence | 0.35 | 0.30 | 0.20 | 0.10 | 0.05 |
| | Minor serious influence | 0.20 | 0.20 | 0.40 | 0.10 | 0.10 |
| | Serious influence | 0.10 | 0.25 | 0.30 | 0.20 | 0.15 |
| | Extremely serious influence | 0.05 | 0.15 | 0.20 | 0.25 | 0.35 |

Table 4. The Weight Vectors of Fuzzy Evaluation

| Relations between layers | Weight vectors | Relations between layers | Weight vectors |
|---|---|---|---|
| $\boldsymbol{B} \leftarrow \boldsymbol{R}_1$–$\boldsymbol{R}_8$ | $A$=[0.15,0.10,0.20, 0.10, 0.10, 0.10, 0.15, 0.10] | $\boldsymbol{R}_{31} \leftarrow \boldsymbol{R}_{311}$–$\boldsymbol{R}_{312}$ | $A_{31}$=[0.40, 0.60] |
| $\boldsymbol{R}_1 \leftarrow \boldsymbol{R}_{11}$–$\boldsymbol{R}_{13}$ | $A_1$=[0.40, 0.40, 0.20] | $\boldsymbol{R}_{32} \leftarrow \boldsymbol{R}_{321}$–$\boldsymbol{R}_{323}$ | $A_{32}$=[0.40, 0.30, 0.30] |
| $\boldsymbol{R}_3 \leftarrow \boldsymbol{R}_{31}$–$\boldsymbol{R}_{35}$ | $A_3$= [0.25, 0.25, 0.10, 0.20, 0.20] | $\boldsymbol{R}_{41} \leftarrow \boldsymbol{R}_{411}$–$\boldsymbol{R}_{412}$ | $A_{41}$=[0.55, 0.45] |
| $\boldsymbol{R}_4 \leftarrow \boldsymbol{R}_{41}$–$\boldsymbol{R}_{45}$ | $A_4$=[0.20, 0.20, 0.20, 0.25, 0.15] | $\boldsymbol{R}_{42} \leftarrow \boldsymbol{R}_{421}$–$\boldsymbol{R}_{422}$ | $A_{42}$=[0.55, 0.45] |
| $\boldsymbol{R}_5 \leftarrow \boldsymbol{R}_{51}$–$\boldsymbol{R}_{57}$ | $A_5$=[0.20, 0.20, 0.10, 0.10, 0.10, 0.20, 0.10] | $\boldsymbol{R}_{43} \leftarrow \boldsymbol{R}_{431}$–$\boldsymbol{R}_{432}$ | $A_{43}$=[0.55, 0.45] |
| $\boldsymbol{R}_6 \leftarrow \boldsymbol{R}_{61}$–$\boldsymbol{R}_{63}$ | $A_6$=[0.30, 0.40, 0.30] | $\boldsymbol{R}_{44} \leftarrow \boldsymbol{R}_{441}$–$\boldsymbol{R}_{442}$ | $A_{44}$=[0.45, 0.55] |
| $\boldsymbol{R}_7 \leftarrow \boldsymbol{R}_{71}$–$\boldsymbol{R}_{73}$ | $A_7$=[0.20, 0.30, 0.50] | $\boldsymbol{R}_{51} \leftarrow \boldsymbol{R}_{511}$–$\boldsymbol{R}_{512}$ | $A_{51}$=[0.60, 0.40] |
| $\boldsymbol{R}_{11} \leftarrow \boldsymbol{R}_{111}$–$\boldsymbol{R}_{112}$ | $A_{11}$=[0.60, 0.40] | $\boldsymbol{R}_{55} \leftarrow \boldsymbol{R}_{551}$–$\boldsymbol{R}_{552}$ | $A_{55}$=[0.45, 0.55] |
| $\boldsymbol{R}_{12} \leftarrow \boldsymbol{R}_{121}$–$\boldsymbol{R}_{122}$ | $A_{12}$=[0.60, 0.40] | | |

## 5. Applications—Hui-long-shan Tunnel Conclusion

### 5.1 Overview of Hui-long-shan Tunnel

The Hui-long-shan tunnel was built in 2010. It is a separated tunnel that belongs to Shaogan Highway with six lanes in two directions. Its net width is 14.5 m in the main section and 17.0 m in the emergency parking section. The left line of Hui-long-shan tunnel is 1,155 m (ZK3+790 to ZK4+945), whereas the right line is 1,145 m (YK3+800 to YK4+945). The vertical section of the left line is shown in Fig. 2. Twenty-seven karst caves have been treated with mortar flag stones during the typical karst tunnel construction. Although the karst area has been meticulously disposed, the health status and the potential risk of the tunnel remains ambiguous after being subjected to sustained overload.

