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ORIGINAL PAPER

Dynamic Risk Assessment Method of Collapse in Mountain Tunnels and Application

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Abstract The collapse is one of the most frequent and harmful geological hazards in the construction process of mountain tunnels. In order to effectively control the occurrence of collapse, a new dynamic risk assessment methodology for collapse based on attribute synthetic evaluation model was established, which includes primary assessment before the excavation and second assessment between excavation and support. According to statistical analysis of many collapse cases, the surrounding rock level I_1, rock mass integrity I_2, buried depth I_3, bias angle I_4, groundwater I_5, construction factors I_6 were selected as assessment indices. Their weights were calculated by using a combination method: subjective weight based on frequency statistic method and objective weight based on analytic hierarchy process. According to the proposed method, the Mountain Tunnel Collapse Risk Assessment System (TCAS) was developed to carry out the real-time assessment for collapse in the mountain tunnel. The TCAS was applied in Hongyansi Tunnel and Shimenya Tunnel. The results were a good agreement with actual excavation situation and the results of other methods.

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1 Introduction

With the rapid development of infrastructure in China since the start of this century, large numbers of highway and railway tunnels are being constructed or will be constructed, especially in mountainous regions of southwest China(Zou et al. 2019; Huang et al. 2017; Chen et al. 2009). However, due to complex terrain and geological conditions, lack of basic information and lag in construction technology, the collapse is one of the most frequent and harmful geological hazards during the construction of tunnel(Shi et al. 2015). Furthermore, since it is difficult to predict the collapse which is sudden and instantaneous, the constructors do not have time to escape. Once the collapse hazard occurs, it may cause serious economic losses and even human casualties (Huang et al. 2017; Chen et al. 2009; Shi et al. 2015; Wang et al. 2010; Zhang et al. 2014).

Many scholars at home and abroad have carried out a large number of studies to assess the collapse risk during tunnel construction (Yuan et al. 2016; Nezarat et al. 2015). In 2004, the international Tunneling association promulgated Guidelines for Tunneling Risk Management (Eskesen et al. 2004). The "Provisional rules of railway tunnel of risk assessment and management"(Provisional rules of railway tunnel of risk assessment and management. The Ministry of Railways of the People's Republic of China, Beijing 2007) and "Highway tunnel construction safety risk assessment guide (trial version)"(Highway tunnel construction safety risk assessment guide (trial version). The Ministry of Transport of the People's Republic of China, Beijing 2009) had been issued in China. The risk of tunnel construction was evaluated and managed by qualitative analysis. In order to realize the quantitative risk evaluation of tunnel collapse, Shin et al. (2009a, b) proposed KICT Tunnel Collapse Hazard Index (KTH-Index) based on neural network for assessing the hazard level of collapse at a tunnel face. Based on Bayesian Networks, Sousa and Einstein(Yuan et al. 2016) presented a methodology combining geologic prediction model and construction decision model to predict geology before construction and determine construction strategy that leads to minimum risk respectively. Chen et al. (2009) and Nezarat et al. (2015) developed the multi-criteria decision making (MCDM) techniques based on fuzzy analytical hierarchy process (FAHP) to determine ranking of risks in tunnel construction. Su et al.(Su et al. 2007) established a fuzzy synthetical evaluation method based on theory of barycenter of fuzzy which can solve the judgment information loss. Huang et al. (2017) regarded the relationship between tunnel collapse and its influencing factors as an unascertained system, and established risk prediction model of tunnel collapse based on unascertained measure theory and information entropy theory. Cao et al. (2012) formulated a two-stage evaluation index system and set pair analysis method of collapse risk during construction of mountain tunnel. Zhou et al. (2013) proposed a fuzzy analytic hierarchy process model of risk assessment for tunnel collapse including Static evaluation and dynamic evaluation, and a risk aversion method. Wang et al. (2010) analyzed risk factors of collapse and established catastrophe theory model for risk assessment of tunnel collapse. Zhang et al. (2016) and Wu et al. (2015) presents a systemic Bayesian network (BN) based approach for dynamic risk analysis of adjacent buildings in tunneling environments. Chen et al.(Chen et al. 2019) established a risk evaluation model of mountain tunnel collapse based on rough set and conditional information entropy that can extract the main influencing factors from redundant factors. In addition, there were attribute evaluation model (Li et al. 2013), cloud model (Zhang et al. 2015), fault-tree method (Hyun et al. 2015), extension theory (An et al. 2011) and efficacy coefficient method (Wang et al. 2010).

However, the limitations of the above methods are obvious. One limitation is that the analytic hierarchy process (AHP) has strong subjectivity and its evaluation results are easily influenced by artificial experience; the fuzzy model has fuzziness and easily leads to information losses; the cloud model has high discretization and is difficult to calculate; the efficacy coefficient method requires that the evaluation index is opposite. Another limitation is that these models generally assume that the relationship between tunnel collapse hazard and its influencing factors is linear, which is nonlinear in fact. Also, the limitation is that the evaluation process is mainly artificial and possesses hysteresis.

The attribute recognition model can effectively realize comprehensive evaluation and quantitative ordering of complex research objects with multi-factors. Therefore, a dynamic risk assessment method for collapse in the mountain tunnels based on attribute synthetic evaluation theory was proposed, including primary assessment before excavation and second assessment after excavation. Then the Mountain Tunnel Collapse Risk Assessment System (TCAS) was developed to realize the real-time control of collapse risk in the construction of mountain tunnels. The proposed method was applied to Hongyansi Tunnel from Baokang County to Yichang City expressway and Shimenya Tunnel from Yichang City to Yiba County expressway.

