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Original Research

Dynamic Risk Assessment Method of Tunnel Collapse Based on Attribute Interval Assessment Model and Application

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Abstract

Due to its complexity, collapse during the construction of tunnels is a hot issue. A dynamic risk assessment methodology based on a new attribute interval assessment model was presented, which consists of pre-assessment before excavation and post-assessment after excavation and before primary support. The surrounding rock level I_1, rock mass integrity I_2, buried depth I_3, bias angle I_4, groundwater I_5, and construction factors I_6 were selected as assessment indices. The value of every evaluation index is an interval rather than a definite value. On the basis of the traditional attribute assessment model, the integration method was introduced to compute the single index attribute measure of the interval. The index weight was determined by employing the combination weighting method, including subjective weight based on frequency statistic method, and objective weight based on analytic hierarchy process (AHP). The proposed method was applied in the right Duanjiawu Tunnel. The results were good agreement with actual excavation situation and the results of other methods, which proved the science and feasibility of this method.

Keywords: tunnel collapse, dynamic risk assessment, attribute interval, application

Introduction

With the rapid development of infrastructure in China since the start of this century, a great number of highway and railway tunnels have been constructed or planned, especially in the mountainous regions of southwest China [1-3]. However, due to complex terrain and geological conditions, lack of basic information and lag in construction technology, collapse is one of the most frequent and harmful geological hazards during the construction of a tunnel [4]. Furthermore, since it is difficult to predict a 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 [2-6].

Tunnel collapse is a rather complex problem because it is strongly affected by random variability, including mechanical properties of the rock in situ, rock and water coupling effect and excavation-induced disturbance and so on [2, 7, 8]. Therefore, the stability

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analysis of tunnel collapse is a hot issue, and has been paid extensive attention by several researchers. Most research has mainly focused on the failure mode of collapse [9], the stability coefficient [10], deformation prediction [11] and calculation of support pressure [12] using experimental, analytical and numerical approaches [13-16]. Risk assessment for collapse hazard has played an important role in the study of tunnel excavation. Shin et al. [17] proposed the KICT tunnel collapse hazard index (KTH-Index) based on a neural network for assessing the hazard level of collapse at a tunnel face. Based on Bayesian Networks, Sousa and Einstein [18, 19] presented a methodology combining a geologicak prediction model and construction decision model to predict geology before construction. Nezarat et al. [3, 20] developed the multi-criteria decision-making (MCDM) techniques based on fuzzy analytical hierarchy process (FAHP) to determine ranking of risks in tunnel construction. Cao et al. [21] proposed a two-stage evaluation index system and set a pair analysis method of collapse risk during construction. Yuan et al. [22] analyzed risk factors of collapse and established a catastrophic theory model for risk assessment of tunnel collapse. Zhang and Wu et al. [23, 24] presents a systemic Bayesian network-based (BN) approach for dynamic risk analysis of adjacent buildings in tunneling environments. Chen et al. [25] 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. Lu et al. [26] proposed a specific targeted assessment evaluation for multilayer geologies suitability based on fuzzy set analytic hierarchy process and TOPSIS (FAHP-TOPSIS). In addition, there were the attribute evaluation model [27], cloud model [28], fault-tree method [29], extension theory [30], efficacy coefficient method [31] and GIS [32].

However, the existing assessment methods are static and the mathematical model has some shortcomings, such as the fuzzy model having fuzziness, which easily leads to information loss. The results with low accuracy and serious lag are mainly based on manual calculation, which cannot really guide tunnel construction. Therefore, a new attribute interval assessment model has been presented, where the measured value of each evaluation index is an interval rather than a certain value, and the integration method was used to compute single index attribute measure value. According to different collapse risks in different periods of tunnel construction, a dynamic risk assessment method based on the new attribute interval model was established, including pre-assessment model before excavation and post-assessment model after excavation. The proposed method was applied to the right Duanjiawu Tunnel from Yichang City to Badong County expressway.

Material and Methods

Dynamic Risk Assessment Method Based on Attribute Interval Theory

The whole life of a tunnel engineering project is divided into feasibility study stage, exploration and design stage, construction stage and service stage, while the collapse hazard is mainly concentrated in the construction stage. However, the collapse risk is different in different periods of construction stage, and the cognition of hydrogeology, geology, monitoring and other information in the different periods of construction stages is different. Therefore, a dynamic risk assessment method for collapse during tunnel construction is established, which includes pre-assessment and post-assessment models. Pre-assessment is carried out before excavation in order to guide the construction method in the mountain tunnels. And post-assessment is conducted after excavation to guide the construction of the supporting structure.

The Assessment Index System for Collapse

According to statistical analysis of many typical collapse cases, the factors affecting collapse hazard are summarized as geological factors, investigation and design factors and construction factors. Although the assessment section of a tunnel at the pre-assessment stage has not been excavated, three types of factors are comprehensively considered for the risk pre-assessment of collapse in the mountain tunnels. Therefore, surrounding rock level I_1, rock mass integrity I_2, tunnel depth I_3, bias angle I_4, groundwater I_5, and construction factors I_6 are selected as the risk assessment index system of collapse in mountain tunnels.

(1) Surrounding rock level I_1.