To determine the health status of this tunnel, geological radar scanning, lining strength testing, lining surface imaging, and headroom sectional measuring are applied (Fig. 3). These techniques can provide technical support for the safe and efficient service of Hui-long-shan tunnel.

After a series of surveys, the main damages are summarized as follows:

(1) Five cavities are present behind the vault lining of the left tunnel, and their lengths are 2, 0.5, 1, 3, 3, and 2 m (Table 5). Only one cavity with a length of 2 m is found at the same position in the right tunnel.

(2) Lining damages have been developed to some degree, but these damages have no impact on traffic safety yet. One ring through-crack is found on the left tunnel, and the maximum width is approximately 3 mm. This crack is roughly parallel to the tunnel cross section. Six cracks are discovered on the right tunnel, and their maximum widths are 1.5, 1, 1, 1, 1.5, and 2 mm. These cracks are circumferential throughout the entire cross-section. The fracture strike roughly parallel to the tunnel cross-section and cracks develop slowly, and a few cracks are leaking. The breakage of the entire lining develops slowly.

(3) Without the occurrence of crushing and material deterioration, the effective lining thickness still corresponds to the design. However, slight peeling with an area of 0.3 m$^2$ and thickness of 1.5 cm occurs on the vault lining. The lining concrete strength also slightly declines.

(4) The backfill is compacted, but intensive caves behind the longitudinal lining of the vault and haunch are present. Given that the elastic modulus of karst cave filler is smaller than that of surrounding rock, the filler can be simplified by uncompacted backfill model, and the continuous length is the original cave size (Rao, 2012). The uncompacted backfill continuous lengths

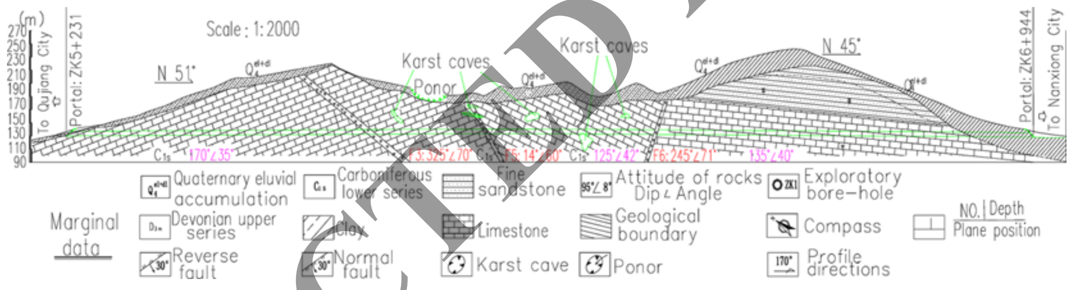

Fig. 2. Longitudinal Section of Left Line at Hui-long-shan Tunnel

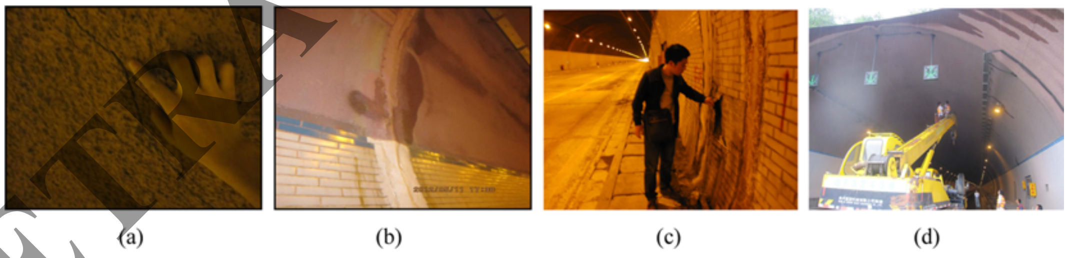

Fig. 3. Damages Investigation and Detection for Hui-long-shan Tunnel: (a) Lining Cracks, (b) Lining Seepage, (c) Lining Breakage, (d) GPR Scanning

Table 5. Lining Quality Defects of Hui-long-shan Tunnel

| Positions | Stakes | Measuring lines | Damage | Surrounding rock grades |
|---|---|---|---|---|
| Left tunnel | ZK4+264–ZK4+262 | Vault | cavity | V |
| | ZK4+102–ZK4+101 | Vault | cavity | III |
| | ZK4+008–ZK3+007 | Vault | cavity | IV |
| | ZK3+878–ZK3+875 | Vault | cavity | V |
| | ZK3+860–ZK3+857 | Vault | cavity | V |
| Right tunnel | YK4+869–YK4+871 | Vault | cavity | V |

are 7.5, 7, and 6.8 m behind the vault, haunch, and soffit, respectively (within measuring line).

(5) Settlement exists in the vault, but in a steady state. The clearance shows slow convergence without intruding tunnel limit and leakage.