2 Dynamic Risk Assessment Method for Collapse in Mountain Tunnels

A lot of construction experience shows that the risk of collapse hazard in the different stage of mountain tunnel construction is different. With the excavation of the tunnel, the risk increases. At the same time, the cognition of hydrogeology, geology, monitoring and other information obtained in the process of tunnel construction is also different. It is very important to make full use of the effective information in each stage to evaluate the collapse risk in the mountain tunnels. Therefore, a dynamic risk assessment method for collapse is proposed, including primary assessment and second assessment.

2.1 Primary Assessment

According to statistical analysis of many typical collapse cases, the influencing factors of tunnel collapse consist of hydrology and geological factor, investigation and design factor and construction factor in Table 1 (Senent and Jimenez 2015; Li 2011). Therefore, based on the probability statistics and previous research (Chen et al. 2009; Yuan et al. 2016; Cao et al. 2012; Li et al. 2013), the surrounding rock level I_1, rock mass integrity I_2, tunnel depth I_3, bias angle I_4, groundwater I_5, construction factor I_6 are selected as the risk assessment index system of collapse in mountain tunnels.

The surrounding rock I_1 is quantified by using longitudinal velocity V_p of seismic wave obtained by advance geological forecast. The rock mass integrity I_2 is described by using integrity degree of rock mass K_v. The tunnel depth I_3 is the difference between the tunnel arch elevation and surface elevation. The bias angle I_4 is generally characterized by using the strata inclination. According to the developed situation, the groundwater I_5 is scored by experts. According to the fatalness, the collapse hazard in the tunnels is divided into C_1 = {No risk}, C_2 = {Low risk}, C_3 = {Medium risk}, C_4 = {High risk}, C_5 = {Very high risk} (Gierczak 2014). The grading criteria of assessment indices are shown in Table 2.

The primary assessment model is carried out before excavation to evaluate the risk of potential collapse in the unexcavated segment of mountain tunnel. The purpose of primary assessment is to provide the evidence for reasonable construction method and scheme. According to the geological sketch of tunnel face and geophysical prospecting and drilling data, the values of 6 assessment indices are quantified.

2.2 Second Assessment

The second assessment model is conducted after the surrounding rock excavation and before structure support, which is used to provide the evidence for adjusting safety supporting scheme. The assessment indices are the same as those of primary assessment model. In order to accurate risk assessment of collapse in the mountain tunnels, the 6 assessment indices are modified according to exposed geological conditions. When the risk level of collapse is unacceptable, the support structure is strengthened.

3 Mountain Tunnel Collapse Risk Assessment System

At present, the risk assessment method is mainly manual work. There are two key disadvantages: (1) The assessment results are greatly influenced by subjective factors, which easily leads to calculation error. It causes the deviation of risk level. (2) The assessment process is so slow that the assessment results present obvious hysteretic nature and cannot effectively guide the construction. Therefore, the mountain tunnel collapse risk assessment system (TCAS) is developed to evaluate the risk of tunnel collapse. The basic framework of the software is shown in Fig. 1.

Table 1 Classification, causes, frequency and proportion of the tunnel collapse (Li 2011)

Classification	Causes	Frequency	Proportion (%)
Engineering geology	Complex geological structure	35	17.5
	Poor surrounding rock	36	18
	Serious bias	20	10
	Buried depth	11	5.5
	Bad geology	15	7.5
Hydrogeology	Complex groundwater	23	11.5
	Enriched surface water	5	2.5
	Heavy rainfall	10	5
Survey, design and construction	unreasonable design	15	7.5
	low construction level	18	9
	inaccurate geological survey	6	3
Other aspects	Other reason	6	3

Table 2 Grade standard of assessment indices(Yuan et al. 2016; Li et al. 2013)

Index	Grade				
	C_1	C_2	C_3	C_4	C_5
Surrounding rock level I_1 (V_p/km/s)	II I > 4.5	III 3.5–4.5	IV 2.5–3.5	V 1.5–2.5	VI < 1.5
Integrity degree $I_2(K_v)$	> 0.75	0.55–0.75	0.35–0.55	0.15–0.35	< 0.15
Tunnel depth I_3 (H/m)	> 60	40–60	20–40	10–20	< 10
Bias angle I_4 (α/°)	< 10	10–20	20–30	30–40	> 40
Groundwater I_5	Undeveloped, and the surrounding rock is dry	Less developed, and the surrounding rock is damp	Weakly developed, and there is a small amount of fissure water	Relatively developed	Developed
	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
Construction factor I_6	The reputation, experience and technical force of unit are excellent	The reputation, experience and technical force of unit are good	The reputation, experience and technical force of unit are average	The reputation, experience and technical force of unit are bad	The reputation, experience and technical force of unit are extreme bad
	I	II	III	IV	V

The system mainly consists of three parts: input area, analysis area and database. The login interface of TCAS is shown in Fig. 2.

3.1 Input Area

The input area consists of Attribute measurement module and Weight module. The Attribute measurement is mainly used to enter the measured values of assessment indices and calculate the single index attribute measure values. The Weight is used to input the subjective weight, objective weight and weight distribution.