The study shows that the occurrence probability of collapse is closely related to surrounding rock level. The lower the level, the higher the probability of collapse, and vice versa. This is because the surrounding rock level reflects rock mass strength. The higher the level of surrounding rock, the greater its strength and the less likely it is to cause failure. Generally, the longitudinal velocity V_p of seismic wave obtained by advance geological forecast is used to quantify and judge the

Table 1. Grade standard of longitudinal wave velocity [27].

Level	Surrounding rock level	V_p/ km/s
R_1	I, II	V_p>4.5
R_2	III	3.5≤V_p≤4.5
R_3	IV	2.5≤V_p≤3.5
R_4	V	1.5≤V_p≤2.5
R_5	VI	V_p<1.5

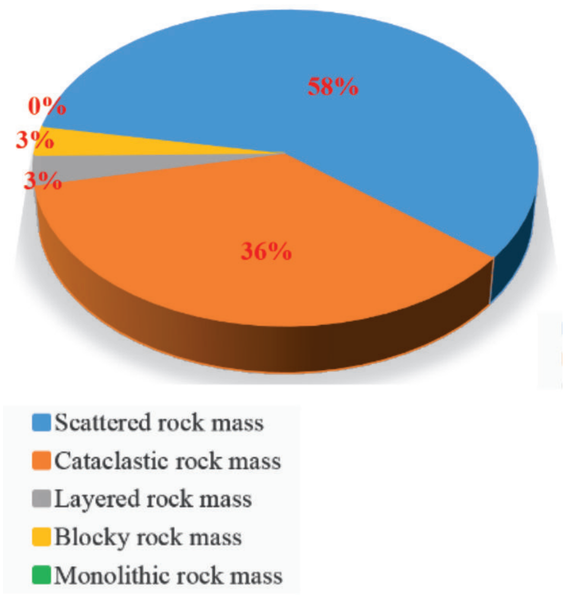

Fig. 1. Collapse statistics of different rock mass structure types.

surrounding rock level [22, 27]. The grade standard of I_1 is shown in Table 1.

(2) Rock mass integrity I_2.

According to the statistics of s large amount of collapse cases, the number of collapse in the scattered and cataclastic rock mass structure accounts for 94% of the total number of collapse, as shown in Fig. 1 [33]. Rock mass integrity can affect the self-stability of tunnel surrounding rock. The poorer the rock mass integrity, the weaker the self-stability. The integrity coefficient of rock mass K_v, which could better reflect the structure type and integrity of rock mass, developed a degree and nature of structure plane selected to quantify index I_2. The equation is as follows:

$$K_v = \frac{V_{pm}^2}{V_{pr}^2} \tag{1}$$

…where V_{pm} is elastic longitudinal velocity of rock mass, which is determined by seismic wave instrument in the advance geological exploration; and V_{pr} is elastic longitudinal velocity of indoor rock, which is tested by sonic parameter measuring apparatus. According to the standard for engineering classification of rock mass and previous research results [27, 34], the grade standard of rock mass integrity is shown in Table 2.

(3) Tunnel depth I_3.

As one of the investigation and design factors, tunnel depth I_3 is a main factor affecting tunnel collapse hazard. According to the relationship between tunnel depth and the number of collapses [3], it is shown that the smaller the tunnel depth, the more likely the collapse is to occur. There are mainly two reasons: First, when the depth is relatively small, it is difficult to form a pressure arch at the top of tunnel [8], meaning that the tunnel structure cannot bear the weight of overlaying rock, and stress redistribution can only be carried out by load release. Second, the rock weathering degree around the deep buried tunnel is weak. The rock mass is hard and its integrity is good, which indirectly affects the occurrence of collapse. The grade standard of tunnel depth is shown in Table 3.

(4) Bias angle I_4.

Bias angle is an important factor affecting tunnel collapse hazard. The bias caused by topographical asymmetry often makes supporting structure uneven loading, which will lead to a serious collapse hazard. The bias mainly appears in the shallow-buried section of deep-buried long tunnels and shallow-buried tunnels – especially in the shallow-buried section of a tunnel entrance. The bias is quantified by bias angle, and the grade standard is shown in Table 4.

(5) Groundwater I_5.

Groundwater is one of the most influential factors regarding tunnel collapse [9, 22]. According to practical data and construction experience, the occurrence of collapse is more or less related to groundwater. The mechanism of groundwater on rock mass can

Table 3. Grade standard of tunnel depth.

Level	Tunnel depth H/m
R_1	>60
R_2	40~60
R_3	20~40
R_4	10~20
R_5	0~10

Table 2. Grade standard of rock mass integrity [27].

Level	Integrity degree	K_v
R_1	Integrated	>0.75
R_2	Relatively integrated	0.55~0.75
R_3	Broken	0.35~0.55
R_4	Relatively broken	0.15~0.35
R_5	Extreme broken	<0.15

Table 4. Grade division of bias angle I_4.

Level	Bias angle α/°
R_1	0~10
R_2	10~20
R_3	20~30
R_4	30~40
R_5	>40

Table 5. Grade division of groundwater [27].