## 5.2 The Fuzzy Evaluation Process and Results Analysis

From the detection and investigation of Hui-long-shan tunnel, the various quantitative and qualitative index values are shown in Tables 6 and 7. To analyze the highest possible state of insecurity, all these indices values are the most unfavorable ones.

Each single factor has been plugged into the membership function or table. The fuzzy evaluation matrix is determined, and the evaluation results at all grades are solved according to Eq. (1) in proper order.

### 5.2.1 The Third Grade Fuzzy Evaluation

The third grade fuzzy evaluation results are shown, as follows:

$$
\begin{aligned}
B_{11} &= A_{11} \cdot P_{11} = [0.305 \ \ 0.474 \ \ 0.178 \ \ 0.043 \ \ 0] \\
B_{12} &= A_{12} \cdot P_{12} = [0 \ \ 0 \ \ 0.348 \ \ 0.652 \ \ 0] \\
B_{31} &= A_{31} \cdot P_{31} = [0.066 \ \ 0.815 \ \ 0.070 \ \ 0.011 \ \ 0.038] \\
B_{32} &= A_{32} \cdot P_{32} = [0.349 \ \ 0.349 \ \ 0.217 \ \ 0.045 \ \ 0.040] \\
B_{41} &= A_{41} \cdot P_{41} = [0.35 \ \ 0.30 \ \ 0.20 \ \ 0.10 \ \ 0.05] \\
B_{42} &= A_{42} \cdot P_{42} = [0.680 \ \ 0.152 \ \ 0.101 \ \ 0.045 \ \ 0.022] \\
B_{43} &= A_{43} \cdot P_{43} = [0.680 \ \ 0.152 \ \ 0.101 \ \ 0.045 \ \ 0.022] \\
B_{44} &= A_{44} \cdot P_{44} = [0.35 \ \ 0.30 \ \ 0.20 \ \ 0.10 \ \ 0.05] \\
B_{51} &= A_{41} \cdot P_{51} = [0.095 \ \ 0.03 \ \ 0.02 \ \ 0 \ \ 0] \\
B_{55} &= A_{55} \cdot P_{55} = [0.95 \ \ 0.03 \ \ 0.02 \ \ 0 \ \ 0]
\end{aligned}
$$

From the third grade fuzzy evaluation results, $B_{11}$ shows a cavity behind the lining (Fig. 1). The five elements in $B_{11}$ correspond to the five grades (I–V) in Table 1. Thus, the grade is generally safe and tends to be safe according to the principle of maximum membership. $B_{12}$ shows an uncompacted backfill behind the lining. Its grade is unsafe and tends to minimally unsafe. The other results in the third grade fuzzy evaluation can also be explained as $B_{11}$ and $B_{12}$.

Table 6. Values of quantitative indices

| Indices | Values | Indices | Values | Indices | Values |
|---|---|---|---|---|---|
| $\boldsymbol{R}_{111}$ / m | 3 | $\boldsymbol{R}_{13}$ / m | 6.8 | $\boldsymbol{R}_{323}$ / mm | 3 |
| $\boldsymbol{R}_{112}$ / m | 5 | $\boldsymbol{R}_{311}$ / m$^2$ | 0.3 | $\boldsymbol{R}_{35}$ / cm | 0.8 |
| $\boldsymbol{R}_{121}$ / m | 7.5 | $\boldsymbol{R}_{312}$ / cm | 1.5 | | |
| $\boldsymbol{R}_{122}$ / m | 7 | $\boldsymbol{R}_{322}$ / m | 3 | | |

### 5.2.2 The Second Grade Fuzzy Evaluation

The second grade fuzzy evaluation results can be determined according to the third grade fuzzy evaluation results, as follows:

$$
\begin{aligned}
B_1 &= A_1 \cdot P_1 = [0.122 \ \ 0.455 \ \ 0.210 \ \ 0.213 \ \ 0] \\
B_3 &= A_3 \cdot P_3 = [0.343 \ \ 0.445 \ \ 0.132 \ \ 0.045 \ \ 0.035] \\
B_4 &= A_4 \cdot P_4 = [0.572 \ \ 0.200 \ \ 0.134 \ \ 0.063 \ \ 0.031] \\
B_5 &= A_5 \cdot P_5 = [0.95 \ \ 0.03 \ \ 0.02 \ \ 0 \ \ 0] \\
B_6 &= A_6 \cdot P_6 = [0.530 \ \ 0.219 \ \ 0.146 \ \ 0.070 \ \ 0.035] \\
B_7 &= A_7 \cdot P_7 = [0.650 \ \ 0.165 \ \ 0.110 \ \ 0.050 \ \ 0.025]
\end{aligned}
$$

$B_1$ shows the safety grade of the contact state between the surrounding rock and lining. It means the safe sate is generally safe and has the tendency to unsafe, i.e., generally safe and tends to unsafe.