3.1.1 Attribute Measurement

Based on single index attribute measure function, the function of each index is determined and programmed into the programming language of Attribute measurement module in Table 3. The 6 property pages designed in the Attribute measurement module are used to enter the measured value t_j (j = 1, 2, …, 6) of assessment index I_j in Fig. 3. According to the equations in Table 3, the single index attribute measure value u_{jk} (j = 1, 2, …, 6; k = 1, 2,…, 5), which is membership degrees of assessment index I_j belonging to risk level C_k (k = 1, 2,…, 5) is obtained, for example Fig. 3a.

3.1.2 Weight

The influence degree of different factors on collapse hazard in the mountain tunnels is different. Therefore, a combined weight method is proposed, including subjective weight and objective weight. The Weight module in the Input area consists of 3 parts: distribution of weight, subjective weights and objective weights (Fig. 4).

The combined weight w_j of assessment index I_j is computed by using the following equation:

$$w_j = k_1 w_{jo} + k_2 w_{js} \tag{1}$$

where w_{jo} and w_{js} is the objective weight and subjective weight of evaluation index I_j respectively. The k_1 and k_2 is the distribution of weight, s.t. $0 < k_1$ or $k_2 < 1$ and $k_1 + k_2 = 1$.

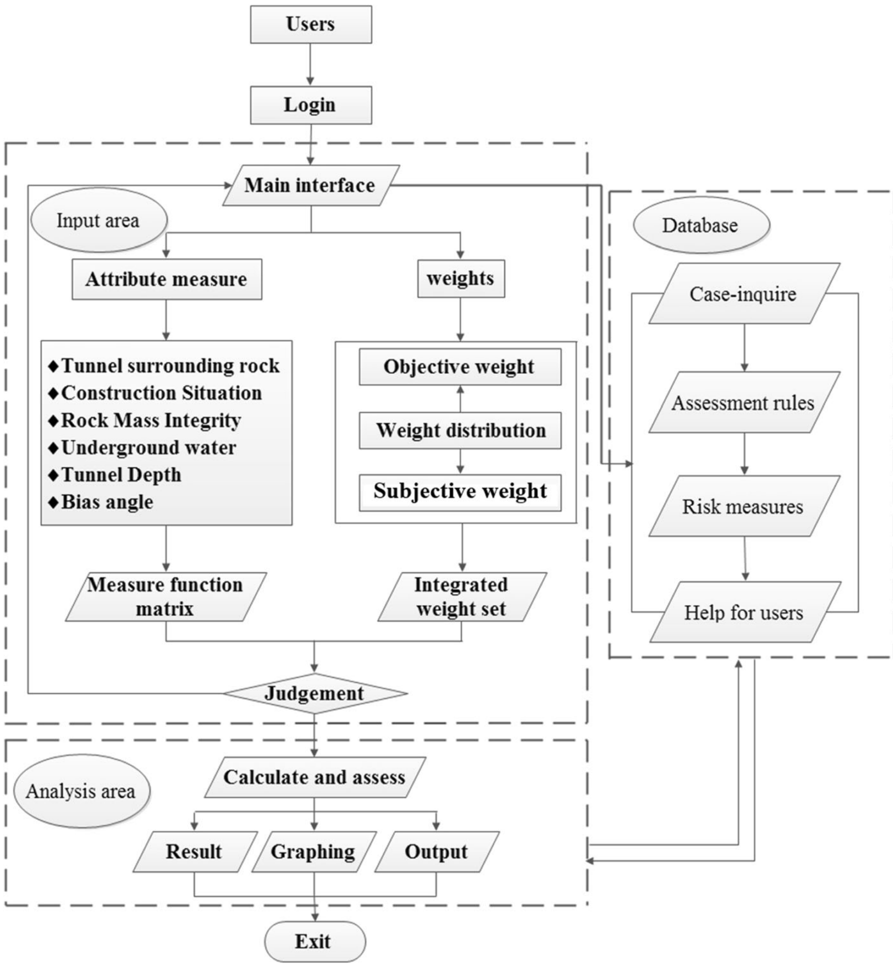


Fig. 1 Basic framework of the software

Fig. 2 Login interface of the software

(1) Objective weights

The objective weight is determined by frequency statistic method. According to statistical analysis of 300 collapse cases in the tunnels (Li 2011), the objective weights of six evaluation indices are calculated.

$$W_o = (w_{1o}, w_{2o}, w_{3o}, w_{4o}, w_{5o}, w_{6o}) = (0.298,\ 0.197,\ 0.088,\ 0.155,\ 0.200, 0.104)$$

(2) Subjective weights

The subjective weight is determined by analytic hierarchy process (AHP), which can integrate the knowledge and experience of experts, and the