Level	Detailed description	Value
R_1	Undeveloped, and the surrounding rock is dry	0~0.2
R_2	Less developed, and the surrounding rock is damp	0.2~0.4
R_3	Weakly developed, and there is a small amount of fissure water	0.4~0.6
R_4	Relatively developed	0.6~0.8
R_5	The groundwater is developed	0.8~1.0

be summarized as: (a) physical action. The action of groundwater on rock mass can be summarized as: Under the effect of water immersion, softening and lubrication, the cementing force among mineral particles of rock is weakened and rock strength is reduced. Besides, the fillers of structural planes are softened into mud, which leads to the decrease of cohesion force and friction force between the structure planes. (b) chemical action. When some acid gas is dissolved in the groundwater, the groundwater is acidic, which will corrode the soluble rock and increase its porosity and permeability. (c) mechanical action. The pore water pressure generated by groundwater seepage not only increases the load of tunnel structure, but also reduces the effective stress of rock mass. Therefore, the groundwater should be considered into the risk assessment index system for tunnel collapse, and its grade standard is shown in Table 5.

(6) Construction management and technology I_6.

Construction management and technology is a direct factor inducing tunnel collapse hazard. In the process of tunnel construction, if the construction method is unreasonable, the support structure is not applied in time or its strength is not enough, the drainage system is imperfect, the monitoring measurement and advance geological forecast are not standardized and so on, and collapse will occur. These causes belong to construction management and technology. Therefore, considering these causes comprehensively, the grade division of this index is conducted as shown in Table 6.

Table 6. Grade standard of construction management and technology I_6.

Level	Qualitative description
R_1	The reputation, experience and technical force of unit are excellent
R_2	The reputation, experience and technical force of unit are good
R_3	The reputation, experience and technical force of unit are average
R_4	The reputation, experience and technical force of unit are bad
R_5	The reputation, experience and technical force of unit are extreme bad

Attribute Synthetic Assessment Model

The traditional attribute assessment model is only applied to cases where the evaluation index is a certain value. In fact, the surrounding rock in underground engineering possesses fuzziness and variability. The measured value of evaluation index is an interval rather than a fixed value. Therefore, a new attribute interval assessment model is proposed. The area enclosed by the upper and lower limits of the interval, and single index attribute measure equation is taken as the attribute measure value of single index.

Suppose that assessment object space $X = \{x_i\}$ ($i = 1,2,\ldots, n$), where every assessment object x_i has m evaluation indices I_j ($j = 1,2,\ldots, m$). The measured interval of index I_j is represented by $[t_j^-, t_j^+]$. The arbitrary value $t_j \in [t_j^-, t_j^+]$ has k risk levels R_k ($k = 1,2,\ldots, K$). The membership degree of value t_j belonging to risk levels R_k is expressed by single index attribute measure u_{ijk}. The comprehensive membership degree of evaluation object x_i belonging to risk levels R_k is expressed by synthetic attribute measure u_{ik}.

$$I = \left\{ I_1, \cdots, I_j, \cdots, I_m \right\} \tag{1}$$

$$R = \left(R_1, \cdots, R_k \cdots, R_K \right)^T \tag{2}$$

(1) Single index attribute measure analysis.

The single index attribute measure function is constructed to compute the single index attribute measure u_{ijk}, which reflects the membership degree of measured value t_j of evaluation index I_j belonging to R_k ($k = 1,2,\ldots, K$). The attribute measure function is established in the form of the data in Table 7.

$$b_{ijk} = \frac{a_{ijk-1} + a_{ijk}}{2} \tag{3}$$

$$d_{ijk} = \min\left\{ \left| b_{ijk} - a_{ijk} \right|, \left| b_{ijk+1} - a_{ijk} \right| \right\} \tag{4}$$

…where $k = 1, 2,\ldots, K$ in Equation (3); $k = 1, 2,\ldots, K$-1 in Equation (4).

Table 7. Level subdivision of single index.

Index	Risk level			
	R_1	R_2	…	R_K
I_1	a_{10}~a_{11}	a_{11}~a_{12}	…	$a_{1(k-1)}$~a_{1k}
I_2	a_{20}~a_{21}	a_{21}~a_{22}	…	$a_{2(k-1)}$~a_{2k}
…	…	…	…	…
I_m	a_{m0}~a_{m1}	a_{m1}~a_{m2}	…	$a_{m(k-1)}$~a_{mk}

When $a_{j0}<a_{j1}<...<a_{jK}$, single index attribute measure function $\mu_{ijk}(t)$:

$$\mu_{ij1}(t)=\begin{cases} 1 & t_j < a_{j1}-d_{j1} \\ \dfrac{a_{j1}+d_{j1}-t_j}{2d_{j1}} & a_{j1}-d_{j1} \le t_j \le a_{j1}+d_{j1} \\ 0 & t_j > a_{j1}+d_{j1} \end{cases} \tag{5}$$

$$\mu_{ijk}(t)=\begin{cases} 0 & t_j < a_{jk-1}-d_{jk-1} \\ \dfrac{t_j-a_{jk-1}+d_{jk-1}}{2d_{jk-1}} & a_{jk-1}-d_{jk-1} \le t_j \le a_{jk-1}+d_{jk-1} \\ 1 & a_{jk-1}+d_{jk-1} < t_j < a_{jk}-d_{jk} \\ \dfrac{a_{jk}+d_{jk}-t_j}{2d_j} & a_{jk}-d_{jk} \le t_j \le a_{jk}+d_{jk} \\ 0 & t_j > a_{jk}+d_{jk} \end{cases} \tag{6}$$

$$\mu_{ijK}(t)=\begin{cases} 0 & t_j < a_{jK-1}-d_{jK-1} \\ \dfrac{t_j-a_{jK-1}+d_{jK-1}}{2d_{jK-1}} & a_{jK-1}-d_{jK-1} \le t_j \le a_{jK-1}+d_{jK-1} \\ 1 & t_j > a_{jK-1}+d_{jK-1} \end{cases} \tag{7}$$