$B_3$ shows the safety grade of lining dehiscence, i.e., generally safe and tends to safe.

$B_4 \sim B_7$ represent the safety grade of leakage and frost damage, lining deterioration, leakage and frost damage, impact on traffic safety. According to their results, they all mean the safe sate is safe and has the tendency to generally safe.

### 5.2.3 The First Grade Fuzzy Evaluation

The first grade fuzzy evaluation is shown, as follows:

$$
B = A \cdot P = \begin{bmatrix} 0.15 \\ 0.10 \\ 0.20 \\ 0.10 \\ 0.10 \\ 0.10 \\ 0.15 \\ 0.10 \end{bmatrix}^T \cdot \begin{bmatrix} 0.122 & 0.455 & 0.210 & 0.213 & 0 \\ 0.350 & 0.300 & 0.200 & 0.100 & 0.050 \\ 0.343 & 0.445 & 0.132 & 0.045 & 0.035 \\ 0.572 & 0.200 & 0.134 & 0.063 & 0.031 \\ 0.950 & 0.030 & 0.020 & 0 & 0 \\ 0.530 & 0.219 & 0.146 & 0.070 & 0.035 \\ 0.650 & 0.165 & 0.110 & 0.050 & 0.025 \\ 0.950 & 0.030 & 0.020 & 0 & 0 \end{bmatrix}
$$

$$
= [0.520 \ \ 0.260 \ \ 0.126 \ \ 0.072 \ \ 0.022]
$$

Table 7. Values of Qualitative Indices

| Indices | Values | Indices | Values | Indices | Values |
|---|---|---|---|---|---|
| $\boldsymbol{R}_{2}$ | Slight influence | $\boldsymbol{R}_{441}$ | Slight influence | $\boldsymbol{R}_{56}$ | No influence |
| $\boldsymbol{R}_{321}$ | Minor serious influence | $\boldsymbol{R}_{442}$ | Slight influence | $\boldsymbol{R}_{57}$ | No influence |
| $\boldsymbol{R}_{33}$ | Slight influence | $\boldsymbol{R}_{45}$ | No influence | $\boldsymbol{R}_{61}$ | Slight influence |
| $\boldsymbol{R}_{34}$ | Slight influence | $\boldsymbol{R}_{511}$ | No influence | $\boldsymbol{R}_{62}$ | Slight influence |
| $\boldsymbol{R}_{411}$ | Slight influence | $\boldsymbol{R}_{512}$ | No influence | $\boldsymbol{R}_{63}$ | No influence |
| $\boldsymbol{R}_{412}$ | Slight influence | $\boldsymbol{R}_{52}$ | No influence | $\boldsymbol{R}_{71}$ | Slight influence |
| $\boldsymbol{R}_{421}$ | No influence | $\boldsymbol{R}_{53}$ | No influence | $\boldsymbol{R}_{72}$ | Slight influence |
| $\boldsymbol{R}_{422}$ | Slight influence | $\boldsymbol{R}_{54}$ | No influence | $\boldsymbol{R}_{73}$ | No influence |
| $\boldsymbol{R}_{431}$ | No influence | $\boldsymbol{R}_{551}$ | No influence | $\boldsymbol{R}_{8}$ | Slight influence |
| $\boldsymbol{R}_{432}$ | Slight influence | $\boldsymbol{R}_{552}$ | No influence | | |

The five elements in matrix B correspond to the five safety levels (I to V) in Table 1. The first element (0.52) is the biggest in matrix B. The safe grade of this in-service karst tunnel structure is Level I, thereby indicating that the structure is safe and tends to be generally safe in this measuring section according to the fuzzy evaluation results with the principle of maximum membership. Only continuous normal conservation is needed to maintain the tunnel, and individual damage should be repaired by maintenance remediation, such as the flaking decorative layer and falling cuttings at vault.

## 6. Conclusions

1. A fuzzy comprehensive evaluation method for the safety of in-service karst highway tunnel is proposed. This method combines qualitative with quantitative indices and overcomes some deficiencies of the traditional evaluation methods based on empirical judgments.
2. The influence of treated karst caves is considered to evaluate safety in an in-service karst highway tunnel structure. The karst cave filler has a lower elastic modulus compared with the surrounding rocks and can be simplified using an uncompacted backfill model, which is used to build three-grade fuzzy comprehensive evaluation model. This model is successfully applied to the Hui-long-shan tunnel.
3. In the fuzzy evaluation model, the assessment parameters are based on the information of a real in-service karst highway tunnel, thereby indicating the health status of the tunnel to a great extent.
4. The membership function and value of each single factor index weight are important to obtain results in this fuzzy evaluation model. The model also needs optimization and constant improvement to achieve more reasonable and reliable evaluation results in engineering applications.

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