Table 3 Attribute measurement functions of 6 assessment indices

Index	C_1	C_2	C_3	C_4	C_5
I_1	$u_{11}(t_1)=\begin{cases}0 & t_1<4\\ t_1-4 & 4\le t_1\le 5\\ 1 & t_1>5\end{cases}$	$u_{12}(t_1)=\begin{cases}0 & t_1<3\\ t_1-3 & 3\le t_1\le 4\\ 5-t_1 & 4<t_1\le 5\\ 0 & t_1>5\end{cases}$	$u_{13}(t_1)=\begin{cases}0 & t_1<2\\ t_1-2 & 2\le t_1\le 3\\ 4-t_1 & 3<t_1\le 4\\ 0 & t_1>4\end{cases}$	$u_{14}(t_1)=\begin{cases}0 & t_1<1\\ t_1-1 & 1\le t_1\le 2\\ 3-t_1 & 2<t_1\le 3\\ 0 & t_1>3\end{cases}$	$u_{15}(t_1)=\begin{cases}1 & t_1<1\\ 2-t_1 & 1\le t_1\le 2\\ 0 & t_1>2\end{cases}$
I_2	$u_{21}(t_2)=\begin{cases}0 & t_2<0.65\\ \frac{t_2-0.65}{0.2} & 0.65\le t_2\le 0.85\\ 1 & t_2>0.85\end{cases}$	$u_{22}(t_2)=\begin{cases}0 & t_2<0.45\\ \frac{t_2-0.45}{0.2} & 0.45\le t_2\le 0.65\\ \frac{0.85-t_2}{0.2} & 0.65<t_2\le 0.85\\ 0 & t_2>0.85\end{cases}$	$u_{23}(t_2)=\begin{cases}0 & t_2<0.25\\ \frac{t_2-0.25}{0.2} & 0.25\le t_2\le 0.45\\ \frac{0.65-t_2}{0.2} & 0.45<t_2\le 0.65\\ 0 & t_2>0.65\end{cases}$	$u_{24}(t_2)=\begin{cases}0 & t_2<0.075\\ \frac{t_2-0.075}{0.15} & 0.075\le t_2\le 0.225\\ 1 & 0.225<t_2\le 0.25\\ \frac{0.45-t_2}{0.2} & 0.25<t_2\le 0.45\\ 0 & t_2>0.45\end{cases}$	$u_{25}(t_2)=\begin{cases}1 & t_2<0.075\\ \frac{0.225-t_2}{0.15} & 0.075\le t_2\le 0.225\\ 0 & t_2>0.225\end{cases}$
I_3	$u_{31}(t_3)=\begin{cases}0 & t_3<50\\ \frac{t_3-50}{20} & 50\le t_3\le 70\\ 1 & t_3>70\end{cases}$	$u_{32}(t_3)=\begin{cases}0 & t_3<30\\ \frac{t_3-30}{20} & 30\le t_3\le 50\\ \frac{70-t_3}{20} & 50<t_3\le 70\\ 0 & t_3>70\end{cases}$	$u_{33}(t_3)=\begin{cases}0 & t_3<15\\ \frac{t_3-15}{10} & 15\le t_3\le 25\\ 1 & 25<t_3\le 30\\ \frac{50-t_3}{20} & 30<t_3\le 50\\ 0 & t_3>50\end{cases}$	$u_{34}(t_3)=\begin{cases}0 & t_3<5\\ \frac{t_3-5}{10} & 5\le t_3\le 15\\ \frac{25-t_3}{20} & 15<t_3\le 25\\ 0 & t_3>25\end{cases}$	$u_{35}(t_3)=\begin{cases}1 & t_3<5\\ \frac{15-t_3}{10} & 5\le t_3\le 15\\ 0 & t_3>15\end{cases}$
I_4	$u_{41}(t_4)=\begin{cases}1 & t_4<5\\ \frac{15-t_4}{10} & 5\le t_4\le 15\\ 0 & t_4>15\end{cases}$	$u_{42}(t_4)=\begin{cases}0 & t_4<5\\ \frac{t_4-5}{10} & 5\le t_4\le 15\\ \frac{25-t_4}{10} & 15<t_4\le 25\\ 0 & t_4>25\end{cases}$	$u_{43}(t_4)=\begin{cases}0 & t_4<15\\ \frac{t_4-15}{10} & 15\le t_4\le 25\\ \frac{35-t_4}{10} & 25<t_4\le 35\\ 0 & t_4>35\end{cases}$	$u_{44}(t_4)=\begin{cases}0 & t_4<25\\ \frac{t_4-25}{10} & 25\le t_4\le 35\\ \frac{45-t_4}{10} & 35<t_4\le 45\\ 0 & t_4>45\end{cases}$	$u_{45}(t_4)=\begin{cases}0 & t_4<35\\ \frac{t_4-35}{10} & 35\le t_4\le 45\\ 1 & t_4>45\end{cases}$
I_5	$u_{51}(t_5)=\begin{cases}1 & t_5<0.1\\ \frac{0.3-t_5}{0.2} & 0.1\le t_5\le 0.3\\ 0 & t_5>0.3\end{cases}$	$u_{52}(t_5)=\begin{cases}0 & t_5<0.1\\ \frac{t_5-0.1}{0.2} & 0.1\le t_5\le 0.3\\ \frac{0.5-t_5}{0.2} & 0.3<t_5\le 0.5\\ 0 & t_5>0.5\end{cases}$	$u_{53}(t_5)=\begin{cases}0 & t_5<0.3\\ \frac{t_5-0.3}{0.2} & 0.3\le t_5\le 0.5\\ \frac{0.7-t_5}{0.2} & 0.5<t_5\le 0.7\\ 0 & t_5>0.7\end{cases}$	$u_{54}(t_5)=\begin{cases}0 & t_5<0.5\\ \frac{t_5-0.5}{0.2} & 0.5\le t_5\le 0.7\\ \frac{0.9-t_5}{0.2} & 0.7<t_5\le 0.9\\ 0 & t_5>0.9\end{cases}$	$u_{55}(t_5)=\begin{cases}0 & t_5<0.7\\ \frac{t_5-0.7}{0.2} & 0.7\le t_5\le 0.9\\ 1 & t_5>0.9\end{cases}$
I_6	$u_{61}(t_6)=\begin{cases}1 & t_6=I\\ 0 & t_6\ne I\end{cases}$	$u_{62}(t_6)=\begin{cases}1 & t_6=II\\ 0 & t_6\ne II\end{cases}$	$u_{63}(t_6)=\begin{cases}1 & t_6=III\\ 0 & t_6\ne III\end{cases}$	$u_{64}(t_6)=\begin{cases}1 & t_6=IV\\ 0 & t_6\ne IV\end{cases}$	$u_{65}(t_6)=\begin{cases}1 & t_6=V\\ 0 & t_6\ne V\end{cases}$