When $a_{j0}>a_{j1}>...>a_{jK}$, single index attribute measure function $\mu_{ijk}(t)$:

$$\mu_{ij1}(t)=\begin{cases} 0 & t_j < a_{j1}-d_{j1} \\ \dfrac{t_j-a_{j1}+d_{j1}}{2d_{j1}} & a_{j1}-d_{j1} \le t_j \le a_{j1}+d_{j1} \\ 1 & t_j > a_{j1}+d_{j1} \end{cases} \tag{8}$$

$$\mu_{ijk}(t)=\begin{cases} 0 & t_j < a_{jk}-d_{jk} \\ \dfrac{t_j-a_{jk}+d_{jk}}{2d_{jk}} & a_{jk}-d_{jk} \le t_j \le a_{jk}+d_{jk} \\ 1 & a_{jk}+d_{jk} < t_j < a_{jk-1}-d_{jk-1} \\ \dfrac{a_{jk-1}+d_{jk-1}-t_j}{2d_{jk-1}} & a_{jk-1}-d_{jk-1} \le t_j \le a_{jk-1}+d_{jk-1} \\ 0 & t_j > a_{jk-1}+d_{jk-1} \end{cases} \tag{9}$$

$$\mu_{ijK}(t)=\begin{cases} 1 & t_j < a_{jK-1}-d_{jK-1} \\ \dfrac{a_{jK-1}+d_{jK-1}-t_j}{2d_{jK-1}} & a_{jK-1}-d_{jK-1} \le t_j \le a_{jK-1}+d_{jK-1} \\ 0 & t_j > a_{jK-1}+d_{jK-1} \end{cases} \tag{10}$$

…where i = 1, 2, ..., n; j = 1, 2, ..., m; k = 1, 2, ..., K.

The integration method is used to solve the attribute measure value of index I_j belonging to risk level R_k (k = 1, 2, …, K). The single index attribute interval measure function $S_{ijk}(t)$ is established. Take $a_{j0}<a_{j1}<...<a_{jK}$ as an example. The equations are as follows:

$$S_{ij1}(t)=\begin{cases} \int_{t_j^-}^{t_j^+}\mu_{ij1}(t)dt & t_j^+ \le a_{j1}+d_{j1} \\ \int_{t_j^+}^{a_{j1}+d_{j1}}\mu_{ij1}(t)dt & t_j^- \le a_{j1}+d_{j1} \le t_j^+ \\ 0 & t_j^- \ge a_{j1}+d_{j1} \end{cases} \tag{11}$$

$$S_{ijk}(t)=\begin{cases} 0 & t_j^+ \le a_{jk-1}-d_{jk-1} \\ \int_{a_{jk-1}-d_{jk-1}}^{t_j^+}\mu_{ijk}(t)dt & t_j^- \le a_{jk-1}-d_{jk-1} \le t_j^+ \le a_{jk}+d_{jk} \\ \int_{t_j^-}^{t_j^+}\mu_{ijk}(t)dt & a_{jk-1}-d_{jk-1} \le t_j^- \le t_j^+ \le a_{jk}+d_{jk} \\ \int_{t_j^-}^{a_{jk}+d_{jk}}\mu_{ijk}(t)dt & a_{jk-1}-d_{jk-1} \le t_j^- \le a_{jk}+d_{jk} \le t_j^+ \\ 0 & t_j^- \ge a_{jk}+d_{jk} \end{cases} \tag{12}$$

$$S_{ijk}(t)=\begin{cases} 0 & t_j^+ < a_{jK-1}-d_{jK-1} \\ \int_{a_{jK-1}-d_{jK-1}}^{t_j^+}\mu_{ijK}(t)dt & t_j^- \le a_{jK-1}-d_{jK-1} \le t_j^+ \\ \int_{t_j^-}^{t_j^+}\mu_{ijK}(t)dt & t_j^- \ge a_{jK-1}+d_{jK-1} \end{cases} \tag{13}$$

…where t_j^- and t_j^+ are the low and upper value of measured interval of index I_j respectively.

(2) Multiple index synthetic attribute measure analysis.

The multiple-index synthetic attribute measure function is as follows:

$$\mu_{ik}=\sum_{j=1}^{m} w_j S'_{ijk} \tag{14}$$

$$S'_{ijk} = S_{ijk} \Big/ \sum_{k=1}^{K} S_{ijk} \tag{15}$$

…where ω_j is the weight of index I_j, s.t. $0 \le \omega_j \le 1$ and $\sum_{j=1}^{m}\omega_j = 1$.

(3) Attribute recognition analysis.

Let an ordered set R = {R_1, R_2, …, R_K}, and the confidence degree $\lambda \in (0.5,1]$, which is usually taken as 0.6~0.7.

When $R_1>R_2>…>R_K$:

$$k_0=\max\left\{l:\sum_{k=l}^{K}u_k \ge \lambda, 1 \le l \le K\right\} \tag{16}$$

When $R_1<R_2<…<R_K$:

$$k_0=\min\left\{l:\sum_{k=1}^{l}u_k \ge \lambda, 1 \le l \le K\right\} \tag{17}$$

…where x_i belongs to risk level R_{k0}.

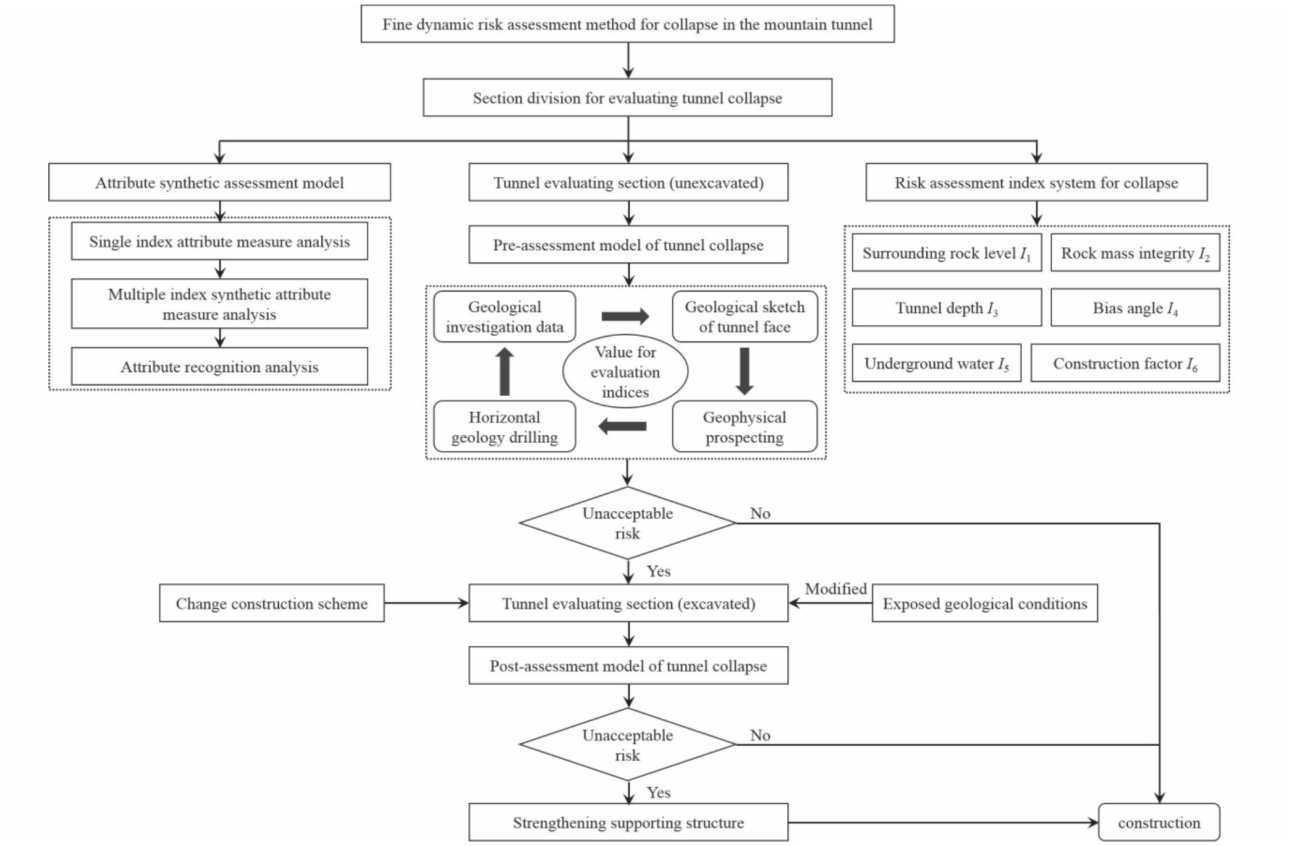

Fig. 2. Flow chart of dynamic risk assessment method for tunnel collapse.

Dynamic Risk Assessment Method for Collapse

The risk of tunnel collapse varies between different periods of construction. Therefore, the fine dynamic risk assessment method is established, which includes pre-assessment and post-assessment models. The flow chart of this method is shown in Fig. 2.

(1) The pre-assessment model.

The purpose of establishing the risk pre-assessment model is to determine the potential collapse of an unexcavated section of mountain tunnel in advance, which can provide the evidence for selecting a reasonable construction method and construction scheme. Therefore, the risk pre-assessment for collapse in mountain tunnels is carried out before excavation. The values of 6 evaluation indices are determined according to geological investigation data, geological sketch of tunnel face, geophysical prospecting data and horizontal geology drilling data. When the risk level of collapse is unacceptable, the construction method and scheme are improved in order to avoid the occurrence of collapse in the process of excavation.

(2) The post-assessment model.

Compared to the pre-assessment model, the post-assessment for collapse in mountain tunnels is conducted after the surrounding rock is excavated and before the support structure is applied. The purpose is to provide evidence for adjusting the support structure. On the basis of the pre-assessment model, the values of 6 evaluation indices are modified according to the exposed geological conditions. When the risk level

Table 8. Standard of risk acceptance for collapse.

Level	Comment	Acceptance criterion	Control decision
R_1	No risk	Disregardful	Normal construction
R_2	Low risk	Negligible	Normal construction
R_3	Medium risk	Acceptable	Normal construction and strengthening monitoring
R_4	High risk	Unacceptable	Cease work and starting early warning. Some measures should be taken to avoid the risks
R_5	Very high risk	Non-acceptance	Cease work, high attention and starting early warning. The specialist consultation should be employed to develop some control measures for avoiding risks

of collapse is unacceptable, the support structure is strengthened.