(a) Surrounding rock grade I_1

(b) Rock mass integrity I_2

(c) Tunnel depth I_3

(d) Bias angle I_4

(e) Groundwater I_5

(f) Construction factor I_6

Fig. 3 The input interface of attribute measurement

intension and preference of decision-makers. Based on the 1–9 scale method proposed by Saaty (2000) (Table 4), the judgement matrix $M = (m_{ij})_{6\times 6}$ can be constructed by pair-wise comparison. The m_{ij} is the importance degree of I_i compared with I_j to evaluation object.

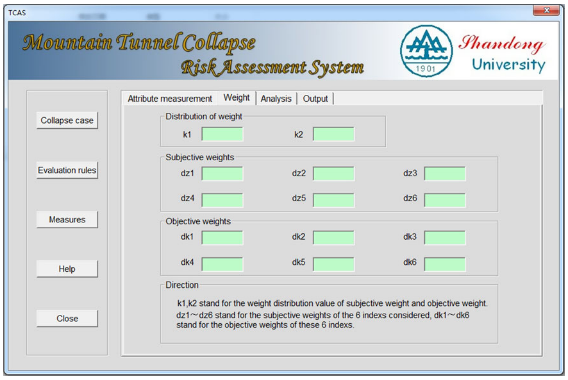


Fig. 4 The input interface of weight

Assuming that the weight vector $W = (w_1, w_2, \ldots, w_n)$, w_i ($i = 1, 2, \ldots, n$) can be obtain by the following equations:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \tag{2}$$

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} b_{ij}} \quad (i = 1, 2, \ldots, n) \tag{3}$$

where $\overline{w_i}$ is geometric average value of ith index.

The consistency test between the simulation and practical test results is carried out by the following equations:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(B \cdot W)_i}{w_i} \tag{4}$$

where λ_{max} is the maximum eigenvalue of the eigenvector.

$$CI = \frac{\lambda_{\max} - n}{n - \infty}, \quad CR = \frac{CI}{RI} \tag{5}$$

where CI is the consistency index and CR is the coincidence coefficient. RI is the mean random consistency index, which takes its value from Wang (2016). When CI and CR are less than 0.1, the constructed judgment matrix is scientific.

3.2 Analysis Area

The property page of Analysis consists of two parts: Result 1 and Result 2 (Fig. 5). The Result 1 is synthetic attribute measure values and the Result 2 is the level of collapse risk in mountain tunnels.

The synthetic attribute measure value μ_k is calculated by using the following equation, which is programed into the TCAS:

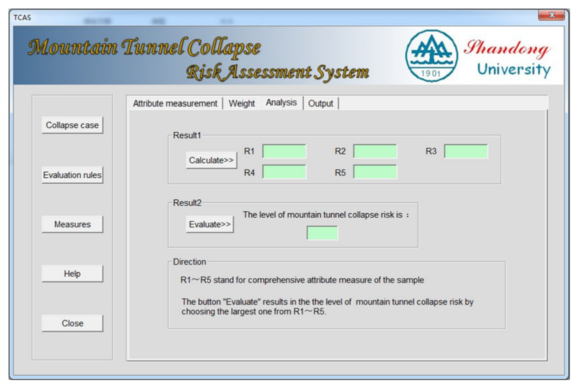


Fig. 5 The output interface of analysis

Table 4 Scale of preference between two elements in AHP (Saaty 2000; Pourghasemi et al. 2012)

Scales(m_{ij})	Degree of preference	Explanation
1	Equally important	Two elements contribute equally to the objective
3	Moderately important	Experience and judgement slightly to moderately favor one element over another
5	Strongly important	Experience and judgement strongly or essentially favor one element over another
7	Very strongly important	An element is strongly favored over another and its dominance is showed in practice
9	Extremely important	The evidence of favoring an element over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
1/2, 1/3, …, 1/9	Opposites	Used for inverse comparison

$$\mu_k = \sum_{j=1}^{6} w_j \mu_{jk} \tag{6}$$

where μ_{jk} and ω_j is the single index attribute measure value and combined weight of assessment index I_j respectively. The μ_k is synthetic attribute measure value of assessment object belonging to risk level C_k.

3.3 Database

The Collapse case in the Database is designed to store many typical collapse cases collected in the mountain tunnels. Its effect is to modify the assessment results of tunnel collapse. The Measures can make decision based on the risk level of collapse to give the treatment measures. The interface of Database is shown in Fig. 6.