(3) Risk acceptance criterion.

According to the fatalness, the collapse hazard in the tunnels is divided into R_1 = {No risk}, R_2 = {Low risk}, R_3 = {Medium risk}, R_4 = {High risk}, and R_5 = {Very high risk}[35]. In order to control the unacceptable risks within acceptable levels, the risk acceptable criterion has been developed to reduce the possibility of collapse in the mountain tunnels, as shown in Table 8.

Combination Weighting Method

The influence of different factors on collapse hazard in the mountain tunnels is different. Therefore, the effective weighting method is very important to accurately evaluate the fatalness of tunnel collapse. A combination weighting method is proposed based on subjective weight and objective weight. The former is determined by frequency statistic method, and the latter is determined by analytic hierarchy process (AHP).

$$W = \{w_1, w_2, \ldots, w_6\} \tag{18}$$

$$w_j = k_1 w_{jo} + k_2 w_{js} \tag{19}$$

…where w_{jo} and w_{js} is the objective weight and subjective weight of evaluation index I_j respectively, and k_1 and k_2 are weight distribution.

(1) Frequency statistic method.

The frequency statistic method is an objective weighting method that can make good use of the information of historical data and avoid the deviation caused by human factors. In this paper, 300 cases of tunnel collapse were collected, including 208 cases of highway tunnels, 78 cases of railway tunnels and 14 cases of subway tunnels [36]. Through detailed analysis of the causing disaster factor, the objective weights of 6 evaluation indices are calculated based on the frequency statistic method.

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

(2) Analytic hierarchy process (AHP).

The AHP method is a subjective weighting method that can integrate the knowledge and experience of experts, and the intension and preference of decision-makers. Based on the 1~9 scale method proposed by Saaty et al. (Table 9), the judgement matrix can be constructed by pair-wise comparison judgments of evaluation indices of the same level, which is denoted as $M = (m_{ij})_{n\times n}$ (n is the number of risk factors). The m_{ij} is the importance degree of I_i compared with I_j to the evaluation object.

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

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \tag{20}$$

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} b_{ij}} \quad (i = 1, 2, \ldots, n) \tag{21}$$

…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:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(B\cdot W)_i}{w_i} \tag{22}$$

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

$$CI = \frac{\lambda_{\max} - n}{n-1}, \qquad CR = \frac{CI}{RI} \tag{23}$$

…where CI is the consistency index and RI is the mean random consistency index, which takes its value from Wang [39]. CR is the coincidence coefficient. When CI and CR are less than 0.1, the constructed judgment matrix is scientific.

Table 9. Scale of preference between two elements in AHP [37, 38].

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
Reciprocal	Opposites	Used for inverse comparison

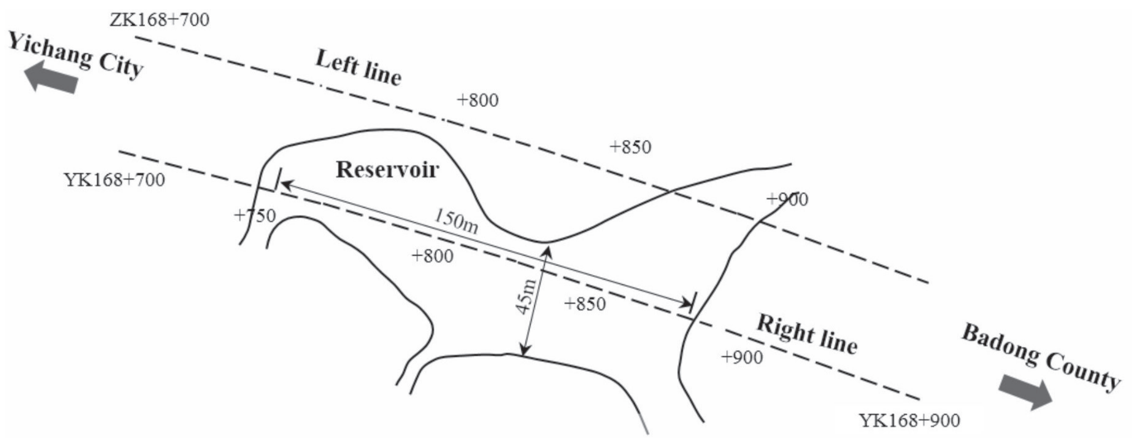

Fig. 3. Positional relationship between reservoir and right Duanjiawu Tunnel [40].

Results and Discussion

Engineering Background

Duanjiawu Tunnel is a separated tunnel of the expressway from Yichang City to Badong County in Hubei Province, which is located in the Yanduhe town in Badong County. The lengths of the left and right tunnels are 3315 m with ZK168 + 165~ZK171 + 480, and 3260 m with YK168 +1 80~YK171 + 440 respectively. The nearest net distance between the left and right tunnels is 23 m, and the headroom area of the tunnel is 10.25 m×5.0 m. Duanjiawu Tunnel has the following hydrological and geological characteristics:

(1) Maximum depth of the tunnel is about 120 m, and its minimum depth is about 20 m. The buried depth is shallow.

(2) The formation lithology is argillaceous siltstone, silty mudstone and marl intercalated with limestone, which are seriously weathered. The grades of surrounding rock are mainly V and IV. The strength and integrity of rock mass is poor.