According to summarize and analyze a lot of successful collapse treatment cases, the adjustment measures are put forward aiming at different risk levels (Table 5)

4 Engineering Application

4.1 Hongyansi Tunnel

Hongyansi Tunnel is located in the expressway from Baokang County to Yichang City in Hubei Province, which is an extra-long and separated tunnel with left line 6678 m and right line 6746 m. The maximum depth of left line and right line are 655.6 m and 654.5 m respectively. The tunnel vertically passes through the Julongshan-xiaojiayan synclinorium axis,

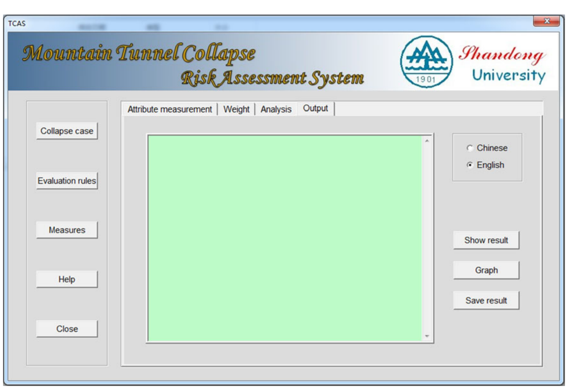


Fig. 6 The interface of database

and intersects with Tongcheng river fault zone (F2). The geological conditions of Hongyansi Tunnel is shown in Fig. 7.

According to the geology data, the surrounding rock in left line ZK15 + 400–ZK15 + 500 is mainly broken shale, and the level is IV. When the rock mass encounters water, it softens and the strength decreases, which easily leads to collapse hazard. In addition, the river and gully in the entrance of Hongyansi Tunnel are well developed, which is favorable to the infiltration of surface water and rainwater. In rainy season, it has a great influence on the stability of tunnel surrounding rock. Therefore, it is very necessary to evaluate the risk of collapse in this section of Hongyansi Tunnel.

4.1.1 *Dynamic Risk Assessment of Collapse*

(1) Values of assessment indices

In the stage of primary assessment, according to the preliminary geological survey data, geological sketch of tunnel face and geophysical prospecting and drilling data, the values of 6 assessment indices are quantified. The surrounding rock is carbonaceous shale of silurian, which belongs to soft rock. According to the TSP seismic wave method, the longitudinal velocity V_p of this section was 2.073–2.219 km/s. The integrity degree of rock mass K_v was calculated by using the Eq. (7). According to the difference between design elevation of tunnel vault and surface elevation, the minimum value of tunnel depth I_3 was 80 m. According to the attitude of rocks obtained by geological sketch of tunnel face, the bias angle I_4 was 60°. The score of groundwater I_5 was 0.6 based on the developed situation of groundwater detected by electromagnetic method of geological exploration. According to the previous construction performance of the unit, the level of construction management and technology was II. In the stage of second assessment, the values of 6 assessment indices were determined based on exposed geological conditions. The detailed values of assessment indices are shown in Table 6.

$$K_v = \frac{V_{pm}^2}{V_{pr}^2} \tag{7}$$

Table 5 Adjustment measures of different risk levels (Yuan et al. 2016; Li 2011)

Risk level	Suggests
C_1	Large-scale lead pipe grouting and advanced small pipe grouting, stiffened steel arch or arch grid, strengthening monitoring frequency, double side-heading method
C_2	Advanced small pipe grouting or grouting bolt, stiffened steel arch or arch grid, strengthening monitoring frequency, three-step excavation method
C_3	Strengthening monitoring frequency, two-step excavation method
C_4	Normal construction
C_5	Normal construction

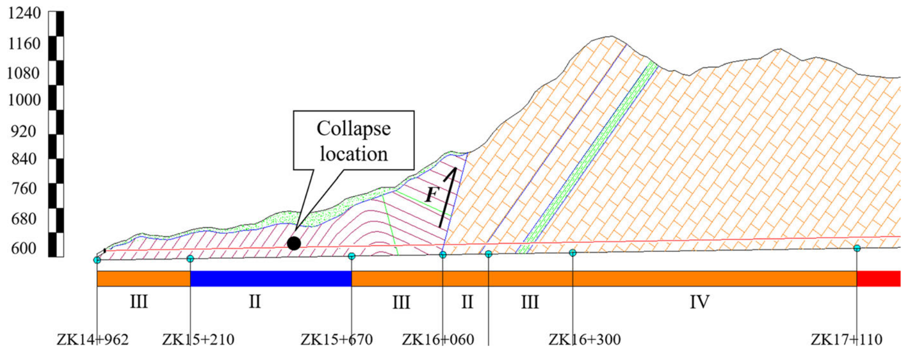


Fig. 7 Geological conditions of Hongyansi tunnel

Table 6 Values of evaluation indices

Value	Surrounding rock level I_1 (km/s)	Rock mass integrity I_2	Tunnel depth I_3 (m)	Bias angle I_4 (°)	Groundwater I_5	Construction factor I_6
Primary assessment	2.073	0.30	80	60	0.6	II
Second assessment	1.815	0.20	80	60	0.8	II

where V_{pm} is elastic longitudinal velocity of rock mass, which is determined by seismic wave instrument in the advance geological exploration. V_{pr} is elastic longitudinal velocity of indoor rock, which is tested by sonic parameter measuring apparatus.