(3) The tunnel site is subordinate to the northern edge area of Zigui depression, which is a monoclinal structure. The fold structures are open and widely developed.

(4) The tunnel area is middle-low mountain area of tectonic erosion and denudation. According to design data and measurements, there is a small reservoir in the surface of the tunnel section YK168 + 720~YK168 + 910. The length, average width and maximum depth of the reservoir is about 150 m, 45 m and 10 m respectively. The common water storage is 40000 m^3, and it will change according to rainfall.

Table 10. Value assignment for evaluation indices.

Stake number		Geological condition	I_1(km/s)	I_2	I_3(m)	I_4(°)	I_5	I_6
YK168 + 720~910	Pre-assessment	Medium weathered argillaceous siltstone (soft rock), a small reservoir; groundwater closely related to surface water, linear-flow seepage	[2.72, 3.29]	[0.31, 0.35]	[37, 50]	[45, 58]	[0.7, 0.8]	II
	Post-assessment	Rock mass reinforced by advanced small pipe grouting	[3.41, 3.74]	[0.71, 0.73]	[37, 50]	[45, 58]	[0.3, 0.4]	II
YK169 + 212~222	Pre-assessment	Medium weathered argillaceous siltstone, broken rock mass; undeveloped groundwater with raindrop-like seepage. Surrounding rock level IV	[2.24, 2.34]	[0.29, 0.30]	[86, 89]	[45, 58]	[0.2, 0.3]	II
	Post-assessment	The exposed surrounding rock is seriously intercalated with mud. The fissure water is developed.	[1.82, 1.93]	[0.22, 0.25]	[86, 89]	[45, 58]	[0.4, 0.5]	II
YK170 + 165~150	Pre-assessment	Medium weathered marl intercalated with limestone (soft rock), broken rock mass, occasional dissolution; undeveloped groundwater with raindrop-like seepage. Surrounding rock level IV	[1.94, 2.14]	[0.23, 0.27]	[86, 89]	[35, 40]	[0.2, 0.3]	II
	Post-assessment	Exposed rock mass: intensely and moderately weathered marl (soft rock), developed joint fissure with seepage and filled mud, fragmental structure; extremely strong water yield property.	[1.84, 1.99]	[0.20, 0.23]	[86, 89]	[35, 40]	[0.6, 0.7]	II

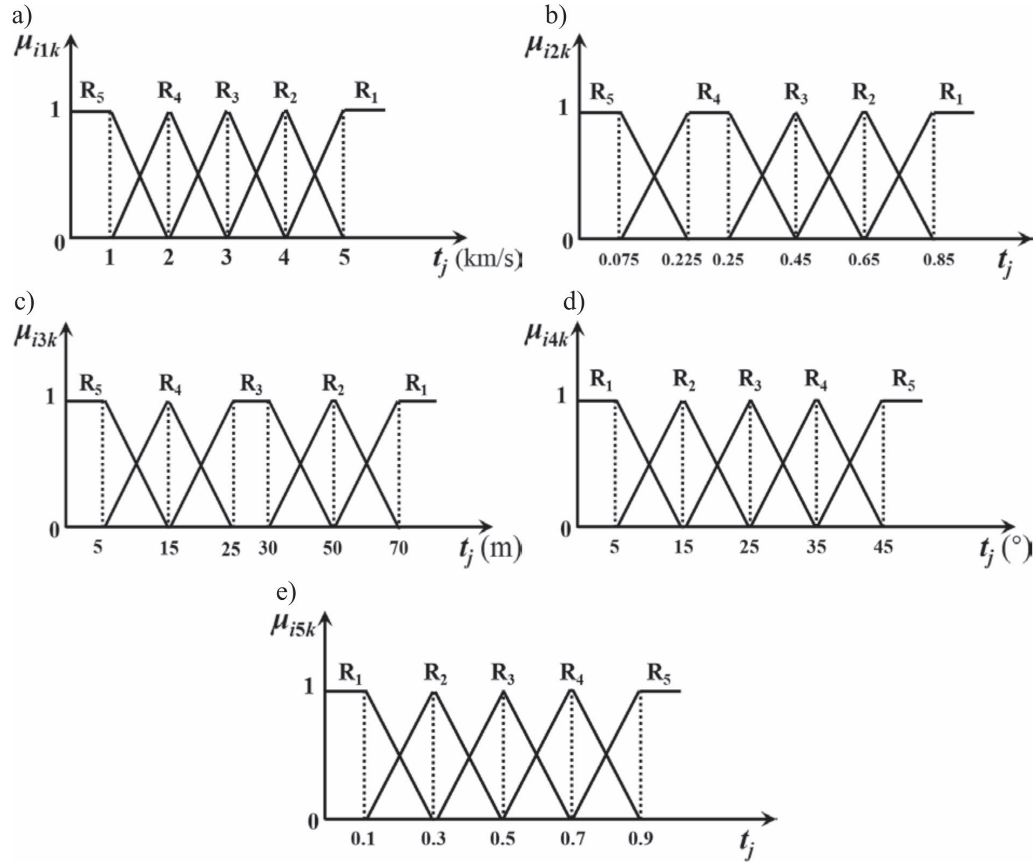

Fig. 4. Single index attribute measure function of evaluation indices: a) Surrounding rock level I_1, b) Rock mass integrity I_2, c) Tunnel depth I_3, d) Bias angle I_4, e) Groundwater I_5.