(2) Weight

The objective weight vector had been determined. Therefore, the subjective weight vector was calculated by using AHP. The judgement matrix was as follows:

$$M = \begin{bmatrix} 1 & 1 & 5 & 3 & 1 & 3 \\ 1 & 1 & 5 & 3 & 1 & 3 \\ 1/5 & 1/5 & 1 & 1/2 & 1/5 & 1/2 \\ 1/3 & 1/3 & 2 & 1 & 1/3 & 1 \\ 1 & 1 & 5 & 3 & 1 & 3 \\ 1/3 & 1/3 & 2 & 1 & 1/3 & 1 \end{bmatrix}$$

where both CI and $CR < 0.1$, so the constructed judgment matrix met consistency check. The subjective weight vector W_s were obtained, and the weight distribution k_1, k_2 were 0.5 and 0.5 respectively.

$$W_s = (0.258, 0.258, 0.049, 0.089, 0.258, 0.089) \quad (8)$$

(3) Assessment results

The values of assessment indices, subjective and objective weights and the distribution of weight were entered into the property pages of TCAS. Through the calculation of system, the risk levels of collapse at the ZK15 + 400–ZK15 + 500 of Hongyansi Tunnel were shown in Fig. 8. In addition, the assessment results are good agreement with those obtained by catastrophe theory(Yuan et al. 2016).

4.1.2 Excavation

Due to the poor attention, when the tunnel face excavated to the ZK15 + 500, the collapse occurred on September 26, 2013 (Fig. 9). After excavation, only original S4b composite lining was adjusted as S5b composite lining. However, the exposed surrounding rock was mainly gravel soil with low strength, broken structure and serious water seepage. Finally, the "closed door" disaster was formed.

4.2 Shimenya Tunnel

Shimenya Tunnel fromYichang City to Badong County expressway is located in Tianba town of Zigui county, Hubei Province. It has two separate lanes with the left line length 7524.0 m and right line length 7493.0 m. The tunnel is a deep and extra-long with a maximum burial depth of 1300 m. The landform of tunnel area belongs to middle-low mountains and deep dissection gully with tectonic denudation and erosion. The geological conditions of Shimenya Tunnel is shown in Fig. 10.

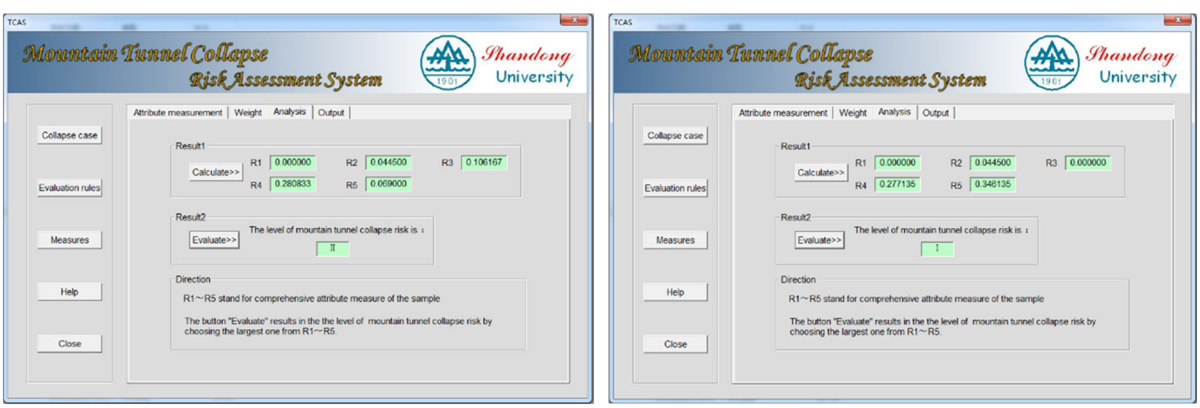
The section ZK123 + 375–ZK123 + 355 is located in the core of Zigui basin. The surrounding rock level is III and the depth is 1200–1300 m. The exposure strata is mauve thin-medium bedded silty mudstone and grey-green and greyish white feldspar-quartz sandstone of Jurassic Penglai Formation (J_3p), which are inter-bedded with different thickness. The joints of rock mass are weakly developed, and the tunnel is only moist or dropwise water.

4.2.1 Dynamic Risk Assessment of Collapse

(1) Values of assessment indices

For primary assessment of the section ZK123 + 375–ZK123 + 355 from Shimenya Tunnel, longitudinal velocity V_p was determined based on physical properties of rock mass obtained by TSP method. The integrity degree of rock mass K_v was assigned according to field acoustic logging result of rock mass and sonic parameter measuring of rock. The tunnel depth I_3 was 1200–1300 m. According to the attitude of rocks obtained by geological sketch of tunnel face, the bias angle I_4 was 40°. Due to weakly developed groundwater, the value of groundwater I_5 was 0.5. Through comprehensive analysis of construction management and technology, the level of construction factor was II (Table 7).

(2) Weight



(a) Primary assessment result **(b)** Second assessment result

Fig. 8 Collapse risk level at the ZK15 + 400–ZK15 + 500 of Hongyansi tunnel

Fig. 9 The collapse situation at ZK15 + 400–ZK15 + 500

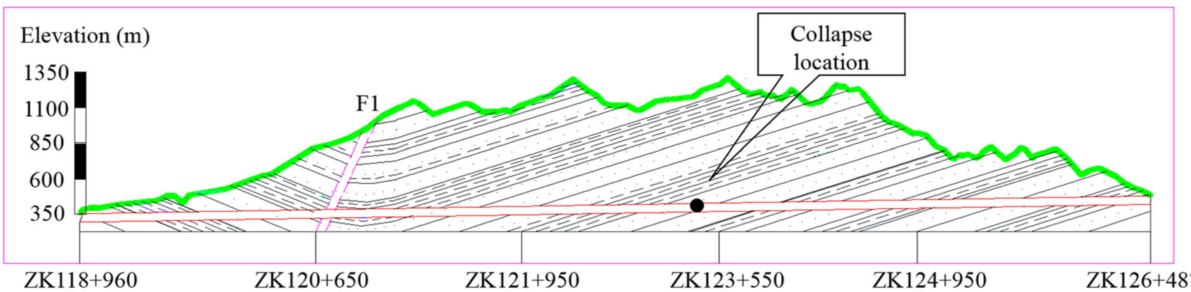


Fig. 10 Geological conditions of Shimenya tunnel

Table 7 Value assignment for evaluation indices

Value	Surrounding rock level I_1	Rock mass integrity I_2	Tunnel depth I_3	Bias angle I_4	Groundwater I_5	Construction factor I_6
Primary assessment	1.890 km/s	0.40	1200 m	40°	0.6	II

According to analyze the important degree of influencing factors based on the actual geological conditions and construction level, the judgement matrix was as follows:

$$M = \begin{bmatrix} 1 & 2 & 4 & 3 & 1 & 3 \\ 1/2 & 1 & 3 & 2 & 1/2 & 2 \\ 1/4 & 1/3 & 1 & 1/2 & 1/4 & 1/2 \\ 1/3 & 1/2 & 2 & 1 & 1/3 & 1 \\ 1 & 2 & 4 & 3 & 1 & 3 \\ 1/3 & 1/2 & 2 & 1 & 1/3 & 1 \end{bmatrix}$$

$$W_s = (w_{1s}, w_{2s}, w_{3s}, w_{4s}, w_{5s}, w_{6s}) = (0.288, 0.170, 0.059, 0.098, 0.288, 0.098)$$

where both CI and $CR < 0.1$, the matrix met consistency check. The weight distribution are k_1 = 0.5 and k_2 = 0.5.

(3) Assessment results

After the data were entered into the property pages of TCAS, the risk level of collapse at the ZK123 + 375–ZK123 + 355 was obtained by calculating (Fig. 11).

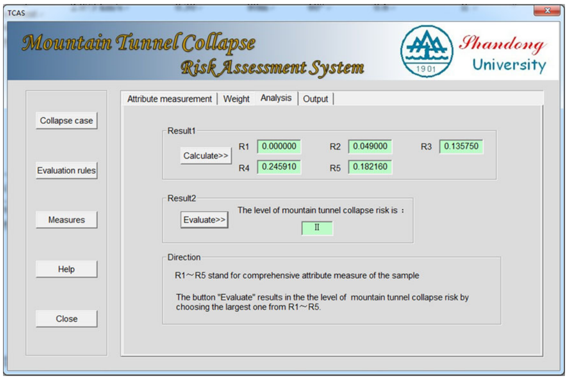


Fig. 11 Collapse risk level of left line ZK123 + 375–ZK123 + 355 of Shimenya tunnel

By comparison, the assessment result of proposed method is consistent with that of the extension theory.

4.2.2 Excavation

During the mucking process of ZK123 + 375–ZK123 + 365, the collapse of the crown, right shoulder and wall happened on December 19, 2011 (Fig. 12). Subsequently, the collapse extended to the supported section. The lithology of collapse body was mauve argillaceous siltstone and linear water seepage developed. The free face of collapse was the interface between feldspar-quartz sandstone and argillaceous siltstone. Finally, the slope toe of collapse body with the height 4 m extended to the mileage of ZK123 + 375. The second assessment had not been carried out.

Fig. 12 Actual situation of the collapse in the tunnel (Li et al. 2014)

5 Conclusion

(1) A dynamic risk assessment method for collapse in mountain tunnels is proposed, which consists of two parts: primary assessment and second assessment. The surrounding rock level I_1, rock mass integrity I_2, tunnel depth I_3, bias angle I_4, groundwater I_5, construction factors I_6 are selected as evaluation index system and their grade standards are established.

(2) In order to realize the real-time risk management and effectively guide the tunnel construction, the mountain tunnel collapse risk assessment system (TCAS) is developed based on the proposed method. The software consists of input area, analysis area and database. In input area, the values of assessment indices, subjective and objective weights and weight distribution are entered. The single index attribute measure values was calculated based on defined single index attribute measure function. In analysis area, the risk level of collapse is obtained.

(3) The TCAS were successfully applied to the section ZK15 + 400–ZK15 + 500 of Hongyansi Tunnel and the section 123 + 375–ZK123 + 355 of Shimenya Tunnel. The results showed good agreement with the results of other method and actual excavation situation, which proved that the proposed method is scientific and practical. It will play an important role in controlling the risk of collapse in different stages of construction.

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