The reservoir is narrow and long along the axis trend of the tunnel, and directly above the top of the section YK168 + 720~YK168 + 910 at the entrance of Duanjiawu Tunnel. The position relationship between tunnel and reservoir is shown in Fig. 3. In addition, the depth of this section is about 37 m, and the surrounding rock is medium weathered argillaceous siltstone, which belongs to soft rock. The grade of surrounding rock is V.

Therefore, Duanjiawu Tunnel is a high-risk tunnel. The self-stability of surrounding rock is poor, and the arch can easily collapse without support.

Dynamic Risk Assessment for Collapse

(1) Value assignment for evaluation indices.

In the pre-assessment stage, the values of surrounding rock level I_1, rock mass integrity I_2, tunnel depth I_3, and bias angle I_4 were quantified according to the longitudinal velocity obtained by tunnel seismic prediction (TSP), acoustic logging result, the difference between design vault and ground elevation, and geological sketch of working face respectively; groundwater I_5 was quantified according to hydrological data obtained by comprehensive advanced geological

Table 11. Dynamic risk assessment results of collapse.

Sample		Synthetic attribute measure value					Collapse risk
		R_1	R_2	R_3	R_4	R_5	
YK168 + 720~910	Pre-assessment	0	0.171	0.331	0.251	0.249	R_4
	Post-assessment	0.064	0.610	0.274	0.110	0.127	R_2
YK169 + 212~222	Pre-assessment	0.135	0.284	0.120	0.336	0.127	R_4
	Post-assessment	0.074	0.162	0.183	0.290	0.293	R_5
YK170 + 165~150	Pre-assessment	0.196	0.223	0.018	0.530	0.034	R_4
	Post-assessment	0.074	0.101	0.061	0.698	0.068	R_4

forecasting, including the electromagnetic method, electric method and horizontal drilling; the construction factor I_6 was determined based on construction performance of previous working circulation. In the post-assessment stage, the values of surrounding rock level I_1, rock mass integrity I_2, bias angle I_4, and groundwater I_5 were modified based on excavated geological conditions; the value of tunnel depth I_3 was obtained according to the difference between the actual vault and ground elevation; construction factor I_6 was determined according to the construction performance of this working circulation. Due to limited space, the high-risk sections of right Duanjiawu Tunnel were selected to verify that this method is scientific and feasible (Table 10).

(2) Combination weight.

The objective weight vector was as follows:

$$W_o = (w_{1o}, w_{2o}, w_{3o}, w_{4o}, w_{5o}, w_{6o}) \\ = (0.256, 0.197, 0.088, 0.155, 0.200,0.104)$$

The subjective weight vector was obtained based on analytic hierarchy process (AHP). First, according to the specific geological conditions of tunnels and expert experience, the relative importance degree of evaluation indices was analyzed, and the judgement matrix was constructed by 1~9 scale method:

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

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

Where the CI and CR<0.1, the matrix meets consistency check. The weight distribution are $k_1 = 0.5$ and $k_2 = 0.5$. The combination weight vector was as follows:

$$W = (0.272, 0.184, 0.074, 0.127, 0.244, 0.101)$$

(3) Assessment results.

Since the single index attribute interval measure value is equal to the area enclosed by the upper and lower limits of the interval and single index attribute measure function, the coordinate graph of the above function is given first as shown in Fig. 4. Then, according to the upper and lower limits and equations (11)~(13), the attribute interval measure value of I_j (j = 1, 2,…, 6) can be determined. The dynamic risk assessment results of the collapse of Duanjiawu right tunnel are shown in Table 11.

Fig. 5. Collapse situation of tunnel face YK169+212.

Excavation Verification

According to assessment results and the close hydraulic relationships between underground water and the reservoir, the collapse and water inrush were very prone to happen at YK168 + 720~YK168 + 910. A lot of treatment measures were used, such as advanced small pipe grouting before construction, the three-bench seven-step excavation method and reserved core soil in the construction, and strengthening the initial support before construction. Therefore, the collapse didn't occur in this section. When the right tunnel was constructed to face YK169+212, exposed surrounding rock was seriously intercalated with mud, and fissure water developed. Therefore, the collapse happened in the tunnel face (Fig. 5). On December 16, 2011, the collapse with 15m long and 1100m^3 collapse amount happened at YK170+165~YK170+150. Nine people who were working in tunnel face YK170+080 were trapped. An almost conical ground collapse of diameter 25m and depth 5m occurred. In addition, these results are consistent with those obtained by the dynamic evaluation model [40, 41].

Conclusions

(1) A new attribute interval assessment model is proposed, where the measured value of each evaluation index is an interval rather than a definite value. The single index attribute measure is equal to the area enclosed by upper and lower interval limits and single index attribute measure function. Therefore, the integration method is introduced to solve the single index attribute measure value. Finally, based on multiple index synthetic attribute measure analysis and attribute recognition analysis, the risk grade of collapse is determined.

(2) A dynamic risk assessment method for tunnel collapse is proposed based on new attribute interval model and combination weighting method, including pre-assessment before the excavation and post-

assessment after the excavation and before the support. 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.

(3) The proposed methods were successfully applied to the dangerous section of right Duanjiawu Tunnel from Yichang City to Badong County expressway. The results showed good agreement with the results of other methods and actual excavation situations, which proved that the proposed method is scientific and practical.

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Conflict of Interest

The authors declare no conflict of interest.

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